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Analysis Model to Optimize Ground Stations in Built-up Areas

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A Charo

“Cuando a Natura place sublimar a un mortal, no es maravilla que muchas cosas logre; debemos alabar en él el poder del Creador, que a tales hombres levanta al frágil barro; más cuando un hombre resiste a la más dura de todas las pruebas de esta vida, y a si mismo se vence, entonces bien podemos mostrárselo con alboroto a los demás y decirles; Ahí lo tenéis; es él, es el de veras.”

***Cuando un hombre a si mismo se vence, Goethe (1749-1832).
Fragmento de los Misterios, 1785.***

ABSTRACT

Geomatics has been revolutionary in research and development in a large variety of domains. This discipline, based on spatial data information involves every method and tool, from geographic data acquisition to distribution. One of its main characteristics is adaptability to a problem which needs to be solved or analyzed through integration of different technologies, taking into consideration the work scale and the required resolution. Another is the visualization of data and deliverables obtained by applying different software tools considering the required digital formats and the most adequate representation for a better understanding of the results.

This research is based on the exploration of geomatics tools and techniques to provide a best solution in the site selection of satellite ground stations in built-up areas. In this sense, the research started with the analysis of the most relevant critical points during site selection to introduce the research problem of the satellite ground station scenario in built-up areas. Whereas the critical points from the analysis of the ground station mission were the limited transmission power on board and the few minutes per satellite pass, as regards the point of view of the ground station location, the critical points were the data set required for the satellite tracking software and the spatial position of the ground station. In this context, the approach adopted was the selection of the most adequate framework. Firstly, the ground station scenario was recreated by updating information regarding the satellite visibility times from the location site and by generating the 3D digital model of the ground station location. Secondly, through the analysis of the current state of the available satellite access times from the ground station site by applying the satellite mission simulation software. Finally, development of a swift data post-processing method for an in-situ preliminary analysis of the ground station location site by simulating the antenna customized elevation mask.

In this thesis, an analysis model is presented as a contribution to optimize ground stations locations in built-up areas. The model stages have been developed to provide the best solution for the possible case scenarios considering; ground station mission requirements and facility constraints as the main location factors in the analysis process within these urban environments, and; application of results of 3D visualization

techniques as useful tools in the decision taking process when different professionals are involved in the project. In addition, this thesis describes the theoretical models applied in the analysis of three possible ground station case scenarios which correspond with; the given location site scenario in the case study at Universidad Politécnica de Madrid (UPM); site selection scenario within a selected location in the case study at California Polytechnic State University (Cal Poly), and; location site selection scenario within a location area in the case study at The Catholic University of America (CUA).

The main goal obtained from the framework experimentation in these case scenarios was the design of the measurement set-up when using different technologies of data capturing sensors, in particular, the antenna support designed in the case study at Cal Poly University that allowed transforming the signal spectrum measurements into azimuth and elevation parameters.

Finally, this thesis concludes with the validation of the analysis model proposed to optimize ground station locations in built-up areas since the model stages have been validated in each case study implementation, and the research objectives established from the analysis of the research problem have been achieved in the possible case scenarios analyzed.

RESUMEN

La Geomática ha sido revolucionaria en investigación y desarrollo en una amplia variedad de dominios. Esta disciplina, que se ocupa de la información de datos espaciales, incluye todos los métodos y herramientas que van desde la adquisición de datos geográficos hasta la distribución de los mismos. Una de sus principales características deriva de la integración de diferentes tecnologías, y radica en su adaptabilidad a la resolución y análisis de un problema concreto, teniendo en cuenta tanto la escala de trabajo como la resolución requerida. Otra de sus características es el hacer posible la visualización de los datos y productos finales con la aplicación de herramientas de software que contemplan qué formatos digitales son necesarios y cuál es la representación más adecuada para obtener una mejor comprensión de los resultados.

La investigación de esta tesis doctoral explora las herramientas y técnicas geomáticas para obtener la mejor solución en la selección de la localización de estaciones terrenas de satélite en áreas construidas. En este sentido, la investigación comenzó con el análisis de cuáles eran los puntos críticos más relevantes durante la selección de una localización de una estación en áreas construidas, tomando como problema de investigación el escenario de las estaciones terrenas de satélites. Los puntos críticos en el análisis de la misión de la estación terrena fueron la limitada potencia de transmisión y los pocos minutos del pase de cada satélite; y en la localización de la estación terrena, el definir el conjunto de datos que eran necesarios para el análisis del problema desde el software de seguimiento de satélites y establecer cuál debía de ser la posición espacial concreta de la estación terrena. En este contexto, para la selección del marco de trabajo se adoptó un nuevo enfoque. En primer lugar, se recreó el escenario de la estación terrena a través de la actualización relativa a los tiempos de visibilidad del satélite desde el emplazamiento seleccionado para su localización, y generando un modelo digital de este escenario tridimensional de la estación terrena. En segundo lugar, se analizó el estado actual de los tiempos de acceso al satélite disponibles desde el emplazamiento de la estación terrena, mediante el software de simulación de la misión del satélite. Finalmente, se desarrolló un método ágil de post-procesamiento de datos que permitiese

llevar a cabo el análisis preliminar in-situ de la ubicación de la estación terrena, con una simulación de la máscara personalizada de elevación de la antena.

En esta tesis se presenta como contribución más importante, un nuevo modelo de análisis que permite optimizar la localización de estaciones terrenas en áreas construidas en relación a los tiempos de transferencia de datos. Las fases del modelo han sido desarrolladas para proporcionar cuál es la mejor solución en los posibles casos de escenarios que pueden encontrarse, considerando en el proceso de análisis en entornos urbanos tanto los requisitos de misión de la estación terrena y las restricciones de instalación, como los factores de su localización; y aplicando a los resultados las técnicas de visualización 3D como una nueva herramienta que puede resultar muy útil en el proceso de toma de decisiones cuando el proyecto cuenta con la participación de diferentes especialistas. Además, esta tesis describe los modelos teóricos que han sido de aplicación en el análisis de tres posibles escenarios de estaciones terrenas que se corresponden con: el estudio de la localización con una estación terrena ya instalada, escenario del caso de estudio en la Universidad Politécnica de Madrid (UPM); tener como tarea la selección de la ubicación concreta de la estación terrena sobre una cubierta ya seleccionada, en el escenario de la California Polytechnic State University (Cal Poly); y la propuesta abierta de emplazamiento en el tercer caso de estudio en The Catholic University of America (CUA).

El principal logro experimental obtenido de la investigación realizada en este marco de trabajo en los casos de estudio indicados, fue el diseño de un nuevo método de medición que considera el uso de diferentes tecnologías y sensores de captura de datos, y en particular el diseño de un nuevo soporte de antena resultado del caso de estudio de la Universidad de Cal Poly, soporte que permitió transformar las medidas de espectros de señal a los parámetros de azimut y elevación.

Finalmente, esta tesis concluye con la validación del propio modelo de análisis propuesto para optimizar localizaciones de estaciones terrenas en áreas construidas, en su implementación en los tres casos de estudio, de acuerdo a los objetivos establecidos en el análisis del problema de investigación, que han sido alcanzados en los escenarios analizados.

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“If you can’t explain it simply, you don’t understand it well enough.”

Albert Einstein (1879-1955)

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LIST OF ACRONYMS

ADC	Analog to Digital Converter
ADCS	Attitude Determination and Control System
AMSAT	The Radio Amateur Satellite Corporation
AOS	Acquisition Of Signal
APL	Applied Physics Laboratory
BIM	Building Information Modeling
CAD	Computer Aided Design
CDF	Cumulative Distribution Function
CUA	The Catholic University of America
CMM	Coordinate Measuring Machine
DSS	Decision Support System
EDM	Electronic Distance Measurement
EMI	Electromagnetic Interference
ESA	European Space Agency
ETSIT	Escuela Técnica Superior de Ingenieros de Telecomunicación
FFT	Fast Fourier Transform
FM	Frequency Modulated
FOV	Field of View
GENSO	Global Educational Network for Satellite Operations
GEOID	GENSO Experimental Orbital Initial Demonstration
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GS	Ground Station
GSFC	Goddard Space Flight Center
IACS	Institute for Astrophysics & Computational Sciences
IDA	Institute for Defense Analyses
INMS	Ion and Neutral Mass Spectrometer
INTA	Instituto Nacional de Tecnología Aeroespacial
ISS	International Space Station
ITU	International Union of Telecommunication

JPL	Jet Propulsion Laboratory
LEO	Low Earth Orbit
LOS	Los Of Signal
MarCO	Mars Cube One
MEMS	Micro Electro Mechanical System
MST	Master Software Tool
NASA	National Aeronautics Space Administration
NEAScout	Near Earth Asteroid Scout
NRCSD	NanoRacks CubeSat Deployer
NSF	National Science Foundation
NSRS	National Space Reference System
ODPO	Orbital Debris Program Office
OPAL	Orbiting Picosatellite Automated Launcher
OPUS	Online Positioning User Service
ESRO	European Space Research Organization
TT&C	Telemetry, Tracking and Command
OSCAR	Orbiting Satellite Carrying Amateur Radio
PCB	Printed Circuit Board
PDM	Panel Deployer Mechanism
P-POD	Poly-Picosatellite Orbital Deployer
RBW	Resolution Band Width
RF	Radio Frequency
RFI	Radio Frequency Interference
RTK	Real Time Kinematic
STK	System Tool Kit
UHF	Ultra High Frequency
UPM	Universidad Politécnica de Madrid
UTCG	Gregorian Coordinate Universal Time
UTM	Universal Transverse Mercator
VHF	Very High Frequency
WGS84	World Geodetic System 84

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1 INTRODUCTION

1.1 Research background

Geomatics have been revolutionary in order to support innovative solutions based on spatial data information, which involve every method and tool from geographic data acquisition to distribution. This recent term indicates an integrated, multidisciplinary approach to the use of specific tools and techniques chosen to acquire, integrate, manage, analyze and spread spatial data in digital format; which can be used for several applications and range over a broad variety of domains such as geography, agriculture, communications, forestry, health, urban management, civil engineering, etc.

From the exploration of geomatics disciplines and techniques and the increasing fields of applications, this chapter introduces the usefulness of those in the optimal location analysis of facilities and its integration for providing proper spatial information.

From an overview of the facility location analysis of the satellite ground segment, the research problem about the increase in demands of ground segment scenarios in built-up areas is introduced, as are the objectives to solve the optimal location analysis.

1.1.1 Geomatics disciplines and techniques

The term *geomatics* (*geos*: Earth, *matics*: informatics) was created at Laval University in Canada in the early 1980s, based on the concept that the increasing potential of electronic computing was revolutionizing surveys and representation sciences and that the use of computerized design (video-diagram) was compatible with the treatment of huge amounts of data. Geomatics is defined as a systemic, multidisciplinary, integrated approach to selecting the instruments and the appropriate techniques for collecting, storing, integrating, modeling, analyzing, retrieving at will, transforming, displaying and distributing spatially georeferenced data from different sources with well-defined accuracy characteristics, continuity and in a digital format. The development of survey disciplines has progressed rapidly over recent decades; from spatial geodesy to precision topography; from photogrammetry to remote sensing, and; from numerical cartography to the processing of observations, to the GIS (Geographic Information System), DSS (Decision Support System) and expert system (Gomarasca, 2009, p. 1-3). Figure 1 shows the geomatics disciplines and techniques (unless otherwise indicated, all illustrations, graphics, and photographs presented were created by Jesús Nieves-Chinchilla).

Figure 1. Geomatics disciplines and techniques.

Geomatics applications in location analysis processes can be seen in a variety of domains in order to update the spatial information of a place or to optimize the location of a facility, and in other applications in research and development (Doran & Daniel, 2014; Schelhorn et al. 2014; Corsini et al. 2013; Castagnetti et al. 2013; Manfré et al. 2012; Artese et al. 2013; Zhan & Lai, 2012; Scaioni & Alba, 2010; Buckley et al. 2009; Alba et al. 2007; Tonini et al. 2009; Fahsi et al. 2000; García-Palomares et al. 2012; Umar et al. 2015; Trubint & Bojović, 2006; Behan, 2013; Kathuo & Mubea, 2016; Hussian et al. 2015; Hugenholtz et al. 2015; Rodríguez Cielos et al. 2016; Mills & Barber, 2004; Zazo et al. 2015; Molina et al. 2014).

This thesis focuses on the in-situ data capturing technologies, as the research approach is based on the particular use of the location term relative to the spatial information of an object with respect to a specified object-point, as it can be seen in Figure 2.

Figure 2. Geomatics tools and techniques integration to update the spatial information of a place, even to recreate the 3D scenario, and; to analyze the optimal site selection of an object within the place by simulating possible scenarios to make an optimal decision relative to specific criteria.

Despite the complexity of the optimal location analysis of a facility with respect to necessary criteria, geomatics discipline allows the integration of different data capture technologies to achieve the desired data resolution, the data fusion between them by compatible software, and different digital format deliverables which allow professionals from different scopes to be better informed and to make more efficient decisions based on spatial data information.

1.1.2 Satellite ground station location analysis

A Ground Station (from now on, GS) is an earth based point of communication with satellites. As a sensor for transmitting and receiving radio waves, it needs coverage both to have a clear communication link in order to receive data and telemetry and, to be able to send commands and data to the satellite for its control and operation.

Generally, the GS location is outside congestion areas where communication links mainly depend on the satellite orbit selected for the mission and the radio frequency spectrum in the GS location area. Figure 3 shows the aerial view of the Kourou station located at the town of Kourou (French Guiana) in South America.

Figure 3. Kourou station aerial view (ESA, 2007).

To introduce the GS mission a typical configuration of a satellite communication system is described in Figure 4 which is basically comprised of a space segment and a ground segment. The space segment consists of one or more orbiting satellites in a cluster or constellation formation and ground facilities, also named TT&C (Telemetry, Tracking and Command) station, to operate and maintain the satellites in orbit. The ground segment, also named earth station, includes two types: stations owned and operated by a service provider, and stations individually owned and managed which require operating the ground segment of the network operator (Elbert, 2001, p. 2).

Figure 4. Definition of the space segment and the ground segment (Elbert, 2001, p. 2).

The ground system mission, integrating one GS or more, is to establish a robust communication link with the satellite providing operational quality and coverage along the mission.

To introduce the research context in relation to the GS location analysis Figure 5 (Wertz & Larson, 2005, p. 623) shows the basic configuration of the satellite communication system which comprises the space segment, the ground system that includes the GS facilities for satellite control and operations, and the data users. In addition, this figure

shows the GS mission relevancy in the relationship between the space segment, ground system and data users.

Figure 5. Relationship between Space segment, Ground system and Data users, (Wertz & Larson, 2005, p. 623).

The GS mission mainly comprises the following operations (Fortescue, 2003, p.477):

- Tracking operations of the satellite orbit in each satellite pass along the mission.
- Telemetry operations to acquire and record satellite mission data and status.
- Commanding operations to control the functions of the satellite.
- Controlling operations to determine orbital parameters, to schedule satellite passes and to monitor and load the on-board computer.
- Data processing operations to provide the engineering and scientific data in the required formats along the mission.
- Data sharing operations to other worldwide GSs and processing centers.

1.1.2.1 Analysis factors in the location site selection

As initially mentioned, the GS locations are outside congestion areas. The analysis of the location site selection mainly addresses issues relative to the cleanness of the radio spectrum in the area, the GS facilities design and construction, and other requirements necessary for installation and operation such as the provision of electrical power to the facilities and to comply with basic power and voltage regulation

requirements among others, and the indoor and outdoor environment in which the power system operates with a significant effect on reliability.

Regarding the analysis relative to the cleanliness of the radio spectrum in the area, in particular, the external noise caused by radio electric emissions from terrestrial, atmospheric, extraterrestrial and man made noise, are analyzed. In addition, there are numerous factors that affect radio wave propagation extracted from the antenna subsystem characteristics, which include transmission power, antenna gain, attenuation factors, and noise (Vasilescu, 2005, pp. 255-257).

Regarding the GS design and construction, normally GS sites are located in isolated places with restricted access which add difficulties to the GS installation and to future works of maintenance. In addition, the terrain altimetry surrounding the GS location affects the technical requirements of satellite orbit visibility (Ebert, 2001, p. 298).

As the thesis approach is based on the analysis of the predefined GS spatial position, Figure 6 shows the critical points identified from the site selection point of view and available solutions in the GS mission performance.

Critical Points	Factors	Solutions	Improvements
Terrain altimetry	Satellite orbit visibility	High geographic location	Increase of operational quality and GS performance
	Design and Construction	Isolated places	
	Constraint: Availability of the GS at low elevation angles, decreasing the available satellite visibility		
Radio spectrum	Potential interferences	Shielding and grounding	Reduce radiated or conducted interference
	Stronger emitters	Measuring signal spectrum	Increase the communication links quality in certain directions
	Constraint: Availability of the GS in particular directions, decreasing the available satellite communication times		

Figure 6. Most relevant critical points identified in the analysis of the GS mission from the site selection point of view.

Despite the available solutions for a given GS site selection, this analysis opens further discussion in relation to the analysis, from the GS spatial location, of these critical points before the GS installation; above all, when ground segment engineers must deal in the system communication design with limitations in the space segment configuration, the space platform unit and the orbit mission selection.

1.2 Research problem

The need for student and research teams to support their own satellite missions in order to achieve the tracking and control operations of the built satellites by themselves, as the final stage of their educational and research projects, has given rise to another philosophy in the GS planning and design. In particular, there have been changes of scale in their outdoor and indoor components and above all in new locations on building roofs within the University and research center facilities.

Technological advances associated to these small space platforms have increased the efficiency of their components in both segments space and ground. However, considering the applied low cost concept in these projects as a limitation in the project design, the need to maximize the data download per satellite pass as a requirement in science missions and the available few minutes per satellite pass in low orbits missions, the GS design and location have acquired a major relevance in the mission success. In this new GS scenario in built-up areas, the study of the GS location should also include the following issues:

- First, related to installation constraints for the GS facilities on building roofs.
- Second, related to physical obstacles and signal interference sources near the GS location site which reduce the communication times with the satellite in certain azimuth directions.

In addition, these small and low cost space experimentation platforms add the limitation of power transmission on board and a reduced mission life as other difficulties in the mission success. These constraints in the study of the GS location site selection are especially relevant in low orbit missions for an effective use of the available access times in each satellite pass.

1.3 Research objectives

The particular analysis of the available satellite visibility times from the GS location point of view, in order to determine how the location site selection affects the satellite communication times, was the motivation to start this research.

Established the above mentioned constraints in the research problem for installation and communications of GS facilities in built-up areas and the limitations in the project design of small space platforms for low orbits missions, which is the most relevant factor to maximize the satellite visibility times?

Would it be possible to maximize the data download per satellite pass from the GS location site point of view?

Obtaining a broader perspective of the new GS scenario in built-up areas through a further analysis of the problem statement, gave rise to other questions to be taken into account in the research:

1. Considering the presence of different professionals in the project involved, which are the most adequate processes and techniques to provide the GS location scenario to be analyzed and to visualize the results?
2. Taking into account this new GS scenario on a building roof within spectrum congested areas, which are the most adequate technologies of data capturing sensors and procedures to update the spatial location information?
3. As an installation project on a building roof within urban areas, which are the main analysis factors to include in the location factor for the process of the GS location site selection? How could the influence of the location factor be measured in this scope?

In a wide focus, the aim of this research is: how to optimize the GS location in built-up areas as a contribution to the satellites communications scope, in the particular case of small space platforms in low orbit missions.

In a more confined sense, the aim is to develop a comprehensive framework based on: Reverse Engineering (RE) processes, the integration of data capturing sensors and

simulation software from different scopes, and the location factor analysis. In this context, the following objectives are set to be achieved:

Objective 1. To recreate the GS scenario by updating the available satellite visibility times from the antenna site and by generating the 3D digital model of the GS location platform. In this sense, the research starts with the analysis of the most adequate **RE (Reverse Engineering) tools**. The framework is twofold:

- To provide GS engineers with the true view and geometry of the location site selected, which include relevant information relative to the future GS installation even that relative to improvement proposals for a given GS;
- To visualize the GS facilities impact on the building roof, which is of great importance to take a decision in the GS site selection when different professionals are involved, GS engineers and facility manager.

Objective 2. To analyze the current state of the available communication links from the GS site by the satellite mission software. In this sense, the research follows the analysis of **technologies of data capturing sensors and simulation software**, hardware and software. The framework is twofold:

- To provide updated information related to the GS site and nearby obstacles;
- To provide updated information related to the signal interference sources surrounding the GS site.

Objective 3. To develop a swift data post-processing for an in-situ preliminary analysis of the GS site. In this sense, the research follows the design of a **measurement set-up** when using data capturing sensors from different scopes to in-situ simulate the horizon elevation from the selected GS location. The framework is twofold:

- The software set-up to obtain the captured data set in the required parameters by the mission simulation software;
- The hardware set-up to obtain the captured data set in the same reference system.

Objective 4. To develop a preliminary analysis process for the provisional site selection, taking into account the **location factor analysis**. In this sense, the research concludes in the analysis of the main factors which affect the GS installation by considering the GS engineers' needs and the facility manager rules. The framework is twofold:

- The selection of the main factors taking into account the satellite mission requirements and the facility constraints;
- The valuation criteria of each analysis factor agreed between the GS engineer and the facility manager.

The analysis model proposed in this thesis is the result of this research and is expected to make a contribution in this new scenario of GS location in built-up areas within the satellite communications scope.

1.4 Contributions

The main contribution of this thesis has been developed at California Polytechnique State University (Cal Poly) as a visiting research in the aerospace department, during the international stay of three months.

The main contributions of this thesis have been presented in the following international journals:

Measurement: Journal of the International Measurement Confederation

- Nieves-Chinchilla, J., Farjas, M., & Martínez, R. (2017). Measurement of the Horizon Elevation for Satellite Tracking Antennas Located in Urban and Metropolitan Areas Combining Geographic and Electromagnetic Sensors. *Measurement*, 98, 159-166.

Automation in Construction: International Research Journal

- Nieves-Chinchilla, J., Farjas, M., & Martínez, R. Reverse Engineering of Grond Stations Scenarios on Building Roofs: a case study. (Under Review: 2017, April).

Other contributions of this research have been disseminated through the following conferences and presentations:

American Geophysical Union (AGU)

- Nieves-Chinchilla, J.; Farjas, M.; Martínez, R. (2013, May). 3D Modeling and Optimization of the Location Monitoring Antennas for Picosatellites and Small Satellites. Poster presentation in the *American Geophysical Union's Meeting of the Americas*, Cancun, Mexico, 17-19.
- Nieves-Chinchilla, J.; Farjas, M.; Martínez, R. (2013, December). Analysis Methodology for Optimal Selection of Ground Station Antennas Site in Space Missions. Poster presentation in the *American Geophysical Union's 46th annual Fall Meeting*, San Francisco, CA, USA, 9-13.

European CubeSat Symposium

- Nieves-Chinchilla, J.; Farjas, M.; Martínez, R. (2013, June). Optimization of Ground Station Sites for the Tracking of Nanosatellites using 3D Modeling Techniques. Oral presentation in the *5th European CubeSat Symposium*, Brussels, Belgium, 5-6.

Annual CubeSat Developers' Conference

- Nieves-Chinchilla, J.; Farjas, M.; Martínez, R. (2014, April). Optimization of the Antenna Elevation Mask in CubeSat Missions. Poster presentation in the *11th Annual CubeSat Developers' Conference*, San Luis Obispo, CA, USA, 23-25.

1.5 Thesis structure

The structure of this thesis has been formed as illustrated in Figure 7 to address the research objectives based on the validation proposal of the proposed analysis model:

Chapter 1 **Introduction**; introduces the research background to present the problem statement of the satellite GS scenario in built-up areas, the research objectives,

the contributions along the research period, and the thesis structure including a short description of each chapter.

Chapter 2 **Satellite ground stations location in built-up areas**; describes the new GS scenario in built-up areas to propose a solution in the location site selection by analyzing the influence of the CubeSat era in this new GS scenario for the current state analysis of this GS scenario from the location point of view.

Chapter 3 **Analysis model**; describes the proposed framework to develop the analysis model as the solution to optimize the GS location site in built-up areas. In addition, this chapter describes the analysis model stages and their application including specific results from the analyzed case studies.

Chapter 4 **Case studies**; presents three case studies, which describe the possible GS scenarios to be analyzed from the location point of view: a given location site to re-design, a specific location to select the site, and a location area to select the location site. Moreover, this chapter includes the description of the implemented framework which involves the proposed analysis model, providing the best solution in each case study.

Chapter 5 **Conclusions**; contains final conclusions in relation to each analyzed case study and in relation to the proposed analysis model. It is followed by final reflections and describes future works to further improve the analysis model, the model adaptability in other case scenarios and, suggested applications.

Figure 7. Thesis structure based on the validation proposal of the analysis model.

2 GROUND STATIONS LOCATION IN BUILT-UP AREAS

In the last two decades, the increase of low orbit satellite projects and GS installations within spectrum congested areas has increased the difficulties in the system communication design, in particular from the ground segment point of view. Regarding the satellite orbit selection, the number of low orbit satellite projects has increased in order to provide low cost communication services and also science missions relative to the Earth and the Atmosphere. Regarding the radio frequency spectrum, the new GS locations in built-up areas are associated to the emergence and increase in the number of small satellite projects and their development at universities and research centers to provide low cost access to space in the fields of education, science and space based component testing. In this scenario for satellite communications, the GS location site

has a great influence in the GS performance in relation to the required quality links and coverage along the satellite mission.

The GS scenario in built-up areas is associated to a new generation of small satellites called CubeSats initially developed in the late 90s by a number of organizations and universities in an attempt to accelerate construction opportunities of small and low cost space experimentation platforms (Heidt et al. 2000). The development of CubeSat projects at universities gave rise to another concept of GS in relation to the scale of its components and its location site on building roofs. The need to support their own satellite projects as an educational challenge conditioned this new scenario for the earth-based point of communication with these space platforms within the University facilities, adding to the design of the communications system difficulties relative to built-up areas. In addition, the LEO (Low Earth Orbit) orbits selection as the main destiny of these small platforms increased those difficulties due to the few minutes per satellite pass.

2.1 The CubeSat era

The CubeSat concept was introduced as an educational platform, giving students hands-on experience building, launching, and operating a spacecraft during their university studies. The fast growth of these CubeSat projects has been enabled by applying a “fast fly-learn-refly” and a “off the shelf” *modus operandi*, but above all, thanks to low cost development and launching availability in conventional space projects by enclosing them in a container as a secondary payload (Board & National Academies of Science, 2016).

The year 2005 is considered the beginning of the CubeSat era due to the increase in mission designs with this space platform unit, accounting more than 100 projects launched during 2006 (Swartwout, 2014). This space platform design, introduced for education and industry, and whose main purpose was low cost space experimentation, was based on the experience in the OPAL (Orbiting Picosatellite Automated Launcher) satellite project at Stanford University (California), which started in 1995 and was launched in January 2000 as the first micro-satellite designed and built by students

(Cutler & Hutchins, 2000). Figure 8 shows comparatively the CubeSat position, relative to mass, with other space platforms.

Figure 8. Mass range of the CubeSat unit within the space platforms scale (Rodríguez-Osorio, R. M. (2010).

Among other CubeSat projects, in 2003 the AAU and the QuakeSat were launched giving student teams the opportunity to experiment a real space project, from the platform design to the mission control. The first project, developed at Aalborg University (Denmark) (Alminde et al. 2003), accomplished the mission regarding a camera rotation control, taking photographs of a specific earth area and sending them to the GS (see Figure 9(a)). The second project, developed at Stanford University (US) (Bleier & Dunson, 2005), accomplished the mission regarding the demonstration of a technique to detect seismic activity by finding magnetic signals at low frequency (see Figure 9(b)).

(a)

(b)

Figure 9. 3D virtual views of CubeSat projects. (a) AAU-CUBESAT in orbit with antennas deployed (AAU-CUBESAT, n.d.). (b) External components of the QuakeSat Nano-satellite (Stanford University, 2004).

The amateur development of satellites in the amateur radio scope is the historical reference of the small satellites concept. In December 1961, almost 4 years after the Sputnik I (Russia) and the Explorer I (US) launches, the first radio amateur satellite, with a mass of 4.5 Kg was launched as a secondary payload (Baker & Jansson, 1994). Without any propulsion system, the 22 days in orbit being followed by amateur radio operators from all over the world were a success. The OSCAR (Orbiting Satellite Carrying Amateur Radio) project, involving volunteers, amateur and students, was revolutionary in a new concept of satellite low cost development, the result being the creation of the AMSAT (The Radio Amateur Satellite Corporation) organization in 1969 (Cho et al. 2004). Starting with the OSCAR 5 project (Baker & Jansson, 1994), this nonprofit international organization has contributed to the aerospace scope with several innovations such as the communication technique “*store and forward*”, the platform stabilization with bar magnets, and above all, simplification in the construction processes which considers the environmental impact of the platform during the testing process. Later, in 1990 the first 6 micro-satellites were launched by ESA (European Space Agency) with the collaboration AMSAT (King et al. 1990), both in the design and building processes of the supporting structure that engaged the small satellites pairs to the Ariane IV rocket (see Figure 10(a)). More than 60 satellites have been built since the beginning of the OSCAR project; from the initial idea of setting up the first signal repeater or transponder in space (see Figure 10(b)), to the implementation of continuous improvement in technological innovations. At present, there are 20 OSCAR satellites operative, most of which have been built under the technical specifications of the standard CubeSat (Baker et al. 1994).

Figure 10. OSCAR projects (AMSAT, n.d.). (a) Ariane Structure for Auxiliary Payloads. (b) The OSCAR III Satellite.

Between 2003, year in which the first CubeSat launched and 2013 more than 100 Cubesats were launched. In particular, 80 CubeSats were launched in 2013 (Swartwout, 2013). Some of them are involved in the study of the atmosphere layers and in climatic change such as the RAVAN and the Firefly missions. The first was developed by APL (Applied Physics Laboratory) at the Johns Hopkins University (US), for taking measurements of the radiation emitted from the earth by radiometers (see Figure 11(a)) for a later evaluation with respect to the radiation from the sun; the second one was developed in collaboration between NSF (National Science Foundation) and NASA, for studying the connection between the lightning and the terrestrial gamma rays which generate energetic bursts in the upper atmosphere (see Figure 11(b)).

Figure 11. CubeSat projects developed for the study of the atmosphere. (a) RAVAN CubeSat (Johns Hopkins (n.d.)). (b) Firefly CubeSat (NASA, n.d.).

In March 2017 more than 600 CubeSats had been launched (Kulu, 2017) and the increase in the developing of nano-satellites based on this platform unit augurs a major presence in space in the future. The recognition of the standard CubeSat in the last decade as a profitable and flexible space platform to experiment new techniques and technologies in space missions and in particular to observe the earth and the atmosphere, has led to it being useful in experimental missions to explore space. Among other projects, MarCO (Mars Cube One) and Near Earth Asteroid Scout (NEAScout) will experiment technological innovations especially important to improve future space missions. The MarCO mission, included in the Mars mission, will improve the communication links during the critical moments from atmosphere entry to landing

by deploying two radio antennas: a bidirectional one in the X band, and another for reception in the UHF band. The NEA Scout mission, scheduled for 2018, poses challenges such as the mapping of a nearby asteroid and the deployment of a solar sail as a propulsion system (see Figure 12), and the experimental results will be very useful for the second mission of the Orion spaceship and scheduled for 2021 (Board & National Academies of Science, 2016).

Figure 12. Virtual view of NEA Scout mission (NASA Jet Propulsion Laboratory, n.d.).

2.1.1 The CubeSat space platform

In 1999 Dr. Robert Twiggs at Stanford University and Dr. Jordi Puig-Suari at California Polytechnic University created the technical specifications of the standard CubeSat (see Figure 13(a)) (Heidt et al. 2000). The purpose of this new concept of space platform unit was to speed up the opportunities for building experimental projects, smaller and at low cost thus providing easy access to space. In addition, the CubeSat Program has also focused on developing an infrastructure composed of an extensive developer community, standards for spacecraft and launch vehicle interfaces, and a GS network (Toorian et al. 2008). To date, launching opportunities are as

secondary payloads thanks to specific deployment mechanisms added to launch vehicles such as P-POD (Poly-Picosatellite Orbital Deployer), developed at Cal Poly (California Polytechnic State University) (Puig-Suari et al. 2001), which is capable of deploying up to three CubeSats each (see Figure 13(b)).

Figure 13. CubeSat standard specifications (CUBESAT, 2015). (a) 1U CubeSat Design Specification Drawing. (b) Poly Picosatellite Orbital Deployer (P-POD) and cross section.

This cube (Heidt et al. 2000), defined as a volume of about $10 \text{ cm} \times 10 \text{ cm} \times 10 \text{ cm}$ with an approximate mass of 1.3 Kg and a minimum power of 1 W, has the same components as a communications satellite, the main parts being; a structure (generally built by alloys of aluminum, titanium and beryllium) which must withstand high

radiation and low temperatures; an electronic part which includes built components and subsystems based on MEMS (Micro Electro Mechanical Systems) technology, and; software for the interface between them. The main PCB (Printed Circuit Board) governs all the subsystems: ADCS (Attitude Determination and Control System), RF PCB (Radio Frequency PCB), Energy distribution, Data processing, etc. This is controlled from the GS to verify the operation of the subsystems, and if needed, to modify satellite parameters. Figure 14(a) shows the structure of a CubeSat unit in which the particular shape of the edges is appreciated to be inserted in the P-POD deployed system. Figure 14(b)) shows the component description of the first CubeSat built at Cal Poly University (Schaffner, 2002).

Figure 14. The CubeSat space platform. (a) CubeSat structure (www.cubesatkit.com). (b) CPI CubeSat components: 1 Main PCB; 2 Data Port Connector; 3 Remove Before Flight Switch; 4 Deployment Switch; 5 Transceiver A; 6 Transceiver B; 7 RF PCB; 8 Antenna Mount; 9 Dipole Antenna; 10 Battery Pack; 11 Solar Panel; 12 Solar Panel (Sun Sensor Side); 13 Sun Sensor (Schaffner, 2002).

These small space platforms are mainly considered as communication satellites thanks to their basic capabilities to establish up/down communication links with the GS; in particular, in the VHF (Very High Frequency) and the UHF (Ultra High Frequency) radio amateur frequency bands (Klofas, 2013). Systematic design and development focusing on CubeSats can be seen in several projects which additionally provide further information on Cubesat subsystems (Waydo et al. 2002; Larsen et al. 2002; Alger & Kumar 2008; Burlacu & Lorenz 2010; Cote, 2011; Franquiz et al. 2014; Spangelo &

Longmier 2015). Figure 15 shows the functionality of the CubeSat platforms as a communications conventional satellite.

Figure 15. Basic functions of the CubeSat space platforms.

2.1.2 LEO orbits missions

LEO orbits are the main destiny for science missions, atmosphere and Earth observations, remote sensing and communications (Guo et al. 2016; Coster & Komjathy, 2008; Esper et al. 2000; Neeck et al. 2005). Some examples include; science missions from the ISS (International Space Station) at an altitude of 400 Km above Earth are related to biology, biotechnology, physical sciences and technology (Macias et al. 2012; Kanas & Ritsher, 2005; Armengol et al. 2008; Fink et al. 2014); the Hubble Space Telescope currently operating at an altitude of 547 Km (Thienel & Sanner, 2007; Krist et al. 2011); Earth observation missions collecting remote sensing data such as the Landsat satellite constellation at an altitude of 705 Km (Goward et al. 2001); the QuickBird satellite at an altitude of 600 Km (Sandau, 2006), and; communication missions such as Orbcomm satellite constellations at different altitudes between 715 to 830 Km (Evans & Maclay, 1998).

LEO orbits are also the main destiny for CubeSat missions (Waydo et al. 2002; Woellert et al. 2011; Selva & Krejci 2012; Straub, 2012; Gill et al. 2013; Moretto, 2008; Long et al. 2002; Portilla, 2012; Crowley et al. 2011), and there are two CubeSat

deployment systems to put them into these orbit, as a secondary payload in a conventional launch rocket (see Figure 16(a)) and from the ISS by the NRCD (NanoRacks CubeSat Deployer) system (see Figure 16(b)).

(a)

(b)

Figure 16. Cubesat deployed systems. (a) 3D simulation of the CubeSat deployed from the VEGA rocket (ESA, n.d.). (b) NRCSD system at the ISS (NANORACKS, n.d.).

Within LEO orbits, CubeSat platforms provide; applications in Earth observation missions such as natural disasters monitoring, cartography, and meteorology by using high resolution cameras and applied filters, and; associated services in communications by using low power Earth transceivers, among others.

Figure 17 shows the distribution of science mission applications in between the years 2000 and 2012 (DePascuale & Bradford, 2013).

Figure 17. Small satellites applications increase in science missions (DePascuale & Bradford, 2013).

This increase in the last years of science missions in LEO orbits can be seen in; small satellites projects which integrate CubeSat platform units, such as FIREBIRD placed into orbit by the Delta II rocket to study the Van Allen belts radiation (Crew et al. 2015), and Centennial placed into orbit by the ISS to validate a satellite monitoring system from Earth; initiatives of CubeSat constellations (Conklin et al. 2013; Leiter, 2013; Subramanian et al. 2015; Peral et al. 2015; Bandyopadhyay et al. 2016), and; experimental studies in CubeSat performances and specific applications (Jones, 2013; Cartwright, 2014; Venturini, 2014; Sakraker et al. 2014; Briggs et al. 2015; Fields et al. 2015; Westerhoff et al. 2015; Carreno-Luengo et al. 2016). In addition, the last report developed by the IDA (Institute for Defense Analyses) and the Science and Technology Policy Institute (US) which analyzed the first decade of the CubeSat era (2005), confirms the rapid growth in CubeSat activity and concludes that due to this there are several issues to solve such as making the launch market sustainable and the space

debris caused by CubeSats in LEO orbits (Board & National Academies of Science, 2016).

2.1.3 New ground station scenario

From a preliminary analysis of the GS scenario in built-up areas, the main conclusion was that the emergence and increase in the number of CubeSat projects and their development at universities and research centers gave rise to another philosophy in the planning and design of satellite GSs. In particular, the changes of scale in outdoor and indoor components and their new locations on building roofs to support satellite missions.

This new GS concept is based on a conventional communications system but simplifies the subsystem components:

- First, by keeping the basic configuration to establish the bidirectional communication.
- Second, by integrating in the space and ground segments the same hardware and software to use the radio amateur frequency bands.

Regarding the location, building roofs is the most common site selection within built-up areas. However, the location site selection addresses issues relative to:

- The availability of highest buildings within the GS location area.
- A flat area within the building roof for the GS outdoor components (antennas configuration).
- A nearby room ideally in the floor just below for the GS indoor components (control room).

Figure 18 shows the components scale of this GS configuration in comparison with a conventional GS related to both outdoor and indoor components. Figure 18(a) shows the Tromsø GS at Norway which was the first LEO satellites GS established in 1967 by ESRO (European Space Research Organization) (Darling, n.d.) versus GS antennas installed at Cal Poly University (see Figure 18(c)). Figure 18(b) shows ESA GS at

Cebreros (Spain) as a conventional GS configuration of antenna and TT&C subsystems versus GS configuration at Vigo Spanish University (see Figure 18(d)).

Figure 18. GS component scales comparison of the GS scenario analyzed respect to a conventional GS configuration. (a) Tromsø GS Antenna (Kongsberg (n.d.)). (b) Cebreros GS configuration (ESA, 2006). (c) Cal Poly GS antenna (PolySat, 2015). (d) Vigo GS configuration (HumSat, 2017).

A typical GS configuration is formed of four main components (see Figure 19): antennas, rotor units, a transceiver and a modem (Rodríguez-Osorio et al. 2008). These are integrated in the outdoor and indoor GS components:

- Outdoor components: antennas for amateur radio bands, helix and yagis are normally used for VHF and UHF whereas reflectors or patches can be used for the S band; a positioner, which controls the antenna orientation to track the satellite by using rotor units, and; polarizers and amplifiers.
- Indoor components: a transceiver, which translates the modulated signal to a carrier frequency in the GS link band; a modem, which modulates or demodulates the information frames transmitted by the GS or received from the satellite, respectively; a computer in charge of data encoding/decoding, and; tracking software in charge of the pointing and tracking systems.

Figure 19. Outdoor and indoor components of a basic GS configuration.

As regards antennas configuration, yagi antennas are especially adequate for outdoor environments when a high gain antenna in UHF/VHF is required as they present low wind resistance. Yagi antennas are linear antennas formed by an array of dipoles allocated along the antenna axis. These antennas are used for satellite tracking in UHF and VHF have directivities between 11 and 15 dBi, leading to antenna beam widths between 51 and 32 deg. Figure 20(a), shows a 10-element Yagi antenna, and Figure 20(b) shows the principal cuts, E-plane and H-plane, of the normalized antenna pattern of a 10-element Yagi antenna in UHF (435 MHz), with a gain of 14 dBi. In this case, the dipoles are allocated along the direction of the antenna pattern peak ($\theta=90$ deg) (Balanis, 2005, pp. 468-478). Currently, the S band is being incorporated in small

satellite communication systems in a 2.2-2.3 GHz frequency range as a cost-effective radio solution for these satellites (Figure 20(c)).

Figure 20. Antennas configuration. (a) Yagi antenna elements description (Balanis, 2005). (b) Principal cuts of the yagi antenna pattern (Balanis, 2005). (c) VHF/UHF/S-band configuration (ISIS, n.d.).

2.2 Ground station mission scenario

The need to support CubeSat missions within the university and research center facilities has conditioned this new scenario for the earth-based point of communication with these space platforms. The environment of these built-up areas add difficulties in the design of the communications system relative to the satellite FOV due to the presence of physical obstacles higher than the GS location, and relative to the signal transmission due to the presence of signal interference sources surrounding the GS location.

In these GS scenarios the system communication design must take into account those phenomena that reduce the available satellite communication times from the GS location along the horizon in certain azimuth directions; in particular, in the satellite AOS (Acquisition Of Signal) and LOS (Loss Of Signal).

The presence of signal interference sources is even more relevant than the physical obstacles in the communication outage, reducing the signal quality. Interference effects depend on the amount of frequency overlap between the interfering spectrum and the wanted channel pass band (Richharia & Westbrook, 1999). Their effects will depend on the frequency band range, the interfering signal waveform, the bandwidth, and the signal-to-interference power ratio. Several studies and measurements in urban and industrial environments indicate the presence of man-made interference sources which affect mainly VHF and UHF frequency bands (Murthy & Krishnamraju, 1995; Lauber & Bertrand, 1984; Victory, 2001; Leferink et al. 2010; Irving, 1998).

Figure 21 shows the simulation of a particular satellite tracking pass from a GS located on a building roof. This simulation shows the graphic representation of the limitations in this new GS scenario in a specific satellite pass:

- Relative to the available satellite visibility time, the white dotted line describes the optimal satellite FOV from the antenna rotor center, and the white discontinuous line describes the current FOV in view of nearby obstacles (white dots).
- Relative to the available satellite communication time, the yellow discontinuous line describes the antenna minimum elevation necessary to reduce the signal interference in the satellite AOS caused by a radio amateur antenna which radiates in the GS mission frequency band.

In this particular case of VHF and UHF signal transmissions, an effective communication link depends on ground wave propagation, but above all on obstructions between the GS and the satellite. This fact is of great relevancy at low elevation angles as it reduces the available satellite communication times.

Figure 21. Simulation of the GS scenario on a building roof in a particular satellite tracking pass.

The presence of signal interference sources in the satellite AOS and LOS azimuth directions along the mission reduce more the limited satellite FOV caused by typical obstacles in built-up areas. These phenomena are even more relevant for a CubeSat mission in LEO orbits due to the limited power on board in these space platform units and the reduced time in each satellite pass in these orbits for signal transmissions.

2.2.1 CubeSat-LEO mission analysis

To complete this GS scenario description for a CubeSat-LEO mission, the ETSIT (Escuela Técnica Superior de Ingenieros de Telecomunicación) GS located at UPM (Universidad Politécnica de Madrid) University was selected. In this scenario simulation the STK (Systems Tool Kit) program (www.agi.com) was applied. This included; first, a circular orbit with 98° of inclination as the orbit parameters selection; second, an antenna minimum elevation of 10° as an antenna constraint, and; third, a mission length of five months as the simulation period of time. Figure 22 shows the CDF (Cumulative Distribution Function) of the satellite duration for the selected orbit altitudes. In this satellite mission simulation duration of the pass was achieved by a single GS for 28, 41 and 50 % of the passes for 380, 600 and 800 km, respectively.

Figure 22. Graphic results of the cumulative distribution function for different analyzed orbit altitudes by applying the STK program.

Table 1 shows the statistics for the duration of visibility passes for the different satellite altitudes without considering the time it takes to track the satellite and to establish communication.

Table 1. Statistics from the visibility passes duration for different analyzed orbit altitudes by applying the STK program.

Satellite Altitude	Raw Data			
	Average pass duration	Longest pass	Number of passes	Daily coverage
380 km	4.72 min	6.02 min	470	1.88 %
600 km	6.69 min	8.51 min	616	1.03 %
800 km	8.31 min	10.60 min	712	2.70 %

The average pass duration is inversely proportional to the satellite altitude, and as can be seen the number of passes is reduced as the satellite altitude decreases. In addition, as the altitude of the satellite decreases the opportunities to track or communicate with it from a GS become more restricted further complicating satellite scheduling (Vallado, 2001, p. 844). Despite the great advantage of LEO orbits being the short distance thus reducing transmission power requirements and minimizing the propagation delay (Elbert, 1999, p. 23), the radio signal must pass through. Therefore, for science and communication missions it is becoming necessary to have a detailed analysis of the GS coverage to take advantage of every single satellite pass. Taking into account that the communication time between the satellite and the GS is of 5-15 minutes, 6-8 minutes during the day (Zee & Stribany, 2002; Keim & Sholtz, 2006), for those science missions that require a huge download data, a satellite visibility duration of 8 min per pass was considered as a reference value for these missions.

However, satellite orbits are imposed by mission and payload requirements and the GS engineers must deal with this limitation to operate the mission efficiently such as in the QBito nano-satellite mission with an initial orbit altitude of 380 Km (Calvo et al. 2016).

This fact has a great relevance in the amount of data download in each satellite pass taking into account that the bit rate is of 9600 bits per second and the average pass duration is of 4.72 minutes.

From the analysis of the CubeSat-LEO missions, the following critical points which add difficulties in the system communication design were identified; first, limited transmission power on the satellite board; second, a short life mission relative to the CubeSat units selection, and; third, a few minutes per satellite pass relative to LEO orbit selection as the mission altitude. In this sense, advances in technology in platform capabilities and cluster or constellation formations in low orbits coverage have been able to make CubeSats a real alternative for access to LEO missions:

First, regarding the CubeSat performance, several technological solutions have been developed in the communication and power subsystems; compact high-gain antennas when large quantities of payload data need to be transmitted at high speed (Klofas & Leveque 2012); megabit-class transmitter compatible with the CubeSat size and power restrictions provided by radio manufactures as the solution for high-speed communications (Gao et al. 2009); small mechanisms for the antennas and solar array deployment (Yousuf et al. 2008; Jansen et al. 2010; EncinasPlaza et al. 2010; Santoni et al. 2014; Prodoningrum et al. 2015; Vilán et al. 2015; Nascetti et al. 2015; Suárez-Fajardo et al. 2016), and; high performance components (Ballester-Gúrpide, 2000; Galli, 2008; Aguado et al. 2008; Jayaram, 2009; Rani et al. 2010; Bhuma & Balsu, 2012; Radhakrishnan et al. 2016). Moreover, MEMS technology integration has increased CubeSat capabilities by replacing subsystems such as the inertial measurement and thruster propulsion units, and by substituting larger and heavier components of the attitude control system such as gyroscopes and magnetorques (Steyn, 2001; Huang & Yang, 2009; DeRooij et al. 2009; Shea, 2009; Moore et al. 2010; Conversano & Wirz, 2011; Gauer et al. 2012; Li et al. 2013; Cahoy et al. 2013; Quadrino, 2014; Cervone et al. 2016). Figure 23(a) shows the Panel Deployer Mechanism (PDM) for the Xatcobeo mission which allowed a mission life increase of two years. Figure 23(b) shows two mounted gyroscopes on the SwissCube PCB built with MEMS technology, which reduce the required power for the attitude control operations but maintaining high sensibility.

Figure 23. Technological advances in CubeSat units. (a) Solar array deployment in the Xatcobeo platform (USC, 2012). (b) MEMS technology integration in the SwissCube platform (www.swisscube.epfl.ch).

Second, regarding the CubeSat unit, increasing the number of these units is a solution to increase the amount of power on board and in consequence the mission life. Figure 24 shows a 3U CubeSat built by students at Delf University of Technology in The Netherlands (Brower et al. 2008). This was launched in April 2008 and was designed for a life time of one year (to date operational).

Figure 24. View of the deployed Delfi-C3 spacecraft (www.delfispace.nl).

In particular, this space platform configuration based on standard CubeSat units from 2U to 6U increases the propulsion and deployment subsystems capacity and the solar panels surface, and allows a major number of instruments on board, or a larger or heavier instrument such as a infrared spectrometer, a hyperspectral camera, a solar sail, a star tracker, and other specific payloads in relation to the mission concept (Tsitas & Kingston, 2010; Moore et al. 2010; Lappas et al. 2011; Näsilä et al. 2011, McBryde & Lightsey, 2012; Sakraker et al. 2014; Mouroulis et al. 2014; Franquiz et al. 2014; Fields et al. 2015; Westerhoff et al. 2015; Carrero-Luengo et al. 2016; Calvo et al. 2016; Hegel, 2016).

Third, regarding the coverage area in LEO missions, increasing the number of platforms is the solution to increase the coverage in a particular Earth area. A single space platform has a limited coverage during its daily orbital period which, depending on orbit altitude which is between less than 2 hours and 12 hours (see Figure 25(a)). Therefore, a constellation is the ideal satellite formation for a total coverage. Figure 25(b) shows a 66 satellite constellations, distributed in 6 orbital planes, for a total coverage for an altitude of 780 Km. This constellation corresponds to the Iridium system, built by the Planet Labs company (California, US) in a market context designed to provide a mobile satellite service for hand-held personal telephones (Keller & Salzwedel, 1996).

Figure 25. Coverage area in LEO orbits. (a) Limited area by a single space platform (Rosado, 2008, p. 6). (b) Total area by a nano-satellite constellation (Cambridge Consultants, 2017).

Flying formations from a pair of CubeSats to a cluster or constellation can be seen in current projects, research and initiatives such as; a pair of cubesats to measure terrestrial gamma-ray flash beams (Briggs et al. 2015); a constellation of 50 nano-satellites to study the low thermosphere (Gill et al. 2013); others relative to the subsystem performance and efficiency (Calvo et al. 2016, Guo et al. 2013); the formation flying demonstration using 6 cubeSats (Subrmanian et al. 2015); the constellation mission requirements using nano-satellites (Catalin, 2009; Bandyopadhyay et al. 2015), and; others relative to specific applications in space optical 3D scanning (Straub, 2015) for Earth geodesy and aeronomy (Conklin et al. 2013), and for real time geolocation (Leiter, 2013).

Despite current satellite constellations being mainly lead by market projects for permanent metric, met data and imagery, use of these nano-satellites platforms and their application in formation flying have made it possible to establish small satellites projects based on CubeSat units as a real alternative to conventional satellites for LEO orbit missions. Obviously, these solutions reduce the impact on the above mentioned critical points in the mission success from the space segment point of view. However, due to a Cubesat unit being the most typical space platform selection at universities and research centers, technological challenges remain related to the described critical points.

2.2.2 LEO ground station mission analysis

From the analysis of the GS scenario in built-up areas those critical points are even more relevant in the communication system design along the mission, mainly due to factors such as the antenna gain in relation to its size and the noise temperature at GS locations within spectrum congestion areas. In this scenario, it is becoming necessary to increase the GS operational quality of the components in relation to the antenna subsystem performance and to increase the communication times by connecting several GS in relation to particular LEO satellite coverage along the mission.

Regarding the GS operational quality, critical points identified are; first, the assembly adaptability to any direction in azimuth and elevation; second, the accuracy of the initial orientation derived from the position of the satellite and the antenna; third, the

effectiveness of satellite tracking through a continuous system in order to avoid possible signal losses, and; fourth, the antenna support system used. In this sense, available solutions can be seen in satellite projects and research associated in these scenarios. These include: the use of azimuth-elevation pedestals to minimize tracking losses along the satellite passes (Willey, 2000; Sarlak et al. 2016), antenna size selection to achieve the desire gain margin to establish satellite communication links (Willey, 2002; Wallace, 2009)), the antenna positioning system using stepper motors and the design of software driver for this positioning system (Seavey 2000, Broilo 2002, Preindl et al. 2009, Mulla & Vasabekar 2014, Linderer & Dunkin 2015), and recent advances in optical and laser communication systems (Kingsbury 2015, Riesing 2015, Yoon et al. 2016). Figure 26 shows some of these technological advances such as the azimuth-elevation-tilt pedestal and digital control of the antenna rotor.

Figure 26. Antenna positionin systems. (a) Azimuth-Elevation- Tilt pedestal (Willey, 2000). (b) horizontal/Vertical RAS (WiMo, n.d.).

Regarding the LEO satellite communication times, connecting several GSs worldwide to track a particular satellite or cluster, is a solution to give total coverage to these satellite projects along the mission. In this sense, GENSO (Global Educational Network for Satellite Operators) software was presented in 2007 as the solution to increase the access to a particular satellite, by implementing a software networking standard via internet (Klofas et al. 2008; Dascal et al. 2011).

To date, other network initiatives range from developed networks such as Mercury and MC3 in US and GSN in Japan, to the SATNet project presented in 2014 at Cal Poly University (Cutler & Kitts, 1999; Mann & Cutler, 2008; Alcaide, 2014; Felt, 2014). In this sense, further research proposes models and tools to analyze the GS networks usability such as a tool which computes the number of required GS (March, 2014), and a model to evaluate space communication network capacity (Spangelo et al. 2012), both of which increase the network mission efficiency. This fact is especially important to recover the daily amount of data generated by a single satellite or by a satellite constellation as the QB50 project previously mentioned, which integrates 50 GS located worldwide (see Figure 27).

Figure 27. Network of ground stations for the QB50 project (Scholz, 2015).

In addition, the GEOID (GENSO Experimental Orbital Initial Demonstration) initiative is expected to be the communication backbone of the initial version of the HumSat system. The main goal is to use the constellation of satellites and the GENSO network to provide support for humanitarian initiatives, especially in developing areas or areas without infrastructure (Ridolfi et al. 2011; Vilán et al. 2015). Figure 28 shows the HumSat mission concept as an example of the GS networks implementation in relation to the satellite coverage, particularly in the development of a standard interface via internet to use existing GS and to share data services.

Figure 28. Scheme of the HumSat mission concept (HumSat, n.d.).

Technological advances include: those in the GS components, those in hardware and software which increase the operational quality of the GS mission. In turn the implementation of GS networks increases the reduced satellite coverage in LEO missions from a single GS, and in consequence maximizes the required satellite contact times for command and telemetry operations. Despite the above, a high per cent of these operations depend on GS networks availability, and hence on the probability of the designed satellite communications system operating correctly throughout the mission (Maral & Bousquet, 2002, p. 725). In this sense, as GS locations in built-up areas are the most typical selection sites for ground segment facilities in these CubeSat projects, signal obstructions caused by phenomena within these environments affect satellite communications at low elevation angles and hence the GS mission performance, including the GS network mission efficiency.

2.2.3 Analysis from the location point of view

From the GS location point of view the presence of signal obstructions in built-up areas, caused by buildings and surrounding interference sources, affect the

communications system design in specific satellite passes along the mission. As previously mentioned, in the GS scenario simulation on a building roof (see Figure 21), physical obstacles and signal interference sources located in certain azimuth directions from the GS site reduce the available satellite FOV. These phenomena become specific critical points in relation to the GS location site as they reduce the communication times between the satellite AOS and LOS, thus increasing critical points identified in the analysis of CubeSat-LEO missions from the GS point of view.

In addition, an installation project on a building roof requires considering the building rules as another specific critical point when determining the GS location site. It follows that these rules affect the GS installation project and in consequence the GS components design as flat areas are required for the outdoor (antennas subsystem) and indoor components (control room). In particular the following are to be taken into account:

- Technical specifications of the antennas configuration such as the antennas maximum height and the fastening and anchor systems.
- Safety systems for the installation and for future works of maintenance.
- The structural and visual impact of the GS facilities.

In this sense, there are several examples of solutions that have been applied in engineering projects after location analysis and before the installation stage. These affect the GS components design during the installation stage, and can be seen; first, the first GENSO GS installation planned at the ESA ESTEC facilities (The Netherlands) (Shirville, 2008), which was finally installed at International Space University in Strasbourg (France) to solve the required area for equipments and antennas, and; second, in the antenna support design and safety systems at University of Strathclyde (Glasgow) (Strath, 2017), to solve the non penetrating roof requirement for the installation.

Figure 29 shows the technical solutions applied as examples of problems to solve in these GS case scenarios on building roofs from the point of view of facility constrains:

- Technical solutions in the installation process of the antenna base frame onto the roof (see Figure 29(a)).
- Implementation of safety systems for access and maintenance (see Figure 29(b)).

Figure 29. Technical solutions on a building roof GS installation processes. (a) Mounted system of the antenna base frame onto the roof (Shirville, 2008). (b) Anchoring system by non-penetrating roof mounts and safety systems for access and maintenance (Strach, 2017).

As regards signal obstructions caused by physical obstacles higher than the GS location site such as surrounding buildings and mountains, selecting the highest building within the area maximizes the satellite FOV (see Figure 30(a)) and is the best solution. This can be observed in the GS located at Eindhoven University of Technology (The Netherlands) for the Delfi-C3 mission operations (Hartanto, 2009). Similar solutions to track CubeSat missions in this new GS scenario can be seen at National Cheng Kung University (Taiwan) (Hsiao et al. 2000), at Narvik University (Norwegian) (Eide & Ilstad, 2003) and at Budapest University (Hungary) (Dudás et al. 2014), among others.

Figure 30. Signal obstructions solutions to the GS location within built-up areas. (a) Highest building locations to avoided physical obstacles (Hartanto, 2009). (b) Modular GS to in-situ test communication links in the mission frequency bands (Ichiwaka, 2006).

In relation to potential interference sources surrounding the GS location, the antenna system design and a simulation to achieve the required gain is considered before the installation process for a given site (Stenhaug, 2011). However, a mobile modular GS (see Figure 30(b)) is the best solution to analyze the communication quality in the mission bands from different sites within the location area (Ichiwaka, 2006), as this method allows in-situ measurements to test the required gain for a given antenna design.

Despite the available solutions in the GS selection site process to avoid or to reduce signal obstructions before the GS installation, in most cases the location of the GS is conditioned by the available facilities within the complex at universities or research centers. Cases range from a limited area to a restricted location in which both the best location must be selected. In addition, the existing control room facilities determine the GS location site in the roof area just above, which is not always the best case scenario.

In this GS scenario for tracking LEO satellites, the GS location analysis takes into account the radio spectrum area, the terrain topography and the existing facilities for installation and operations. However, in these scenarios it is becoming more necessary to consider the balance between the quality link and the mission concept in the GS location analysis.

From the link quality point of view, applying a standard antenna elevation mask with a fixed minimum elevation of 10° would guarantee adequate conditions for the satellite communication links, as this would avoid most of the surrounding obstacles and interferences (Cakaj et al. 2007).

From the mission concept point of view the above mentioned standard mask reduces the amount of data download per satellite pass in a science mission. Hence, the satellite FOV must not be considered as a link quality parameter but for the amount of telemetry data in downlinks with minimum possible elevations (Gill et al. 2010).

Figure 31 shows a scheme of the critical points identified from the analysis of the LEO GS scenario located in built-up areas for a CubeSat mission, the available solutions, and constraints identified for a given GS design and its location in a built-up area for tracking a CubeSat unit as the worst case scenario in a LEO satellite mission.

Critical Points	Factors	Solutions	Improvements
Scale of GS components	Antenna Gain	Antenna size	Increase of operational quality and GS performance
	Tracking system	Software driver	
	Constraint: Given antennas subsystem design		
LEO orbit missions	Few minutes per satellite passes	GS network	Increase of satellite coverage along the mission
	Constraint: Availability of the GS network		
CubeSat unit		High-gain antennas	Increase of transmission speed
	Limited power on-board	Solar-array deployment	Increase the amount of power on-board
		CubeSat units increase	Increase the mission life time
	Constraint: Mission concept relative to the low-cost project		
Built-up areas	Facility constraints	Mounted and safety systems	Increase the security requirements for installation and works of maintenance
	Nearby obstacles	High Buildings	Increase the satellite FOV
	Signal interference sources	Standard elevation mask	Increase the communication links quality
	Constraint: Available facilities and even limited area for installation		

Figure 31. Critical points identified in the analysis of the GS scenario in built-up areas for tracking CubeSat-LEO missions.

2.2.3.1 Further analysis from the location point of view: antenna elevation mask concept

In these scenarios of CubeSat-LEO tracking missions from GS located in built-up areas, the GS mission has acquired a relevant position in the mission concept success,

since all critical points identified in the analysis of CubeSat-LEO missions from the GS point of view increase the relevancy of the location site selection.

By considering a given GS design and its location in a built-up area for tracking a CubeSat unit in a LEO satellite mission, the mission success depends on the available communication times in each satellite pass from the GS site. In this scenario, in-situ physical obstacles and signal interference sources remain on the selected building roof when installing the GS antenna subsystem. These are added to create the worst case scenario where there is an existing signal obstruction surrounding the GS location area.

These scenarios are not strictly analyzed from the spatial location of the antenna positioning system center. The antenna subsystem works as follows: the antenna steering needed to acquire and to track the satellite signal is typically established using a system motor called rotor which is governed by specific software. The tracking software with information of the satellite orbit is engaged to the antenna rotor controller to start the tracking process when the satellite is in view over the horizon visible from the antenna rotor center. The rotor controller governs the operation of the antenna rotor to generate the required voltages to steer the antenna in the correct angular position along the satellite pass. Then, the antenna comes to stow position once the satellite goes below the horizon.

These programs require a data set from the spatial location of the antenna positioning system center to establish the satellite angular position from the antenna rotor center along the passes. This data set contains:

- The satellite azimuth and elevation to predict when and in which direction the satellite is available to communicate with it until the satellite exit in each pass.
- The orthometric height of the antenna rotor center is needed to establish the real horizon plane from the GS location site.

This data set needed to create the satellite mission scenario from the ground segment point of view is called antenna elevation mask and contains; the geographic coordinates and height of the antenna location site, and; the geographic information surrounding the GS location area that provides the altimetry profile (azimuth, elevation) from the antenna site.

Figure 32 shows the graphic representation of the required data set from the spatial position of the antenna site needed to establish contact in a single satellite pass.

Figure 32. Antenna elevation mask concept applied from the spatial position of the antenna site, in particular, from a predefined antenna point.

Generally this mask is defined by the local terrain geometry obtained from the available digital cartography source, and hence the spatial location of the GS site and obstructions surrounding depend on the source accuracy. In these LEO GS scenarios in built-up areas a further analysis from the geospatial information point of view is needed, particularly as regards the spatial location of nearby physical obstacles and signal interference sources surrounding the GS location site, to propose a best estimation of the antenna elevation mask.

From the point of view of the satellite visibility times, the in-situ capture of the data set in relation to the spatial position of the antenna site and nearby obstacles on the building roof and surrounding provides: first, the available satellite FOV for a given GS site by capturing the horizon visible from the spatial position of the antenna site and, second, the optimal antenna site selection within the building roof area by 3D digitizing the scenario (Nieves-Chinchilla et al. 2013 May; Nieves-Chinchilla et al. 2013 June).

From the point of view of the satellite communication times, the in-situ capture of the data set in relation to the spatial position of potential interference sources on the

building roof and surrounding provides: first, the identification of signal interferences in the satellite mission frequency bands by capturing the signal spectrums along the horizon and, second, the antenna minimum elevation needed to acquire the satellite signals in the interference sources located in certain azimuth directions from the antenna site (Nieves-Chinchilla et al. 2013 December; Nieves-Chinchilla et al. 2014).

Figure 33 shows the in-situ data capturing processes from both points of view at the UPM (Spain) and Cal Poly (US) universities.

Figure 33. In-situ data capturing processes relative to the antenna elevation mask. (a) Satellite FOV from the GS site at UPM University by applying Total Station Survey equipment. (b) Antenna minimum elevation in the interference source azimuth direction from the GS site at Cal Poly University by applying Signal Spectrum Analyzer equipment.

As initially stated, in the analysis of this new GS from the location point of view, both phenomena which cause signal obstructions and facility constraints must be taken into account when installing GSs in built-up areas.

Further analysis from the point of view of the location determines that the antenna elevation mask obtained by in-situ data capturing process provides a best estimation of the satellite communication times from the GS location site. Hence, the usefulness of simulating the horizon elevation diagram for a given site before installation of the GS is

to test the efficiency in satellite tracking operations and, if needed, to apply mitigation techniques either in the redesign or relocation of the antenna (Nieves-Chinchilla et al. 2017).

In these GS scenarios, the antenna customized elevation mask is proposed as the most relevant factor in the location site analysis to optimize the GS site selection.

3 ANALYSIS MODEL

This chapter describes the proposed analysis model to optimize GS locations in built-up areas. The approach of the proposed model is the analysis of the GS scenario from the location point of view, taking into account the facility constraints and GS mission requirements which are established as the main factors in the site selection analysis. Generally, in urban and metropolitan areas the facilities available to install antennas are very limited. Within a university campus or institution area which develops the satellite project, there are even more facility constraints. In most cases the GS location site is given on the building roof, since the control room is already installed as happens for the GS case study at UPM University (Madrid, Spain). In these cases, the application of this model provides GS engineers with updated information of the current state and the solutions available to increase the efficiency in the use of the available communication times from the antenna site. In other cases, the GS location is given on a specific building within the University campus such as the GS case study at Cal Poly University (California, US). In these cases the application of this model provides the optimal site within the location selected considering satellite mission requirements and

facility constrains. The complete application of this analysis model and cases where it has a maximum usefulness are those in which there are several location proposals such as the GS case study at CUA (The Catholic University of America) University (Washington D.C., US). In these cases the application of this model through a preliminary analysis which contains the main analysis factors required by GS engineers and facility manager provides the best location between the proposals. Figure 34 shows the above mentioned cases of application and the particular case study for each one which will be described in chapter 4.

Figure 34. Cases of application of the analysis model to optimize GS location in built-up areas.

Following the implementation of the framework, the main aim of this analysis model is to provide GS engineers with the GS location scenario to take a decision related to the GS design. If it is necessary to improve efficiency in satellite tracking operations, mitigation techniques will be proposed either in the redesign or relocation of the GS facility. The scope of this analysis model is basically: first, for a given GS, to provide updated information of the current state, and solutions to increase the efficient use of the available communication times from the antenna site and, second, for a satellite mission that does not have a GS, to provide the best location between the proposals available and the optimal site within the selected location. In this sense, this chapter introduces the framework to develop this model and in particular, the most adequate processes and techniques for the implementation of each stage. This framework is based on the analysis of the GS location scenario in built-up areas seen in the previous chapter, the

conclusions of which are; first, that the antenna elevation mask is the most relevant factor in the GS selection site where presence of signal interference sources surrounding must be considered for clear radio links with the satellite; second, that facility constraints on building roofs add difficulties in the GS installation; third, that the GS engineers must deal with these constraints in the communication system design which are especially relevant for CubeSat-LEO missions due to the available transmission power on board and the few minutes per satellite pass per day, and; finally, that the GS installation permit requires the facility manager approval which depends on other factors relative to the facility constraints on building roofs. In this sense, 3D digital techniques are of great usefulness for the interaction between several professionals in order to visualize the GS project impact and even to take decisions through the different stages.

3.1 Framework

Following the issues discussed in the previous chapter, this section describes the framework considering the given theoretical approach to propose a solution relative to the current state of the GS scenario in built-up areas. The implementation of the proposed framework is structured in order to achieve the main objectives of the research:

- To recreate the GS scenario by updating the available satellite visibility times from the antenna site and by generating the 3D digital model of the GS location platform.
- To analyze the current state of the available satellite access times from the GS site by applying the satellite mission simulation software.
- To develop a swift data post-processing for an in-situ preliminary analysis of the GS site by simulating the GS antenna elevation mask.

RE (Reverse engineering) has been selected as the reference process in the development of the framework, as this process provides an overall view of the work line to achieve the purpose of this research, which is mainly decomposed into three stages as regards the scenario information: extracting, analyzing and visualizing. In addition, simulation,

as one of the most common RE applications, is the main application to take into account in the framework implementation from the simulation of the current state of the GS scenario and the location proposals based on the generated digital model, to the simulation of the GS antenna elevation mask and the GS mission in different locations within the recreated scenario.

The description of the fundamental knowledge and techniques of the implemented framework allow understanding the stages of the analysis model as the proposed solution to optimize the GS location in this scenario and the included procedures in the framework implementation to solve the problem in each case study.

3.1.1 Reverse engineering

RE is a powerful tool to reproduce real objects in a virtual world. RE enables engineers and designers to scan the geometry of an object as it exists in the real world, and to create a CAD (Computer Aided Design) model of that object. These processes of creating digital realities that represent real-world scenarios is called Reverse Modeling by the industry, and enables extracting missing information from anything which is man-made, by going backwards through its development cycle and analyzing its structure, function and operation (Dennet, 1995; Eilam, 2005; Raja, 2008; Wang, 2011). This is an innovative solution for modeling objects without physical contact enabling the representation of their complex architecture, and a realistic interpretation (Farjas et al. 2011). In addition, the application of new 3D survey methods can be adapted to different needs and highlight the possibility to carry out reliable engineering processes (Wehr, 1999; Guidi, 2012). RE is used for distinct applications such as; the development of competing products in the aerospace, automotive, medical, and software industries; product inspection and quality control; architectural and construction documentation and measurement; fitting clothing or footwear to individuals and determining the anthropometry of a population; generating data to create dental or surgical prosthetics, tissue engineered body parts, or for surgical planning; documentation and reproduction of crime scenes; competitive technical intelligence in order to uncover the uncoordinated features of commercial products; as a learning tool

for academic and other learning purposes; to recover lost documentation due to the original design documentation is inadequate, has been lost, or never existed; product analysis and data acquisition in order to examine how a product works; the components it consists of and its features; the interoperability between all the component parts of an object; replacement of archaic parts in long-lived equipment (e.g., nuclear reactors, airliners, and ships), and; digital update/correction to update obsolete materials or antiquated manufacturing processes to match an 'as-built' condition, to improve product performance and features, and to strengthen the good features of a product based on long-term usage of the product (Reilly, 1992; Fowles, 2000; Pieraccini et al. 2001; Guipert, 2003; Scopigno et al. 2003; Beraldin, 2004; Guidi et al. 2005; Mara et al. 2004; Hermon et al. 2005; Pieraccini et al. 2006; Farjas & García-Lázaro, 2008; Farjas et al. 2004; Frischer, 2008; Arnold & Geser, 2008; Bathow & Wachowiak, 2008; Forte & Pietroni, 2009; Georgopoulos et al. 2010; Guidazzoli et al. 2012; Creté et al. 2013; Tapete, 2013; Friess et al. 2002; Astruc et al. 2003; Astruc et al. 2011; Carcagni et al. 2005; Karasik et al. 2005; Karasik & Smilanshy, 2008; Zapassky et al. 2006; Moitinho, 2007; de Almeida et al. 2013; d'Errico et al. 2009; El-Zaatari, 2010; Lin et al. 2010; Stemp & Chung, 2011).

RE has shown increasing potential in the above mentioned application fields, extracting complex information from raw data and structuring this information in order to provide specific data from digital models. In addition, RE techniques and tools allow a swift relationship between different professionals from different disciplines thanks to its capabilities of simulation, multi-view representation, real time visualization and, digital data extracting in any project stage.

RE consists of a series of iterative steps (Dennet, 1995; Eilam, 2005; Raja, 2008; Wang, 2011), each addressing different questions regarding, in this case, a scenario. These steps may be repeated as often as needed until all steps are sufficiently satisfied. In this sense, the implementation of the RE process as the framework in this research scope requires combining skills and technical knowledge of different disciplines, from satellite communications to engineer and computer science. Figure 35 shows the scheme of the main RE stages which has been composed from the reference in the issue above mentioned.

Figure 35. Main stages of the RE process.

Simulation of the research scenario of the GS locations in building roofs is the main reason to apply the RE process, in particular to analyze the current state for a given GS location or the location proposal for a new GS. In this sense, the simulation of the real scenario for a given GS allows professionals involved in the project to visualize and to extract any digital data to be analyzed. Thus, the simulation of the virtual scenario for a new GS allows these professionals to approve the GS design and the location site before the installation, testing the GS mission requirements and the facility constraints.

In this context, the planning process is the next stage. This must contain an overall view of the requirements and constraints of the scenario to be analyzed, and where the framework is going to be implemented. In this sense, this stage requires project information from the professionals involved to establish the main work lines and the operability of the plan taking into account human resources, equipment, software, logistics, budget, time, etc. Physical to digital process is the following stage which includes the selection of the 3D data acquisition equipment and modeling technique. This stage contains the 3D data capture of the real scenario and the data post-processing. In this case the resultant 3D digital model of the GS location area represents the real scenario from the geometric point of view, considering the characteristics of the selected equipment and the applied measurement system, in particular those related to the resolution, accuracy and outputs for the established physical to digital process. In this stage, before generating the 3D digital model of the scenario, the required 3D information described in the planning stage should be considered in order to accomplish

the objectives in the following stages, extracting knowledge and interpretation. The extracting knowledge stage is divided into two steps:

- Geometric information from the 3D digital scenario.
- Data integration in the current scenario and computer simulation.

The interpretation is the final stage, where results should respond to the reason for applying the RE process as the framework in this research scenario. However, as RE consists of a series of iterative steps, and regarding other requirements and constraints to be included or requested by GS engineers or facility manager, these steps may be repeated as often as needed until all steps are sufficiently satisfied.

3.1.2 3D digital model of the ground station scenario

3D digital model generation of urban scenarios by applying 3D laser scanning technology is especially useful for accurate 3D mapping of other man-made structures, in particular for data capturing from in-situ based views of indoor and outdoor structures of buildings without there being physical contact (Leberel et al. 2010; Finat et al. 2005; Zhao et al. 2005; Biber et al. 2004; Vaaja et al. 2015; Tang et al. 2010; Mill et al. 2013; Arayici, 2007; Jung et al. 2014; Valero et al. 2015). Within these scenarios, there are technical considerations and above all operational constraints and environmental conditions which must be taken into account when planning survey techniques. In addition, it is very important to have good functional knowledge of each workflow step, in order to set clear objectives and expected results in each one which allows an effective sequence of the steps. In this sense, the proposed workflow is based on the experience in 3D digital model generation of archaeological objects and scenarios (Dennet, 1995; Eilam, 2005; Raja, 2008; Wang, 2011) as in this discipline the use of laser scanning technology has wider historical background than in engineering and architecture disciplines. This fact can be seen in numerous publications included in the next section. In this case of the GS location on a building roof, the main purpose is to recreate the scenario taking into account the physical entities which affect the GS location analysis including the GS facilities.

Figure 36 shows the proposed 3D scan workflow, from the selection of a 3D data acquisition system to the generating a 3D digital model.

Figure 36. 3D scan workflow developed to recreate the GS location scenarios in a 3D digital model.

The sections below describe the selection within the proposed RE process of the adequate 3D laser scanner and the sequence of steps to be followed to digitalize a model from real scenarios, from data acquisition to view registration and to data integration.

3.1.2.1 3D laser scanners

3D digital survey techniques and their science and technology evolution in the last two decades have made it possible to approximate the complexity of a physical design or a scenario under study by generating the 3D digital object or scenario. These techniques such as the laser scanner technology which can record huge numbers of points with high accuracy in a relatively short period of time, allows obtaining surface-free forms and generating high density clouds of points. Laser scanners are line-of-sight instruments, so to ensure complete coverage of a structure, multiple scan positions are required (Van Genechten, 2008). The potential of 3D scanning and the capability of working and conducting experiments with 3D digital models in different scenarios are already well-known. It is being applied in documentation processes, conservation monitoring, preservation, restoration, replicas, virtual reconstruction, visualization, virtual reality, dissemination, etc. All of these applications provide the advantages of the

3D data capture (Reilly, 1992; Fowles, 2000; Pieraccini et al. 2001; Guipert, 2003; Scopigno et al. 2003; Beraldin, 2004; Guidi et al. 2005; Mara et al. 2004; Hermon et al. 2005; Pieraccini et al. 2006; Farjas & García-Lázaro, 2008; Farjas et al. 2004; Frischer, 2008; Arnold & Geser, 2008; Bathow & Wachowiak, 2008; Forte & Pietroni, 2009; Georgopoulos et al. 2010; Guidazzoli et al. 2012; Creté et al. 2013; Tapete, 2013); at the same time, it is showing the usefulness of the 3D digitized models as a research tool (Friess et al. 2002; Astruc et al. 2003; Astruc et al. 2011; Carcagni et al. 2005; Karasik et al. 2005; Karasik & Smilanshy, 2008; Zapassky et al. 2006; Moitinho, 2007; de Almeida et al. 2013; d’Errico et al. 2009; El-Zaatari, 2010; Lin et al. 2010; Stemp & Chung, 2011). In the case of urban scenarios, the 3D laser scanner is an ideal solution for any building project, from the design to the inspection stage, or for any survey project, from historic homes to international airports. In this sense, 3D scanning and measurement have become essential in urban projects related to architecture, engineering, construction and surveying. The main 3D data acquisition systems appear in numerous publications (Beraldin et al. 2003; Blais, 2004; Moitinho, 2007; Chen, 2008; Lanman et al. 2009; Sansoni et al. 2009; Remondino, 2011). Every scanner system has a particular resolution, accuracy and data quality, and there is a background of studies related to the measurement parameters and the analysis of the accuracy of results (Boehler et al. 2003; Beraldin et al. 2003; Li, 2011; Havemann, 2012) which must be considered for a particular project in order to determine the most adequate 3D scanner. Figure 37 shows the main 3D data acquisition systems (Beraldin et al. 2003; Blais, 2004; Remondino et al. 2006; Moitinho, 2007; Chen et al. 2008; Lanman & Taubin, 2009; Sansoni et al. 2009; Remondino, 2011).

Figure 37. 3D data acquisition systems.

Contact scanners are useful to manufacture pieces with high accuracy, which require low scanning speed, such as a CMM (Coordinate Measuring Machine). Recreating objects and scenarios which require massive data collection with no physical contact is the most common usefulness of this technology, and in this sense, non contact scanners are the adequate equipment. These are divided into two types, *Passive* and *Active*. Passive scanners instead of emitting radiation by themselves detect reflected radiation (e.g. stereoscopic systems and silhouette techniques). Active scanners emit radiation or light and detect their reflection, so they require a transmitter and a receiver to be integrated in the equipment. Some of the advantages are automatic data collection, massive information collection in a short period of time, ambient light not being required, and usability for different shapes (Paulus et al. 2014; Ebrahim, 2015). In this sense, an active scanner selection is appropriate to generate the digital model of the GS location scenario in urban environments. These active scanners can be divided by the applied system to measure objects range: time of flight, triangulation, phase based, conoscopic holography, and structured light (Van Genechten, 2008). In this case scenario of a building roof scanning, the most adequate system is the phase based, as it takes into account the workspace requirements and in consequence the required data acquisition process (Lerma & Biosca, 2008).

3.1.2.1.1 Phase based scanner

This measurement system type is based on time as a parameter as is the time of flight system, but being faster, since it captures hundreds of thousands of points per second (EH, 2010). The main reason for selecting this system is based on the experience in related scanning projects, which determine that it is the most applicable system for short range distances in heavily congested areas. Phase based scanning uses a constant beam of laser energy that is emitted from the device, and then measures the phase shift of the returned laser energy to calculate distances. The target distance is proportional to the phased difference and the wavelength of the amplitude modulated signal. In addition, the amplitude of the reflected beam provides the reflected power. Some of the advantages of this measurement system are, amongst others: an increased scanning

speed of few minutes per scan, high resolution of up to 0.5 mm, capture of a grey-scaled laser image, large coverage by rotating 360 degrees both horizontally and vertically, and a scanning range of up to more than 100 m. Figure 38 shows the measurement in both systems.

Figure 38. Measurement principles. (a)Phase-based system. (b)Time-of-Flight system (Van Genechten, 2008).

Figure 39 shows these scanner types.

Figure 39. Phase based scanners types. (a) FARO Photon 80 (www.faro.com). (b) Leica HDS6200 (www.leica-geosystems.com).

3.1.2.1.2 Physical to digital process

Once the 3D data acquisition system is selected and the scenario to scan has been delimited, the next stage consists of preparing the workspace for an effective data acquisition process. The following sections briefly describe these stages, and the data post-processing which includes the main steps in order to understand the physical to digital process applied in the research scenario.

3.1.2.1.2.1 Workspace

This first stage consists of preparing all the issues in the 3D data acquisition process involved taking into account the selected equipment and any necessary additional components, and the required objects to scan within the scenario. In this case scenario of the GS location on a building roof the following specific issues relative to the equipment and to the data acquisition process must be considered (Baracchini et al. 2006; Bathow & Wachowiak, 2008; Bruno et al. 2011):

- As regards the equipment, it may be necessary to include a portable power supply (batteries, generator), extension cords, a tent or piece of fabric to block interfering light, or even to build a structure to ensure a complete scanning of the surfaces of interest.
- As regards the data acquisition process, it may be necessary to develop a strategy to ensure efficient scanning of the scenario, taking into account both GS requirements and facility constraints. This fact is of great relevance to determine the goals and objectives during the scanning process and in particular to achieve the requested deliverables.

In this sense, the following recommendations must be considered before the data acquisition process: analyzing the location area to scan, selecting the objects and other physical entities, targeting the optimal locations of the laser scanner, and selecting the optimal locations of the targets. In addition, it is very important to consider measurement error and uncertainty of measurement results before the data acquisition process from possible error sources which may include; resolution and accuracy in the laser equipment; the material and the scale of the scenario and objects to scan; the

temperature and lights in the environment, and; scanning and data post-processing methods part of the methodology, which in most of the cases depends on the experience of the technician (Boehler et al. 2003; Beraldin et al. 2003; Georgopoulos et al. 2010; Li, 2011; Van Genechten, 2008; Havemann, 2012; Son et al. 2002; Huisin et al. 1998; Shultz & Ingensand, 2004).

3.1.2.1.2.2 Data acquisition

This stage consists of capturing the clouds of points from each scanning location previously planned. Appropriate location for station set-up must be considered to reach maximum scanning coverage. In urban scenarios and due to the presence of obstacles close to the objects or to the scenario to scan, several scanning locations are necessary. In order to join the different clouds of points between adjacent scanings, it is necessary to measure targets (common points) with major resolution from the different scanning locations (Georgopoulos et al. 2010; Xiao et al. 2007; Wang et al. 2014; Becerik-Gerber et al. 2011; Franaszek et al. 2009; Bosché & Guenet, 2014). Figure 40 shows these two steps within the data acquisition process in each scanning location applied in the case study at UPM University, by using the Trimble TX5 laser escaner provided by Geotronics (www.geotronics.es). Figure 40(a) shows the scanning target process as this uses the common points from the different scans to join the clouds of points, and Figure 40(b) shows the laser scanner positioning to scan a particular object or a scenario area previously planned.

Figure 40. Data acquisition process in the case study at UPM University by using the Trimble TX5 3D laser scanner equipment (a) Scanning processes of targets. (b) Scanning the object/scenario.

Once the FOV is determined and the resolution is set, the scanning process can be started. Each captured point contains the 3D coordinates (x,y,z) and the pixel obtained from the digital camera included in the equipment. The clouds of points scanned are directly visualized, and represent the real view and geometry of the surface scanned. Figure 41 shows the screenshot from the Trimble Real Works Survey software, provided by Geotronics (www.geotronics.es), which represents the scanning locations, in different colors, of the data acquisition process in the case study at UPM University.

Figure 41. Scanning locations of the roof surface in the case study at UPM University represented in different colours using the Trimble Real Works Survey software.

3.1.2.1.2.3 Data post-processing

This stage comprises mainly two steps in order to form a surface model of objects based on a cloud of points (Tao, 2005; Eybpoosh et al. 2012; Shi et al. 2010; Budak et al. 2012; Walsh & Hajjar, 2009; Van Genechten, 2008). The first step is the preliminary data treatment undergone by applying software for viewing and processing the data from the clouds of points, which includes two actions: noise filtering and registration point. Filtering noisy points consists of removing extraneous, erroneous or other unwanted points. This action can be done by hand or by using automatic algorithms. Registration point consists of performing a concluding fine alignment by bringing

together the scans from different locations into a common reference system, with respect to a global site coordinate system. 3D modeling is the second step which consists of generating a polygonal mesh by connecting all the points in the clouds of points with small triangles. This mesh is an interpolation of the points in three dimensions which generates a surface representation of the object. Figure 42(a) shows the cloud of points of the scanned antenna in the case study at UPM University once the above mentioned filtering and registration actions have been done. Figure 42(b) shows a 3D textured model obtained by applying the 3D tools in the Trimble Real Works Survey software.

(a)

(b)

Figure 42. Data post-processing in the case study at UPM University using the Trimble Real Works Survey software. (a) Cloud of point's registration of the scanned antenna. (b) 3D modeling process of the antenna components.

In order to generate a quality mesh, this process includes other actions such as re-sampling and filling, and reducing the number of points and generating non measured points, respectively. In addition, the quality of the final 3D digital model can be analyzed comparing the raw data and the final mesh by using quality inspector tools (Farjas et al. 2010). The 3D digital scenario and the 3D model can be exported in the required file format to achieve the established objectives (deliverables) in the planning stage, which corresponds to the final stages in the RE process, extracting knowledge and interpretation. For instance, these deliverables in the case scenario of the GS location on a building roof are the cleaned clouds of points data of the GS platform and the 3D model of the selected objects.

3.1.2.2 Geometric information extractions from 3D digital scenario

Object extraction from laser scanning has been a research domain in the last years, from RE problems to building reconstruction, among others (Vosselman & Maas, 2010). The advantage of high density three-dimensional information allows faster and easier extraction of building (indoor and outdoor) elements, and has many applications: deformation monitoring, interfering design, construction archiving, as-built surveys, BIM (Building Information Modeling), etc. (Gielsdorf et al. 2008; Coiner et al. 2002; Tang et al. 2010; Jung et al. 2014; Sternberg et al. 2004; Giel & Issa, 2011; Walsh et al. 2013; Hawarey & Falk, 2004; Anil et al. 2013; Valero et al. 2012).

2D/3D geometric information extractions are the main deliverables obtained from the clouds of points data or a meshed model, before and after the modeling process, such as drawing plans, elevations, 3D objects and surface models, and cross-sections. To represent a cloud of points, a depth which is a matrix structure (2D) in which each pixel represents the distance of the point to the scanner in the form of a gray value is used. These closer to reality representations can be obtained by using complex meshing algorithms and artificial shading which can be used to highlight surface details. In addition, point splatting can be used to generate small surface elements by primitive surface shape (circle, ellipse, etc.) (Van Genechten, 2008). This speed surface representation is very useful for viewing and analyzing a scenario, such as in the GS

location scenario where the meaningful information to extract and analyze are the positions and dimensions of the elements of interest within the GS platform. In this case scenario of the GS location on a building roof, the analysis by a viewer software of the cleaned cloud of points data provides GS engineers and facility managers with; first, the current state of the GS location site in relation to the range and height between the antenna and obstacles or electronic devices which affect the satellite FOV and communication links respectively; second, the analysis of the GS scenario to propose GS re-design or re-location, and; third, the selection of the objects to model in order to simulate the GS location scenario. Figure 43 shows the geometric information extraction between the antenna and electronic devices as an application in the analysis process of the 3D digital scenario of the GS location in the case study at UPM University, using the Trimble Real Works Survey software.

Figure 43. Geometric information extractions from 3D digital scenario in the case study at UPM University using measurement tools available in the Trimble Real Works Survey software.

3.1.2.3 Virtual scenario simulations by 3D data integration

Simulations of real scenarios and the creation of virtual scenarios by 3D data integration based on those have become very useful in many disciplines with different purposes, in particular to represent scientific information and results, to communicate knowledge and techniques, to predict events, among others, but above all to generate understanding of data between other professionals from different disciplines. Computer simulation is a comprehensive method for studying the entire process of complex systems and may be iterative at any step. Once the phenomenon to be studied or

analyzed is theorized and the 3D digital scenario is generated, some issues must be considered in order to test, analyze and predict possible scenarios of real world operating conditions (Winsberg, 2010). In the case scenario of the GS location scenario model this stage comprises the following steps (see Figure 44):

- **Treatment:** it consists in establishing boundary conditions, after generating the 3D digital scenario, in order to define the type of simulation such as the selection of the obstacles which affect the satellite FOV from the virtual spatial position of the antenna rotor center.
- **Solver:** it consists in defining the parameters for the simulation in order to solve a specific problem such as the maximum antenna high to reduce the obstacle impact.
- **Results:** it consists in the analysis of the results comparing different scenarios by exporting 3D deliverables and numerical reports.

Figure 44. Computer simulation steps proposed for the GS location scenario.

3D modeling of the problem scenario, 3D data integration and the use of 3D CAD tools by importing 3D deliverables in CAD programs are very useful to visualize the results of the simulation and to represent the solution proposals by the professionals in the problem involved (Tang et al. 2010; Pătrăucean et al. 2015; Sansoni et al. 2009; Benko et al. 2002; Axelsson, 1999; Arayici, 2008; Erdős et al. 2014; Zhang & Arditi, 2013). In addition, for preliminary analysis of the scenario, direct 2D modeling from clouds of points by using standard CAD tools is very useful to obtain both, a basic 3D view of the

object or scenario (Van Genechten, 2008), and the visual impact of an object within a scenario such as in the case scenario of the GS facilities on a building roof.

Figure 45 shows the virtual view in the case study at Cal Poly University in which the new antenna on a real building roof scenario accomplishes the facility constraints and includes the visual impact from the street point of view.

Figure 45. Virtual scenario simulations by 3D data integration in CAD program in the case study at Cal Poly University.

3.1.3 Real simulation of the ground station antenna elevation mask

Considering the implemented framework to recreate or to simulate the GS scenario, for an installed GS or a new GS, respectively, additional information is required to complete the 3D digital scenario of the GS location. This information is contained in the antenna elevation mask field, which comprises two types of data sets: first, the geographic data surrounding the GS location (buildings and mountains highs) which it is out of the laser scanner range and affects the satellite FOV, and; second, the electromagnetic data in the surroundings of the GS location from signal interfering sources which are located on building roofs and affect the satellite communication links. The following sub-sections describe the studies within the implemented framework to complete the GS digital scenario information from the antenna elevation mask point of view.

3.1.3.1 Geographic study from the antenna location site

The geographic information of an object or scenario has spatial boundaries and a set of attributes. Points, lines and areas represent these geographic objects in a defined and absolute geographic reference system. This study is the process to produce an accurate and detailed digital map and other deliverables of the features, both man-made and natural within an area. The spatial information of such geographic phenomena with implicit or explicit reference to a location relative to the Earth is called geographic data by the ISO/TC 211, in geomatics and geographic information terminology (Kresse & Fadaie, 2004). In particular, this study relates to the analysis of the available geographic information of the GS location and surroundings. If updating is needed, the study includes the geographic data acquisition and post-processing processes.

In the case scenario of geographic data capture in built-up areas different 3D survey techniques can be applied, from direct survey by total stations or GNSS equipment, to remote sensing by; extracting data from aerial and satellite imagery; applying radar and sonar techniques, and; applying photogrammetric techniques. The selection of the most adequate survey technique or data capturing sensor depends on different factors such as the area to be surveyed, the required detail, the grid and datum the survey is to be related to, or how the data is to be presented, but mainly on the required accuracy and on operating in a particular location (Someswar, 2013; Stilla et al. 2003; Kondo et al. 2008; Mallupa & Sreenivasula, 2013; Lam & Tang, 2001; Lato & Diederichs, 2014; Berberan et al. 2007; Wolf, 2002; Mills & Barber, 2004; Nelson et al. 2009; Fradkin & Doytsher, 2002; Bannister, 2006; Hofmann-Wellenhof et al. 2007; Llife & Lott, 2008; Kaula, 2000; Leick, 2015; Seeber, 2003; Uren, 2010; Van Sickle, 2008). In this case scenario of the GS location on a building roof and taking into account the required data set to simulate the antenna elevation mask from the geographic point of view, the following factors must be considered in the survey equipment selection:

- Regarding the location area, non-contact equipment to get roof obstacles heights and to fix nearby building heights must be considered for a quick data capture process of the survey area and for safety and security conditions related to site access and working restrictions.

- Regarding the measurement, a GNSS receiver must be included to establish the level datum in the required official reference system (World Geodetic System 84 (WGS84) as this is the coordinate reference system used by satellite receivers that usually gives positions in terms of latitude and longitude (Leick, 2015).
- Regarding the accuracy, with a non-direct laser shot must enable to measure with high precision levels related to the scale factor of the required deliverables (CAD drawings).
- Regarding the deliverables, the equipment must be capable of in-situ visualizing graphic and numerical results, as the purpose of the survey plan is the in-situ export of horizontal and vertical angles measurements and slope distances to directed points.

In this sense, the most adequate data capturing sensor is total station equipment which includes GNSS technology. The total station may be operated as a robotic instrument by the surveyor alone if site conditions such as safety and security allow it. All data is electronically logged and coded on the instrument to be processed and plotted out later from a computer. The time required for office processing is considerably shorter than the time spent on site. Survey control on site may also be established on site by either GNSS or total station.

3.1.3.1.1 Total station equipment with GNSS technology

Total stations are a surveying instrument that combines the angle measuring capabilities of theodolite with an EDM (Electronic Distance Measurement) to determine horizontal angle, vertical angle and slope distance to the particular point (Brincker & Minnick, 2012). A GNSS receiver is an instrument that processes the signals received from a GNSS satellite constellation to compute time and position to the end user application (Hewitson & Wang, 2006; Hein et al. 2006; Bakula, 2012; Rizos, 2005). Total stations and GNSS receivers are used separately due to fact that they use different reference systems and different kinds of measurements, so surveys normally require to combine optical and GNSS data by applying both survey techniques, respectively

(Ghilani & Wolf, 2010; Lin, 2003; Merkle & Myers, 2004; Kizil & Tisor, 2011; Brown et al 2007; Calina et al. 2014; Sanhu, 2008; Lachapelle et al. 2002; Lohnert et al. 2001; Al-Bayari & Sadoun, 2005). In 1993 the integration of both instruments was done by Leica Geosystems firm (Biasion et al. 2005). This has now been implemented as an instrument which provides a new survey methodology with great advantages in survey scenarios in which control points are not needed and where there are no long traverses or resections. Figure 46 shows this smart station with integrated a GNSS receiver (see Figure 46(a)). In addition, Figure 46(b) shows other quick survey solution to collect GNSS and optical data by switching between sensors of the same controller.

Figure 46. Quick survey solutions. (a) Leica SmartStation (www.leica-geosystems.com) (b) Combination of GNSS and Total Station (www.trimble.com).

3.1.3.1.1.1 Data acquisition

This stage consists in the collection of the geographic data required to represent the basic map of the GS location area and the altimetry profile from the spatial position of the antenna rotor center due to high buildings and mountains present in the surroundings. By applying total station and GNSS equipment in the data acquisition process, measurement errors from both survey techniques must be considered: systematic errors relative to calibration errors, tension in analogue meters, temperature, etc., gross errors relative to the operator, and random errors relative to inconsistent measurements. Those errors can be corrected by applying correction factors, by

checking control points during the acquisition process, and by increasing the frequency of measurement, among others. However, new technologies of data capturing sensors include hardware performances and data processing software which reduce or eliminate common errors. Regarding measurement errors in total stations, digital readouts eliminate the uncertainty associated with reading and inter-poling scale and micrometer data. The electronic angle-measurement system eliminates the horizontal and vertical angles errors. Measurements are based on reading an integrated signal over the surface of the electronic device that produces a mean angular value and eliminates the inaccuracies from eccentricity and circle graduation. In addition, an integrated dual-axis compensator automatically corrects both horizontal and vertical angles for any deviation in the plumb line (Ghilani & Wolf, 2010; Beshr & Elnaga, 2011; Martin & Gatta, 2006; Afeni & Cawood, 2013). Regarding GNSS error sources, these are related to satellite clocks, orbit errors, ionospheric and tropospheric delays, receiver noise and multipath. To mitigate or eliminate errors within the position calculation there are techniques to solve them: averaging repeated observations, applying correction values by predicting causes of error, and applying differential corrections (Wu & Yiu, 2001; Schön et al. 2005; Fotopoulos et al. 2003; Featherstone & Stewart, 2001; Mauro et al. 2010). In addition, RTK (Real Time Kinematic) which is a technique that enables high accuracy using carrier-based ranging, provides ranges and therefore positions reducing and removing errors common to a base station (Jonson et al. 2003; Brown et al. 2006; Cai et al. 2011; Sioluis, 2015). Considering the purpose of the data acquisition process on a building roof, a total station with integrated GNSS is the best solution to determine the position coordinates of the spatial position of the antenna location site in a few seconds to centimeter accuracy and, the radial survey of the roof platform and surroundings. This process does not need setting-up the equipment, transferring the coordinates, or control points. Generally, total station and GNSS survey techniques are separately used, and in this sense, this conventional process can be performed by combining both equipments with the same controller. Although the proposed solutions increase survey accuracy and quality control, there are checking mechanisms in the conventional process to detect and reduce gross errors (Csanyi & Toth, 2007). In addition, quality control refers to the efforts and procedures that researchers put in place to ensure the

quality and accuracy of the data being collected by using the methodologies chosen for a particular study (Lavrakas, 2008). Figure 47 shows the scheme of the data acquisition process as the conventional way when the proposed solutions cannot be applied. This process basically consists on fixing several control points throughout the area using GNSS equipment, transferring the coordinates into the total station, and by occupying the control points with the total station: first, to orient to other control points and, second, to survey the required geographic data.

Figure 47. Scheme of the data acquisition processes: Conventional process versus total station with integrated GNSS technology.

3.1.3.1.1.2 Data post-processing

This stage comprises mainly two processes in order to provide the geographic information based on captured survey points: preliminary data processing and data post-processing. Integrated software in newest generation of total stations allows a swift data post-processing, either transferring data from the data logger to a computer and then into CAD software, or working connected directly to a computer rather than to a data logger. In addition, some models can also show the map on the touch-screen of the instrument immediately after measuring the points and even the selection of the measurement points by importing the available cartography of the survey area into the total station from specific computer software (CAD files, images, etc.). Although data post-processing software is specific to the total station model, the newest software generation can manage data from most modern equipments as these are capable of exporting in different file formats (ASCII, CVS, etc.). The first process consists on extracting 2D/3D basic maps and the altimetry profile, considering the purpose of in-situ visualizing the location area both to verify the GS project planning, and to test the

satellite FOV from the selected GS site. This preliminary process allows assessing the required level for the second process, that is, data post-processing, for an effective processing and production of data and document deliverables. Figure 48 shows the graphic deliverables from in-situ preliminary data processing in the case study at UPM University, obtained by transferring survey points from the total station software to specific computer software.

Figure 48. Graphic and numerical deliverables from the preliminary data processing of the survey points in the case study at UM University.

3.1.3.1.2 Geographic mask

This mask is the most important deliverable of the geographic study and contains the antenna elevation mask from the geographic information point of view. This mask represents the antenna minimum elevation in each azimuth direction, to start or to stop satellite access in each satellite pass, from the spatial position of the antenna rotor center. Figure 49 shows the geographic mask concept applied in a satellite mission simulation on a specific mission day from the GS located at UPM University, where satellite entry and exit points indicate the available satellite FOV from the GS location

in this specific satellite pass (see Figure 49(a). Figure 49(b) shows the 3D view of the satellite tracking along its trajectory in the specific satellite pass, from the antenna minimum elevation in the entry azimuth direction to the exit azimuth direction when the satellite goes below the antenna minimum elevation.

Figure 49. Satellite passes simulation from specific GS located at UPM University considering the customized geographic mask. (a) 2D view of the satellite access in specific day. (b) 3D view of a single satellite pass.

3.1.3.2 Electromagnetic study from the antenna location site

Electromagnetic information obtained in this study includes the meaning of electromagnetic interference as defined by the ITU-RR (International Telecommunication Union-Radio Regulations) as “*The effect of unwanted energy due to one or a combination of emissions, radiations, or inductions upon reception in a radio communication system, manifested by any performance degradation, misinterpretation, or loss of information which could be extracted in the absence of such unwanted energy*” (ITU-RR, 2012, p. 23). Even though regulatory agencies and standard organizations define operation and protocols within each frequency band, unintentional interferences (electrical equipment, mechanical machinery, power lines, etc.) can produce broadband noise or modulate the radio signals propagating in the surrounding environment. Other unintentional interferences (satellite, radar, mobile radio, etc.) can also affect communication systems performance due to the presence of a similar radio

system operating within the area. These interferences are classified in the following types: In-band, Co-channel, Out-of-band, Adjacent Channel, Uplink and Downlink (Brown, 1997). In particular, this study analyzes the available electromagnetic information of the GS location and its surroundings which affects up/down links, and if necessary, updates such information. In the case scenario of electromagnetic data capture in built-up areas, capture of intentional or unintentional signals is a complex and long process, and even more when these emitted signals are intermittent. In this sense, the selection of the most adequate signal analyzer equipment requires a storage solution such as a PC hard disk or external mass storage drive in order to be effective in characterizing interference signals. In addition, GNSS receiver must be integrated to locate the spatial position of the interference sources, thus improving the estimated location process by applying the triangulation technique. The spectrum analyzer, as interference testing equipment, must provide: a broad range of frequency coverage, high dynamic range, ruggedness and portability. In addition, the selection must take into account measurement categories in the analysis of frequency, time and modulation of related electrical signals (see Figure 50).

Figure 50. Measurement categories (Anritsu. Retrieved from <https://dlcdn-anritsu.com/en-en/test-measurement/files/Technical-Note/spectrumanalyzer-eel400.pdf>).

There are various types of equipment, from the swept spectrum analyzer developed in the 1960s as the first test equipment (Deery, 2007), through the FFT (Fast Fourier Transform) spectrum analyzer based on the transformation of discrete or digitized signals into the frequency domain using the discrete Fourier transform, to the latest high performance equipment with analog to digital converters implemented since 1980s. In this sense, there are different processes and techniques for measuring and locating interference sources according to the type of analyzer selected (Brown, 1997; Nagano et al. 2008; Hunter et al. 2011; Gorin, 2003):

- Swept or super-heterodyne spectrum analyzers, which operate on the principle of the relative movement in frequency between the signal and a filter. The technique is to sweep across the frequency range of interest displaying all the frequency components present. It is able to have very wide scan spans to several GHz and to operate over wide frequency range, making significant contributions to frequency-domain signals analysis for applications such as the manufacture and maintenance of microwave communications links, radar, telecommunications equipment; cable TV systems, and broadcast equipment; mobile communication systems; EMI (Electromagnetic Interference) diagnostic testing; component testing, and; Signal surveillance.
- FFT spectrum analyzers which use digital signal processing techniques to analyze a waveform with Fourier transforms to provide in depth analysis of signal waveform spectra. The input signal is digitized at a high sampling rate, similar to a digitizing oscilloscope, and the resulting digital time record is then mathematically transformed into a frequency spectrum using an algorithm known as the Fast Fourier Transform. It can be considered to comprise of a number of different blocks: Analogue front end attenuators/gain, Analogue low pass anti-aliasing filter, Sampling and analogue to digital conversion, FFT analyzer, and Display. Some of the advantages are the short capture time and that it is able to analyze signal phase. Some of the main applications are: real time and offline signal analysis by SIGVIEW software (www.sigview.com), real time bandwidth and overlap processing, and EMI measurement.

- Real time spectrum analyzers operate in free from any type of tuning and it works on real time signal generated on real time basis. The analyzer can acquire a particular bandwidth or span either side of a centre frequency and captures all the signals within the bandwidth and analyses them in real time. To achieve their performance a real time spectrum analyzer captures the waveform in memory and then uses fast Fourier transform technology to analyze the waveform very quickly. Some of the advantages are the use of an ADC (Analogue to Digital Converter) capable of digitizing the entire bandwidth of the pass band, and sufficient capture memory to enable continuous acquisition over the desired measurement period. Some of the main applications are the signal quality analysis of analog and digital modulation, understanding frequency and spectral occupancy behavior over time, capture and characterization of undesired, unknown, or interfering signals, signal spectrum monitoring, and characterization, troubleshooting, and verification of wireless designs (Katsibas et al. 2009).

Although many modern types of spectrum analyzer include a down conversion to place the signal into the required range for digitizing the signal, they mainly use digital techniques. The availability of high speed, high dynamic range ADC coupled with high speed DSP (Digital Signal Processing) has brought changes in the architecture of the spectrum analyzer. Most of the specific signal processing, e.g. RBW (Resolution Band Width) filtering, can now be done digitally, improving performance and reducing calibration requirements. The DSP integration has improved the performance of the swept spectrum analyzer, and has led to the development and prevalence of the FFT based spectrum analyzer. Basically, once the local oscillator module provides a sinusoidal signal to the down-converter module it is mixed with the input signal producing the desired frequency; in a swept type, the sinusoidal signal is swept linearly over the frequency band or span to be measured; in an FFT type, the local oscillator module provides a frequency stepped sinusoidal signal whose step size is determined by the frequency coverage of the FFT. Figure 51 shows the simplified block diagram of these types of spectrum analyzers (Hunter et al. 2011).

Figure 51. Simplified block diagram of spectrum analyzer equipment.

Considering the purposes are to locate signal interfering sources surrounding the GS location, to capture signal spectrum data relative to the frequency versus level, and to in-situ preliminary analysis, spectrum analyzer specifications such as the frequency coverage and accuracy, the amplitude accuracy and the resolution bandwidth must be taken into account when selecting the equipment. In this sense, the most adequate data capturing sensor is the Real time spectrum analyzer equipment.

3.1.3.2.1 Spectrum Analyzer equipment with GNSS technology

Basically, a spectrum analyzer is an instrument that is used to measure the magnitude of an input signal set versus the full frequency range of the instrument. The primary use is to measure the power of the spectrum of known and unknown signals, to display data in a graph with the proper settings where the amplitude is represented on the y-axis and the frequency on the x-axis, and to analyze the signal spectrum in order to estimate the following parameters: dominant frequency, power, distortion, harmonics, bandwidth and other spectral components. Other applications include, seeing the overall spectrum of a modulate signal, investigating whether unwanted signals are present, finding out the right frequency of a signal, etc. (Brown, 1997; Byrd & Caspers, 1999, Caspers & Hutter, 2005; Victory, 2001).

Figure 52 shows the relative levels of signals on different frequencies within the range of the particular sweep or scan. The vertical axis or amplitude is on a logarithmic scale

and calibrated in dB units, the horizontal axis or frequency is linear, and the term span refers to the frequency range to scan.

Figure 52. General format of the spectrum analyzer display.

In the case scenario of signal interference sources surrounding the GS location which affect the up/down links, a best estimation of their locations is fundamental to capture the azimuth direction from the antenna site. In this sense, a spectrum analyzer with integrated GNSS receiver improves the interference sources location process. Figure 53 shows the interference source location applying the triangulation technique.

Figure 53. Interference sources location applying spectrum analyzer with integrated mapping solution and triangulation technique.

Basically, by applying the on-screen map of the area, the location of transmitted signals can be identified and documented on the analyzer display where the intersection from multiple GNSS locations indicates the source of the interference. However there are different techniques and processes which depend on the spectrum analyzer capabilities and the applied software (Hunter et al. 2011).

3.1.3.2.1.1 Data acquisition

This procedure consists in the collection of the electromagnetic data required in order to detect the presence of signal interference sources in the frequency ranges of the satellite mission bands, to locate the azimuth direction of the identified interferences, and to capture the signal spectrum from the spatial position of the GS location site. Before data acquisition some issues, described as follows, must be taken into account for an effective process, (Brown, 1997; Thomas et al. 2003; Note, 1998):

- As regards equipment specifications, error sources in the measurement set-up must be considered; frequency accuracy, which it is made up of frequency reference inaccuracy and span, and center frequency selection; amplitude accuracy, which refers to measurements where the absolute level is required and when signals are expressed in terms of decibels when compared to another signal, and; resolution bandwidth, when it is necessary to measure signals that are close together. However, calibration process can be used for specific measurements and for instrument settings by applying correction coefficients. In addition, an included self test in the equipment software summarizes the status of several key functions that are common to all applications.
- As regard hardware set-up, this refers to its mounting onto a specific antenna, Omni or directional, which establishes the data acquisition process. This includes mounting an amplifier (if needed) to amplify the received signal, and mounting and setting-up a GNSS antenna, to check the tracked satellites and antenna status before the data acquisition process.

Figure 54 shows the basic steps of the measurement set-up, including specific parameters setting, and selection of the measurement type.

Figure 54. Basic steps in the measurement set-up for the data acquisition processes in the different frequency bands.

As previously mentioned there are different procedures, application depending on the purpose of the signal analysis process. In this sense, the required spectrum analyzer equipment must be taken into account (see Figure 55(a)) in order to reach the expected results in the proposed electromagnetic study. These include specific antennas capable of receiving in the frequency bands selected for the GS mission (see Figure 55(b)).

Figure 55. Hardware elements required in the data acquisition process to capture the electromagnetic mask. (a) Spectrum analyzer. (b) Omni-directional and directional antennas.

These two types of antennas determine the two procedures in the data acquisition process; first, to detect the potential interference signals in the selected frequency ranges by using the Omni-directional antenna which allows the radiation coverage in all directions, and; second, to capture the signal spectrums in the interference source azimuth direction by using the directional antenna which allows the radiation in specific directions (Dhande, 2009).

From the communication systems point of view the basic concept of the measurement procedure is to determine the existence and location of interfering signals which affect the operational quality of the system. In spectrum congested areas, such as in the case scenario of a satellite tracking antenna mounted on a building roof, the capturing of intermittent signals sources which affect the up/down links is a complex process. In this sense, an Omni-directional antenna is used to capture data from all directions from the antenna location site in the first stage of the capture process. The radio performance occasionally suffers from interference at what may seemingly be random times of the day. For cases when the interference is pulsed or intermittent, the spectrum analyzer can be configured to store the maximum trace values over many sweeps combining different available functions such as the maximum and minimum hold, stored memory and peak power, among others. Another useful display option is the spectrogram which allows analyzing on the same display frequency, time, and amplitude. The second stage is the location of the azimuth direction of the interference sources. A directional antenna is used, as these high gain antennas provide pointing capability within the wireless environment. Observing the amplitude of the signal on the spectrum analyzer as the directional antenna is moved around the environment could potentially point to the physical location of the interference when the signal amplitude is at a maximum. Due to fact that multipath reflections in the surrounding environment could reduce the pointing accuracy, it is important to make the measurement from as high as possible such as on rooftops or tall buildings, and from several locations for a best estimation of the interference source location.

Figure 56 shows the stages of the data acquisition process from the detection of the presence of potential interference sources in the mission frequency bands and the location of those which affect up/down links, to the data post-processing.

Figure 56. Stages of the data acquisition process in the interference sources location in the different frequency bands.

Within the selected measurement procedure with each antenna, a preliminary data processing is considered in order to in-situ simulate the antenna elevation mask by analyzing preliminary results. This preliminary data processing allows to re-start the measurement process when missing data or to capture more specific data.

3.1.3.2.1.2 Data post-processing

The data post-processing of the captured measurements allows further analysis of the signals spectrums by applying specific tools. This procedure consists in performing the preliminary analysis by using the spectrum analyzer software which is a compatible program for transferring and editing saved measurements to a PC. The most common software capabilities, among others, are; capturing traces from the instrument for further analysis; uploading measurements and other files such as images, maps, etc.; 3D simulating of a measurement set by applying the spectrogram function, and; creating measurement deliverables. In the specific post-processing of spectrum signals working with limit lines and using markers it is very useful to compare and to evaluate measurements relative to the average power within one channel or within a specific frequency range (Brown, 1997). Figure 57 shows common specific tools for the preliminary analysis which are also used in the data post-processing creating the expected deliverables:

- Trace average, a function which allows analyzing the trace average of the interference source within the selected frequency band range,
- Spectrogram, a function which shows the progression of the frequency spectrum as a function of time where colors scale represents the signal.

(a)

(b)

Figure 57. Analysis software functions. (a) Trace average. (b) Spectrogram.

3.1.3.2.2 Electromagnetic mask

This mask is the most important deliverable from the electromagnetic study and contains the antenna elevation mask in the frequency bands selected for the satellite mission. This mask represents the antenna minimum elevation in the interference sources azimuth directions from the spatial position of the antenna rotor center, to start and to stop the satellite communication link from the selected GS. Figure 58 shows the simulation of a satellite pass from the GS located at UPM University, and describes reduced access time due to the presence of a signal interference source in the azimuth direction of the satellite entry. The satellite visibility times obtained from the

geographic information are reduced due to the presence of a signal interference source in the satellite entry azimuth direction.

Figure 58. Simulation of the satellite access from specific GS located at UPM University considering the electromagnetic mask information. (a) 2D view of the available satellite access taken into account the geographic elevation (Satellite Entry-Exit) and acquisition and loss of satellite signal (Satellite AOS-LOS). (b) 3D view of the starting satellite access due to the presence of a signal interference source in the satellite entry azimuth direction.

3.1.4 Simulation of the ground station mission scenario

To complete the implemented framework in the research scope of satellite communications from ground base stations, in the particular case scenario in building roofs locations, additional information is required to take a decision relative to the GS location. In this sense, this section describes the final stage of the implemented framework which extracts relevant information from the GS location by simulating a satellite mission.

Satellite mission analysis is a complex process of studies and analyses of the relationship between orbits, attitude and budgets (link, mass, power, thermal, etc.) in order to satisfy the mission requirements. Thus, identification of mission requirements and constraints, evaluation trade-off scenarios, analyzing system budget, etc., must be undergone. The primary issue in the satellite mission analysis is the selection of the optimal orbit which best enables the satellite and payload to perform their missions.

This is performed by first analyzing the mission, payload and satellite design requirements to determine if the satellite mission is feasible. If so, trade-offs are performed in order to find a suitable orbit that meets the mission goals. Through mission simulations, the orbit design is determined by testing different altitudes and inclinations. Finally the lifetime of the satellite mission is estimated. In addition, for imposed orbits such as in LEO missions or during launch and an early orbit phase, access time to communications involves the selection of an ideal or several GSs to cover these mission periods, in all satellite missions (Larson & Wertz, 1992; Fortescue et al. 2011). When fixing the space segment parameters, the GS selection is based upon maximum access time. In this sense, the framework implies determining the optimal GS through simulation the satellite mission from different GS scenarios. Results provide the current state of the communication times for a given GS location or the optimal location between proposals by comparing the antenna calculated elevation mask from each location. Following sub-sections describe the basic knowledge necessary to use the satellite mission software, the required information relative to the ground segment which is extracted from the previous stages of the implemented framework, and the GS scenario simulation by data integration.

3.1.4.1 Satellite mission simulation software

The simulation of a satellite mission is a widely used effective way to test and verify the overall space mission parameters. Simulation techniques are an important means to improve the performance of the spacecraft, to ensure the development quality, reduce development costs and risks, to shorten the development cycle and to ensure reliable operation on orbit. Space mission stages, spacecraft development and mission planning, require specific software for testing of satellite components and for mission analysis in order to increase the efficiency and to decrease the mission cost. By applying these software, mission simulations provide information values related to both the space and ground segments, and above all the potential accomplishment of the mission requirements (Sheng & Sun, 2012; Kuwahara et al. 2016; Hendricks & Eickhoff, 2005; Burns, 2003; Robertson et al. 1999; Guang, 2007; Kaslow et al. 2014; Al-Jarrah &

Hasan, 2011). There are many types of software for space systems and interactive visualization. Within the aerospace industry STK is recognized as the leading commercial off-the-shelf analysis tool (Zhang & Zeng, 2006).

3.1.4.1.1 STK software

The STK software provides the platform and tools for solving system level problems of motion and time, and includes a free 2D and 3D modeling environment to model complex systems and evaluate their performance in real or simulated time, analyzing mission simulations and visualizing dynamic datasets in 4D (x, y, z, time). STK is used in a variety of applications and throughout all phases of the program lifecycle, from space and missile systems to sensor systems. Figure 59 shows the main STK functions from building a scenario to generating reports and graphs, which are briefly described below:

Figure 59. Main functions using STK software.

- Build a scenario, comprises the following steps: first, to create a new scenario which includes the setting of the start and stop times of the analysis period and other scenario properties such as the animation cycle, the units of measure, the Earth orientation parameters, the database and the terrain elevation; second, to add and to define STK objects from the standard data base such as the satellite, the facility, the area target, etc.; third, to customize 2D/3D graphics windows to display scenario information, and; fourth, to impose constraints relative to shapes, ephemerides and coordinate systems.
- Analysis workbench tools, are application-wide tools designed to streamline, organize, and extend the fundamental computational capabilities of STK such as time, vector geometry, calculation and spatial analysis.

- Perform analysis, comprises the following types of analysis on a scenario: access, coverage and communication systems.
- Manage data, comprises tools and utilities to manage, update and export data relative to the created scenario or to an individual object.
- Generate reports and graphics, provides reports and graphics that summarize static data, reports that update during animation (dynamic displays), and graphics that update during animation (strip charts).

These STK main functions allow understanding how to create satellite mission scenarios from specific GS locations by using the scenario properties tool, and how to analyze different scenarios by extracting scenario reports and graphics.

3.1.4.2 Scenarios simulation by AzElMask data integration

In the implemented framework of the GS location analysis, simulating the satellite access times along the mission is very useful to evaluate the mission requirements (e.g. the amount of data download in each satellite pass for a telemetry mission), and to take a decision related to the selected GS scenario, its re-design or re-location. Considering the purpose of simulating the GS mission scenario as the final stage of the implemented framework, STK software provides reports and graphs relative to satellite access times from the selected GS location by simulating a satellite mission. In this sense, scenarios simulation by data integration from the ground segment point of view is a solution to test the optimal GS location site.

To simulate the satellite mission from different GS scenarios, STK software requires the following data set: the antenna elevation mask field and the geographic coordinates (North, East) in the selected reference system and the orthometric height of the spatial position of the antenna rotor center. This data set is extracted from the previous stages of the implemented framework. The spatial position of the GS site and the altimetry profile of nearby obstacles are extracted from the 3D digital model of the GS scenario. In turn, the AzElMask (Azimuth-Elevation Mask) field which contains antenna elevations results from both studies, geographic and electromagnetic, is extracted from the simulation of the antenna elevation mask (see Figure 60).

Figure 60. Data set requires from STK software to simulate GS scenarios.

To compare different GS scenarios in specific periods of time in a satellite mission simulation, the process basically comprises three steps, taking into account the build scenario, by fixing all the parameters (satellite, orbit, terrain, etc.) except those related to the facility:

- Setting the facility properties (GS spatial position), in particular the coordinates in the selected reference system and the height above ground. In this step different scenarios can be created by imposing antenna height.
- Setting the AzElMask field (GS antenna elevation mask). In this step different scenarios can be created by using the antenna customized elevation mask or by imposing a standard mask (see Figure 61).

Figure 61. Screenshot obtained from STK program to create different satellite mission scenarios.

In this case scenario of satellite GS location in built-up areas, the accuracy of the input data of the updated information is a key factor to determine the accuracy of the simulation results. This can be seen when generating reports and graphics by applying tools such as the access tool to obtain communication times in each satellite pass.

Framework implementation and further technical details will be described in Chapter 4. However, specific data and deliverables from the case studies analysis will be used in the analysis model description which shows the implementation of each stage.

3.2 Analysis model stages

This section describes the stages of the analysis model, developed from the proposed framework in order to validate its implementation in the different case studies which involve the scope of its application. Figure 62 shows the analysis model stages, its main objectives (O) and expected results (R).

Stage 1 Mission requirements & constraints for installation		
O1. Meeting with GS Engineers & Facility Manager	R1. Analysis factors selection	
Stage 2 Preliminary analysis of the location		
O2. Factor analysis	R2. Provisional site selection	
Stage 3 Further analysis in the location site		
O3. Constraints versus requirements	R3. Optimal site selection	
Stage 4 Antenna elevation mask in the mission band		
O4. Electromagnetic mask	R4. Fusion of masks	
Stage 5 Analysis using the satellite mission software		
O5. Amount of data download	R5. Satellite times	communication
Stage 6 Optimal site versus site re-design		
O6.1. Optimal site	R6.1. Final report	
O6.2. Site re-design	R6.2. Stage 3	

Figure 62. Stages of the analysis model developed to optimize the ground station location in built-up areas.

The core of this analysis model is the measurement set-up developed to provide mission analyst with a best estimation of the antenna elevation mask to simulate the satellite

mission. Considering both measurement data, geographic and electromagnetic, the designed measurement set-up is a technical contribution when using different data capturing sensors to provide in-situ quick results by a swift process of data fusion. In addition, the use of 3D techniques for visualization of results allows the interaction between several professionals, the GS team and facilities manager, in order to take decisions through the different stages.

The first stage addresses issues relative to a given location or location proposals, the GS mission requirements, the antenna specifications and antennas configuration, the control room facilities, the official regulations for building roof installations in the location area and, the internal rules for installations within the campus or the institution area, among others. In this stage contributions from GS engineers and the facility manager are of great relevance in order to select the main analysis factors which will be considered in the preliminary analysis (stage 2). Once the provisional site is selected, the next step is to undergo further analysis within the location considering constraints for installation on the building roof (stage 3). This stage is especially important to obtain the installation permit. Stage 4 contains the fusion of masks completing the antenna elevation mask information in the mission band. The used measurement set-up provides geographic and electromagnetic data set in the parameters required (azimuth and elevation) by the satellite mission simulation program. Satellite mission simulation with the resulting mask allows testing the GS mission, as regards communication times in each pass, and the amount of data download required per mission day (stage 5). Analysis of result reports from each stage provides GS engineers with information that allows them to take a decision about the proposed site, and to test another site within the location though the analysis of GS scenario (stage 6). In addition, stages configuration allows its application in different stages of the GS project including the possibility to re-start the analysis process from stage 3 when new factors are added in the GS design, or when it is necessary to improve satellite tracking operations for a given GS design. This fact is of great relevance for the GS re-design for a given site or for the site re-design for a given GS. This is possible thanks both to the antenna elevation mask simulation obtained from the designed measurement set-up, and to the 3D digital model of the GS scenario obtained by applying the laser scanner technology.

3.2.1 Mission requirements & constraints for installation

This first stage involves participation of the GS engineers and facility manager in order to establish the analysis factors, mainly the GS mission requirements and the constraints for installation in the selected location or in the location proposals. This information is vital to set-up the analysis model; first, for the preliminary analysis of the location proposals due to the facility constraints; second, for the planning of the data capture procedures due to the data capturing sensors selection; and finally, to establish the objectives of the following stages and its expected results.

The mission requirements for the analysis are, among others; the mission concept (telemetry reception, telecomm generation, radiometric measurements, etc.); the frequency bands (VHF, UHF, S Band, etc); the satellite transmission power (Tx); the antenna reception power (Rx), and; the required communication times in relation to the mission concept. The constraints for installation are, among others; local regulations for installation on building roofs; safety facilities for installation and maintenance; building facilities on the roof; nearby electronic devices and other terrestrial links, and; the antenna height maximum regarding internal rules and weather conditions in the area. Figure 63 shows the general issues which require GS engineers and the facility manager to meet (O1) for selection of the analysis factor.

Figure 63. General Issues for the analysis factors selection.

Regarding the satellite mission requirements, and in particular the GS design, antenna specifications such as antenna height, and installation type such as fastening and anchor systems, are the specific factors. Regarding facility constraints in built-up areas, and in particular on building roofs, internal rules such as maximum antenna height, and safety systems such as the required safety perimeter for the installation, and future works of maintenance, are the specific factors. Regarding the satellite mission analysis, and in particular the antenna elevation mask, the maximum FOV from the location proposals and the absence of signal interference sources surrounding each one, are the specific factors.

Figure 64 shows these specific factors for the preliminary analysis between the location proposals which correspond to the analysis factors selection (R1) taking into account the most common requirements, and constraints from the GS engineers and the facility manager, respectively.

Factors	Specific Factors
GS Design	- Antenna Specifications
	- Installation Type
Facility Constraints	- Internal Rules
	- Safety Systems
Antenna Elevation Mask	- Maximum FOV
	- No Interfering signals

Figure 64. Factors selected for the preliminary analysis.

The next step is the definition of analysis factors to establish the concept for each factor to be analyzed and to decide the required resources in the data compilation process. This step has a great influence in the selection agreement of the provisional site between the location proposals described in the next stage:

- First, for the interpretation of the obtained graphic results from the preliminary analysis between the location proposals.

- Second, for the agreement on the valuation criteria for each factor as this is of relevance in the selection process of the GS location site.

Regarding the GS design, the antenna specifications and the installation type are the main specific factors since:

- Antenna specifications, is the factor which represents the viability percentage of the GS facilities from the outdoor components point of view considering: antennas configuration, antennas dimensions, structural impact on the roof and, visual impact from the street view.
- Installation type, is the factor which represents the viability percentage of the GS facilities from the installation point of view considering: fastening and anchor systems which require a flat area and access for the installation works, future works of maintenance and, the connection type, which includes its length to the control room and the existence of power points on the roof.

Regarding facility constraints, internal rules and safety systems are the main specific factors since:

- Internal rules, is the factor which represents the feasibility percentage of the facility constraints accomplishment from the internal rules point of view considering: access to the building roof, the flat area proposed for installing the outdoor components, the connection types to the control room and, the maximum antenna high allowed on the building roof.
- Safety systems, is the factor which represents the feasibility percentage of the facility constraints accomplishment from the safety systems point of view considering: the safety facilities required for the installation and future works of maintenance such as the access to the roof, the walkway on the roof and, the safety perimeter around the outdoor components.

Regarding the antenna elevation mask, the maximum FOV from the GS site selected and the absence of potential interference sources surrounding are the main specific factors since:

- Maximum FOV, is the factor which represents the visibility percentage from the GS selection site point of view, considering the blockage area between the

horizon plane from the antenna rotor center and the altimetry profile surrounding the site.

- No interfering signals, is the factor which represents the absence of signal interference source percentage from the GS selection site point of view, considering the presence of potential sources in certain azimuth direction from the selected site which radiate in the mission frequency bands.

Figure 65 shows the analysis factors selected by implementing this stage in the case study at CUA University, and the valuation criteria of each one (coefficient value between 0 and 1) given by the GS engineers and the facility manager in the project involved.

Figure 65. Analysis factors selected in the case study at CUA University.

3.2.2 Preliminary analysis of the location

Once the analysis factors are selected, the next stage is the preliminary analysis of the location proposals. The factor analysis (O2) contains the compilation of all the available information related to each location and the GS design, and the required data set to simulate the GS mission from the selected provisional site in each location. The goal of this stage is the selection of the best location between proposals providing

objective results of each analysis factor by assigning the relevance coefficient between them. Figure 66 shows the scheme of the applied methodology for the data capture processes, which provides GS engineers with specific results to take a decision in the provisional site selection (R2).

Processes	Objectives	Results
Geographic Study I	<ul style="list-style-type: none"> • Taking in situ measurements for the selection site area considering facility constraints over the building roof. • Targeting the spatial position of the virtual antenna center using GNSS technology. • Capturing the altimetry profile surrounding the site using survey equipment. 	Provisional Site Approval Geographic Mask
Electromagnetic Study I	<ul style="list-style-type: none"> • Positioning the Omni directional antenna in the geographic reference system. • Detecting the interference sources surrounding the location using the Spectrum Analyzer equipment. 	Signal Interference Sources Map

Figure 66. Methodology applied for the geographic and electromagnetic data capturing processes.

The first step in *Geographic Study I* is the geographic data capture of the roof platform for each location to create the basic map of the GS facility. This step is of great relevance from the facility manager point of view, as it shows the impact of the GS installation over the building roof and verifies fulfillment of internal rules and safety systems by taking in situ measurements such as the radius of the antenna rotation. From the point of view of the GS engineers, the next step, the data capture process of the geographic mask, is the most important part of this analysis as it allows to estimate the visibility times of the satellite along the mission, and to locate possible signal interferences that reduce the communication times. This step requires the use of total station equipment with integrated GNSS technology or 3D laser scanner to establish the spatial position of the virtual antenna rotor center and to capture the altimetry profile along the horizon from that point. Within the *Electromagnetic Study I* process, the use

of spectrum analyzer equipment with an Omni directional antenna, which includes GNSS technology, is the next step to detect the signal interference sources which could affect the radio links in the mission frequency bands.

Figure 67 shows the graphical data obtained implementing this stage in the case study at CUA University. The numerical data were represented as percentages establishing 100% as the optimal value in each analysis factor. The valuation criterion provides objectivity in the location selection between the proposals and a further valuation applying the coefficient assigned in each analysis factor providing a best estimation of the analysis factors to take a decision.

Figure 67. Preliminary analyzes of the location proposals in the case study at CUA University implementing the selected analysis factors.

3.2.3 Further analysis in the location site

Once the provisional site is selected, a further analysis in the location is required, the main objective being the selection, made by the facility manager and GS engineers respectively, of the GS site within the location considering constraints versus requirements (O3). Figure 68 shows the scheme of the applied methodology for the data capture processes which provides the facility manager and GS engineers with specific results to take a decision regarding the optimal site selection (R3).

Processes	Objectives	Results
Geographic Study II	<ul style="list-style-type: none"> •Capturing the geographic map of the building roof to draw the facility constraints on the digital model. •Capturing with high accuracy the altimetry profile surrounding the site proposals within the selected location. 	Installation Site Approval Maximum FOV Site
Electromagnetic Study II	<ul style="list-style-type: none"> •Positioning the directional antenna in the geographic reference system in each proposed site, establishing the horizon plane. •Geographic location of the signal interference sources: azimuth directions from the proposed site. •Capturing the signal peak power from the located sources using the spectrum analyzer equipment. 	Azimuth direction of signal sources Minimum Interfering Signals Site

Figure 68. Methodology for further analysis within the location selected.

Considering that the purpose is to analyze potential sites within the selected location and the maximum FOV site, the first step within the *Geographic Study II* is to create the basic digital model of the building roof platform by using modeling sensors. This model allows taking specific measurements regarding the spatial position of roof entities, drawing specific constraints regarding the free area for the GS facilities, designing the trajectory of the connections to the control room from the outdoor components and, showing the visual impact of the GS components on the building roof. Once the potential sites are selected, the next step is the capture process of the altimetry profile with high accuracy from each site in the same coordinate reference system, establishing in each one the assigned orthometric height for the future antenna rotor center. The most adequate data acquisition method is chosen to obtain the geographic mask, that is, the geographic elevation in each azimuth direction, allowing determination of the maximum FOV site between the proposals. Within the *Electromagnetic Study II* process the following step is the capture of electromagnetic data from each site proposal using the

spectrum analyzer with the directional antenna. This must be done using the same reference system as in the geographic study. The data capturing method consists in capturing the azimuth direction from the detected sources in the previous stage *Electromagnetic Study I*. The most adequate location technique allows determining the geographic location of the interference sources by triangulation of the captured data from each site proposals. Once the azimuth directions of the interference sources are calculated from the site proposals, the next step is the capture of the signal spectrum in different periods of time along the day and during one week. This time unit is established for characterizing signal interferences: if it is discrete or noise-like; if it is on working days or everyday; if it is daily on weekdays or on weekends, etc.

Figure 69 shows the steps of the *Electromagnetic Study II* from measurement set-up to data post-processing.

Steps	Description
Instrumentation Set-up	<ul style="list-style-type: none"> -Antenna orthometric height using an extendable tripod which includes the antenna support. -Measurement data set-up using the spectrum analyzer software in each frequency band.
Data Capturing	<ul style="list-style-type: none"> -Positioning the directional antenna in the azimuth direction of the interference source. -Capturing the signal spectrum from the sources located and from each 30° azimuth direction.
Post-processing	<ul style="list-style-type: none"> -Processing the data set captured from the site proposals using the spectrum analyzer software. -Analysis of the results from each site and in the frequency bands applying the peak power function.

Figure 69. Scheme of the *Electromagnetic Study II*.

In addition, this study is completed taking measurements in the mission frequency bands in each 30° azimuth direction along the horizon which provide: first, the affected area by the signal beam from the located signal interference sources and, second, capture of missing sources in the previous stage. The data post-processing from each

site allows analyzing the type of interference and its signal power by applying the spectrum analyzer software in-situ, in particular the peak power function. This further analysis within the location provides GS engineers a best estimation of the available communication times to take a decision of the optimal selection site. In the particular case of CubeSat-LEO missions, this decision is of great relevance taking into account the satellite Tx and the antenna Rx for specific GS mission requirements such as the telemetry mission which requires a maximum FOV site selection and, the command operations which require a minimum signal interference site selection for clear radio links.

The core of this study is the instrumentation set-up, in particular the designed antenna support to simulate the antenna physical specifications, the antenna orthometric height and the rotation of the antenna rotor, simultaneously (see Figure 70(a)).

Figure 70. Electromagnetic Study II. (a) Antenna support designed by the author. (b) Experimental set-up applied in the case study at Cal Poly University.

Figure 70(b) shows the prototype built from the designed antenna support which was experimented in the case study at Cal Poly University to simulate the horizon plane on the virtual antenna rotor center, and the antenna rotation in specific azimuth direction and elevation. This support was designed by the author considering how a theodolite

works, by replacing the viewfinder with a cylinder to put inside the directional antenna. This cylinder is contained in an inclinometer in the vertical plane which allows targeting the elevation during the data acquisition by the spectrum analyzer equipment in a specific azimuth direction.

This experimental set-up was applied in the case at Cal Poly University in three sites which were provisionally approved by the facility manager (see Figure 71(a)). The signal spectrum capture from the sources located and for each 30° azimuth direction is the next step to complete the electromagnetic study from the selected site (see Figure 71(b)). The *Electromagnetic Study II* completes the information obtained from the *Geographic Study II* which contains the 3D digital model of the roof platform (see Figure 71(c)) and the geographic mask from each site (see Figure 71(d)).

Figure 71. Further analysis in the GS location site in the case study at Cal Poly University. (a) GS site proposals within the selected roof platform. (b) Electromagnetic study II in the 30° azimuth directions from each site. (c) 3D basic digital model of the building roof scenario. (d) Data capture of the geographic mask the selected site.

3.2.4 Antenna elevation mask in the mission band

To in situ simulate the tracking antenna elevation mask in the selected optimal site a measurement set-up was designed when using different data capturing sensors. This set-up provides quick in-situ results of the electromagnetic mask (O4), which also allows a swift process of fusion of masks (R4). Figure 72 shows the designed measurement set-up which establishes the antenna rotor as the center of the coordinate reference system in both studies, geographic and electromagnetic.

Figure 72. Scheme of the designed measurement set-up to in-situ simulate the antenna elevation mask in the mission frequency bands.

Once the altimetry profile has been captured along the azimuth range where the signal interference source has been located, the 3D modeling equipment is replaced by the antenna support connected to the spectrum analyzer for the data acquisition of signal transmissions from that interference source. The core of this measurement set-up is the antenna support, described in the previous stage, which provides the assembly of the directional antenna establishing the same horizon plane level in each site proposal for data acquisition using the spectrum analyzer equipment once the geographic study has been done. The goal of this designed measurement set-up is the configuration of software for data post-processing to transform the measurement data into azimuth and elevation parameters. This provides the in-situ visualization of the antenna elevation mask information. Figure 73 shows the scheme of the *Electromagnetic Study III*, once the spatial position of the virtual antenna rotor center has been positioned, and the altimetry profile from that point has been captured.

Steps	Description
Measurement Set-up	<ul style="list-style-type: none"> -Spatial position of the virtual antenna rotor center as the horizon plane assembling the extended tripod and the antenna support. -Measurement parameters configuration using the spectrum analyzer software.
Data Capturing	<ul style="list-style-type: none"> -Positioning the directional antenna in the azimuth direction of the interference source. -Capturing the signal spectrum in different elevations, from 0° to 90°, in several periods of time along the day and during one week. -Positioning and capturing processes along the azimuth range affected for the potential interference source beam.
Post-processing	<ul style="list-style-type: none"> -Data set post-processing applying the peak power and the spectrogram functions to visualize the signal spectrum polyline and, targeting the antenna minimum elevation using the inclinometer.

Figure 73. Scheme of the *Electromagnetic Study III*.

The purpose of this measurement set-up is to target a best estimation of the antenna minimum elevation to start communications with the satellite once the signal interference source has been located in a specific azimuth direction. In particular, targeting when the signal power received from the interference source decreases in relation to the satellite Tx established as the reference signal threshold for the analysis of the satellite radio links. This preliminary analysis includes the signal to noise ratio which is required to reduce the signal interference when the satellite AOS is in the interference source azimuth direction. Within the data capture step, the measurements along the azimuth range affected by the potential interference source beam are required in order to complete the electromagnetic mask. This represents how the signal power decreases as the antenna turns away from the center of the source signal beam. By applying this measurement set-up in each signal interference source and also in each frequency band of the mission, the result is a customized elevation mask of the tracking antenna from the site selected. This mask provides a best estimation of satellite visibility times thanks to the geographic mask information and to the electromagnetic mask information from azimuth directions of interference sources. The last has been obtained from information on how the signal interference sources surrounding the antenna site affect the radio links during each day on the different weekdays. The fusion of both masks, geographic and electromagnetic, is the expected result for the in-situ simulation of the tracking antenna elevation mask in the selected mission frequency band from the selected site. The swift data fusion process performed by a basic calculation program is possible thanks to the instrumentation set-up which establishes the same reference system when using different data capturing sensors and, thanks to the measurement data set-up which transforms the results into the required parameters, azimuth and elevation in both studies.

Figure 74 shows the main data obtained when implementing this stage in a specific frequency band, such as in the particular case analysis of a radio amateur antenna which emits in the VHF band in the 120° azimuth directions. Figure 74(a) shows the graphical representation of the captured data analysis process in the interference source azimuth direction. Points (A, B, C) on the graphic represent the signal peak power received with directional antenna elevations of 0°, 10° and 20°, respectively. When establishing the

signal threshold planes in CubeSat missions -80 dBm corresponds to the satellite Tx to downlink communications and, -100 dBm corresponds to the signal power range for a clear communication between the satellite and the GS. Graphical analysis evidences: first, that the signal power received from the interference source with a directional antenna elevation between 0° (point A) to 10° (point B) affects the satellite communications and, second, that a 20° antenna elevation (point C) is quite enough to establish a clear satellite radio link.

(a)

(b)

Figure 74. Data analysis processes of the signal interference source azimuth direction. (a) Relative to the antenna elevation range. (b) Relative to the antenna azimuth range.

Figure 74(b) shows the curves which represent the received signal peak power in azimuth directions between 90° and 150° in specific antenna elevations (0° , 10° and 20°)

considering the interference source in the 120° azimuth direction. They also represent how the signal power decreases as the antenna turns away from the center of the source signal beam (see marked points which represent a signal power decrease to -90 dBm).

The implementation of this stage can be seen in Figure 75. This graphic represents the antenna elevation mask range from the proposal site customized in the VHF band mission in the case study at Cal Poly University, considering a minimum antenna elevation of 13° to start communication with the satellite in the 120° azimuth direction.

Figure 75. Graphic representation of the antenna elevation mask in the VHF band by applying the geographic and electromagnetic data fusion, in the azimuth range affected for the signal transmissions from the radio amateur antenna located in the 120° azimuth direction.

3.2.5 Analysis by the satellite mission software

Once the antenna elevation mask in the mission frequency band is calculated, the next stage is the satellite mission simulation using the STK program. This software allows changing the satellite mission parameters required to simulate the different GS scenarios and also to visualize the scenario created in 2D and 3D dimensions. Basically, this software creates a scenario where the mission is simulated by establishing a set of fixed parameters in relation to the space segment and by changing the parameters relative to the ground segment, the GS geographic location and the antenna elevation

mask. Graphical and numerical results provide the mission analyst with the current state of the communication times for a given GS location or the optimal location between proposals by comparing the calculated antenna elevation mask for each location.

Figure 76 shows the scheme of this stage from the compilation of the data set required by the mission simulation software, to the reporting of graphical and numerical results from the different scenarios simulation.

Steps	Description
Data Set	-GNSS position and orthometric height of the virtual antenna rotor center and, the terrain data or antenna elevation mask from that point.
Compilation	-Satellite parameters (orbit, inclination, height, etc.) and mission constrains (sensor mask, Tx, Px, etc.).
Mission	-Creating the scenario using the data set of the previous step (terrain environment, object properties, etc.).
Simulation	-Selecting the time period for the mission analysis. -Computing access using the scenario animation, selecting the 2D and 3D graphics windows the satellite's GS track. -Imposing constrains on access such as the antenna mask or a tracking time period, analyzing different scenarios.
Data Set	-Reporting the numerical and graphic results of the mission simulations applying functions such as the Access which provides the list of access times, or the AER which provides azimuth-elevation and range relative to the time function in each satellite pass.
Post-processing	

Figure 76. Scheme of the Analysis using the satellite mission software.

The mission analyst requires the antenna elevation mask field to simulate the satellite mission using specific software such as the STK program. This field contains the antenna minimum elevation in each azimuth direction along the horizon from the spatial position of the GS site, obtained in the previous stage. From a communications point of view, it is convenient to have a high satellite altitude in order to maximize the amount of data download (O5). The results obtained by applying this mission analysis software,

in particular, satellite communications times (R5), provide an estimate of the pass duration per day along the mission. This information is of great relevance to evaluate the mission requirements. The amount of data download is obtained by transforming the numerical results of the satellite pass duration per day, using the satellite bit rate. The final results provide the mission analyst with the amount of data download per day. This can be a relevant factor in the selection of the GS site for a telemetry mission.

Figure 77 shows the main data obtained by implementing this stage in the particular case analysis of the given GS scenario in the case study at UPM University, by applying a standard antenna elevation mask and the customize mask calculated in-situ. To create the scenario in the STK program the Xatcobeo nano-satellite mission was selected. This scenario was created fixing the space segment parameters, introducing the new parameters of the ground segment, and selecting the analysis time period (from May 6th to June 7th, 2013). Blue lines represent the satellite passes obtained when applying the antenna calculated elevation mask during the selected analysis time. The numerical results obtained represent the available visibility times in each satellite pass from the spatial position of the GS selection site.

Figure 77. Satellite passes applying the antenna customized elevation mask in the simulation of the Xatcobeo nano-satellite mission.

Figure 78 shows the 3D graphic detail in relation to polar coordinates, azimuth and elevation. These graphics evidence the increase in the visible horizon when applying the antenna customized elevation mask (see Figure 78(a)) as described in the previous stage

versus a 5° elevation mask (see Figure 78(b)). This information provides the mission analyst with a customized mask to be considered in the telemetry operations along the mission, as it maximizes the data download per day.

Figure 78. 3D graphic views relative to the polar coordinates, azimuth and elevation. (a) Customized mask. (b) 5° standard mask.

3.2.6 Optimal site versus site re-design

Once the mission analyst extracts all the information relative to the satellite mission analysis, and taking into account the satellite mission requirements, GS engineers have to decide the optimal site for the GS installation within the selected GS location (O6.1). The next step is the compilation of this information, including the results from the last stages and the installation design, which compose the final report (R6.1). This report that justifies the decision for the GS site is used by the GS engineers to request the installation permit to the facility manager.

This stage includes the option to request the site re-design (O6.2) when new mission requirements or modifications in the installation design by the GS engineers are added, or when other constraints for installation which were not previously considered by the facility manager are made evident. The result implies going back to stage 3 (R6.2) for further analysis for the new GS location site. Figure 79 shows the proposed procedure, within the analysis model, for a new GS location site which fullfils the mission requirements and the facility constraints as agreed between GS engineers and the facility manager.

Stage 1	Mission requirements & constraints for installation	
Stage 2	Preliminary analysis of the location proposals	
Stage 3	Further analysis in the location site	
Stage 4	Antenna elevation mask in the mission band	
Stage 5	Analysis using the satellite mission software	
Stage 6	Optimal site versus site re-design	
	O6.1. Optimal site	R6.1. Final report
	O6.2. Site re-design	R6.2. Stage 3

Figure 79. Proposed procedures within the stage 6 when there is not an agreement between GS engineers and facility manager.

Generally, the installation permit is approved by the facility manager once the selected provisional site in stage 2 has been approved taking into account the established facility constraints. However, the facility manager checks these constraints and particularly the installation design of the outdoor components and its connections to the control room. Possible scenarios can appear due to modifications requested by the facility manager in relation to internal and security rules, or imposed by GS engineers in relation to satellite parameters such as a new mission concept and payload requirements. In such scenarios, the site re-design is the proposed solution.

In this stage, the analysis model proposes to re-create the GS scenario for a further analysis of the optimal site within the location, one that fulfills the requirements and constraints defined by GS engineers and the facility manager respectively. This is possible thanks to the 3D digital model of the GS scenario obtained using 3D modeling sensors such as the 3D laser scanner. In addition, the 3D digital process of the GS location scenario obtained using 3D survey methods provides the digital reality of the selected analysis factors, and also allows real time visualization and geometric information extraction. The core of this procedure is the quick few-hour data capture process possible thanks to the technology capabilities of massive data capture which is only a few minutes per scan. Figure 80 shows the scheme of the processes for the 3D digital model of the location scenario; from the selection of the data capturing sensor to

the modeling of the entities over the location platform which affect the factors for analysis of the site re-design.

Processes	Objectives	Results
Data Capturing	<ul style="list-style-type: none"> • Selecting the 3D modeling sensor most adequate to the data capture, the accuracy and, the timeline required for the GS engineers. • Establishing the same coordinates reference system as in the <i>Geographic Study II</i>. • Targeting the position of the survey markers for an optimal coverage of the GS location area. • Capture process from each marker considering the targets position which will allows the join of the clouds of points. 	Laser Scanner GNSS Position Survey Markers Clouds of Points
Data Processing	<ul style="list-style-type: none"> • Joining the clouds of points using the laser scanning software which uses the common targets in each scanning to compose the 3D real view. • Cleaning the group of points outside the area and which are not requiring for the modeling process. • Modeling the selected entities for the analysis applying the 3D tools includes in the program. 	3D Real View Entities Selection 3D Digital Model
Data Post-Processing	<ul style="list-style-type: none"> • Selecting the site proposal for the GS engineers and the facility manager using the viewer program and the available measurement functions, considering the analysis factors (obstacles and antenna height). • Visualizing the impact of the GS site re-design for the installation permit. • Exporting the required deliverables to CAD program for the new GS site proposal. 	Optimal Site Installation Approval GS Site Re-design CAD Files

Figure 80. 3D digital scenario applying 3D survey methods and modeling techniques.

Next figure shows the main data obtained by implementing this stage in the case study at UPM University, in the particular case analysis of the given GS scenario. Due to the fact that the antenna mast height was a constraint in the outdoor components set-up, re-designing the site was the solution. 3D real view obtained by scanning the location area

allowed GS engineers and the facility manager to analyze the optimal site (see Figure 81(a)). In addition, the 3D model allowed simulating the GS project impact in the proposed site (see Figure 81(b)).

(a)

(b)

Figure 81. 3D digital scenario of the current GS site in the case study at UPM University. (a) 3D real view from the laser scanning process. (b) 3D digital model of the scenario entities to analyze.

The stages described in this section have been developed considering the most adequate framework to achieve an analysis model in order to optimize the GS location in built-up areas, for the most common case scenarios.

This framework includes from techniques and tools exploration to reach the research objectives and in particular the expected results in each model stage, to experimental implementation in real cases.

The model stages set-up has been designed to apply it in the best case scenario when a location area is available for the site selection analysis, and in the worst case scenario for a given GS location site.

This analysis model is mainly based on:

1. Preliminary analysis of the location taking into account the mission requirements and the constraints for installation determined in the meetings between the GS engineers and the facility manager, in order to:
 - a. Analysis factors selection and description.
 - b. Valuation criteria of each one (coefficient value between 0 and 1).
2. Further analysis in the location site to optimize the site applying the antenna customized elevation mask in the mission frequency band, obtained from:
 - a. The geographic study of the the altimetry profile surrounding.
 - b. The electromagnetic study of the potential interferences sources
3. Final analysis to take a decision, reporting results from each stages, mainly:
 - a. Deliverables from the 3D digital scenario of the GS location in relation to the current state and GS facilities impact.
 - b. Antenna customized elevation mask in the mission frequency band from the selected GS site.
 - c. Graphic and numerical data from the satellite mission simulation versus the GS mission requirements.

In addition, this analysis model can be applied in specific case scenarios such as an installed GS by analyzing the current state and if needed by proposing the GS re-design or re-location and a designed GS by testing the available communication times before the installation process.

Further description of the implemented framework in each model stage is described in the following chapter in the theoretical models experimented in the case studies analyzed along this research.

4 CASE STUDIES

This chapter describes the framework implementation and the results obtained from the three different case studies analyzed in the scope of the GS location in built-up areas. The validation of the analysis model proposed in the previous chapter has been possible thanks to the analyses of the results. Particularly, this chapter describes the theoretical models applied in each case study and how they have contributed in the methodological proposal of this thesis. The case studies are described as follows:

1. Case study at UPM University in Madrid (Spain)
2. Case Study at Cal Poly University in California (US)
3. Case study at CUA University in Washington D.C. (US).

The first case study corresponds to the current GS at the UPM University Campus, particularly GS located at ETSIT University (Research period from December 2012 to June 2013). Research of this case study, in collaboration with the Department of Signals, Systems and Radiocommunications, was the starting point of this thesis. The analysis of the current state of the GS location and the improvement proposals from the satellite

FOV point of view were the main objectives. The theoretical model proposed in this case was based on the preliminary analysis of the GS location in built-up areas. In this sense, the following proposals were established:

- To develop a geographic study to capture the current antenna elevation mask.
- To digitalize the GS scenario on the building roof applying 3D techniques.

The second case study corresponds to the new GS at Cal Poly University (Research period from November 2013 to February 2014). This case study was analyzed during the three-month international stay as visiting research in the Aerospace Department. The main objective in this case study was the analysis of the optimal GS site selection within the selected location, by adding to the satellite FOV factor the impact of interfering signals in the communication links. This impact was therefore another factor to take into account in the location analysis process. The theoretical model proposed in this case was based on the real in-situ simulation of the antenna elevation mask from the selected GS location site. In this sense, the following proposal was established:

- To design the instrumentation set-up to in-situ simulate the antenna elevation mask when using different data capturing sensors.

The third case study corresponds to the new GS at CUA University (Research period from March 2014 to May 2014). This case study was the first professional activity related to this research done in collaboration with the Physics Laboratory. The main objective in this case study was the analysis of the optimal GS location within the campus taking into account the satellite FOV and the presence of signals interference sources as the main analysis factors in the selection process of the provisional GS site. The theoretical model proposed in this case was based on the experimental analysis model. In this sense, the following proposal was established:

- Preliminary Analysis Model to select the GS location applying both the Geographic and Electromagnetic studies proposed.

Figure 82(a) shows the geographic location of the case studies, in particular the images of the University buildings where each case was analyzed. Figure 82(b) shows the scheme of the initial proposals to solve the problem statement in each case study.

(a)

(b)

Figure 82. Case studies. (a) Universities location. (b) Initial proposals from the scenario analysis of the GS location in each case study.

4.1 Case study at UPM University, Madrid (Spain)

This is the case study of the GS installed on a building roof at ETSIT, within the UPM University, which corresponds with the starting point of this tesis.

The GS main mission is the tracking of the TELCUBE spatial project (www.telcube.blogspot.com.es) within the QB50 European project (www.qb50.eu), for the study of the lower layer of the thermosphere (90-320 Km) and the research of the re-entry phenomenon. The 50-satellite constellation for this science mission is a European initiative, funded by the Institute of Von Karman and both the ESA and NASA space agencies. This project also involves Universities from European countries, US, Canada and Japan, among others. Each University is building a nano-satellite which includes two CubeSat units: a functional unit for the satellite operations and another which includes an INMS (Ion and Neutral Mass Spectrometer) instrument as the data capturing sensors for the mission. Figure 83(a) shows the virtual view of this constellation where the satellites are separated several Km from each other in a “string-of-pearls” configuration. The mission will start with a circular orbit, at an altitude of 380 Km and with an inclination of 98°. Figure 83(b) shows the virtual view of the QBito nano-satellite built by the UPM University whose dimensions in centimeters are 10x10x26 and has a weight of 2 Kg. It will be deployed from the ISS at an initial circular orbit of 420 km of altitude.

(a)

(b)

Figure 83. Virtual views of the QB50 project. (a) Artist rendition of the QB50 CubeSats (Reinhard, n.d.). (b) QBito nano-satellite (E-USOC, n.d.).

4.1.1 Case study analysis

The ETSIT GS is located on the roof of building “C”, right on top of the Radiation Group Laboratory, where the control center is located. Figure 84 shows the GS components configuration (Gallego, 2013):

- Outdoor components, which contain two yagi antennas with the same rotor, which are installed on top of a metal mast of 2.2 m high. The equipments of polarizers and preamplifiers are embraced to the mast.
- Indoor components, which contain the transceiver, the modem and a satellite tracking software connected to the positioner via the control port.

Each antenna is for transmission and reception in both VHF and UHF frequency bands.

Figure 84. Case study at UPM University: configuration of the outdoor and indoor components (Gallego, 2013).

The main conclusions in the first meeting on December 2012 with GS engineers were: the amount of science data to download as the main mission of the GS, the communication system design in view of the few minutes per satellite pass in LEO missions, and the short data storage available on CubeSat board. The satellite FOV analysis from the GS location was the solution proposed. This was divided into two proposals; first, calculation of the antenna elevation mask applying the geographic study and comparing it with the current mask using mission simulation software, and; second, analysis of the site re-design proposal using the 3D model obtained of the digitalized GS scenario.

4.1.2 Framework implementation

The model approach was to establish procedures to maximize satellite visibility times from the current GS site, and hence communication times in each satellite pass in order to increase the amount of downloaded data. Figure 85 shows the model.

Processes	Specific objectives (SO)	Results
Geographic Study	SO1. Targeting the spatial position of the antenna rotor center using GNSS technology. SO2. Capturing the altimetry profile surrounding the GS site applying survey equipment.	Geographic Mask
Satellite Mission Simulation	SO3. Creating the mission scenario using the STK program imposing the geographic mask calculated as constraints on access, comparing different scenarios. SO4. Reporting the numerical and graphic results of the different scenarios providing the list of satellites access times.	Satellite Access times
3D Model of the GS Scenario	SO5. Capturing the clouds of points (x, y, z) and pixel using the laser scanning technology to compose the realistic view of the GS scenario. SO6. Modeling the entities selected for the scenario analysis applying 3D tools.	3D Digital Model

Figure 85. Theoretical model applied in the GS case at UPM University.

4.1.2.1 Geographic study

To achieve the specific objectives and hence obtain the expected results, a process analyses was developed and used for each proposed process in order to solve the problem statement in each case study (see Figure 86(a)). Figure 86(b) shows the analysis applied to develop the geographic study process for the specific objectives SO1 and SO2. This study contains: the analysis of the scenario, the required data set and their current state, the adequate selection of the data capturing sensors, the post-processing software, and the expected results in the required extension file.

Figure 86. Process analyses. (a) Developed model. (b) Geographic Study.

According to the developed process, the required data set considering the orthometric height of the antenna rotor center contained: the geographic coordinates of the antenna site and the altimetry profile surrounding the GS site. The Trimble S6 total station equipment was selected as the most adequate geographic data capturing sensor in this case scenario. This equipment, provided by Geotronics (www.geotronics.es), includes GNSS technology targeting the antenna site coordinates in the universal system UTM (Universal Transverse Mercator) in real time and with high accuracy. The next step was the data capture of the altimetry profile, targeting the azimuth direction in the different

elevation points along the horizon visible from the antenna site. Figure 87 shows the visual description of the data set captured applying the geographic study. This data set contains; the altimetry profile including high buildings (see Figure 87(a)) and mountains (Figure 87(b)), which reduce the satellite FOV, and; the center of the established coordinate reference system in the spatial position of the antenna rotor center (see Figure 87(c)). Data set capture was performed on December 2012.

Figure 87. Geographic study. (a) High buildings close to the GS location (Screenshot from Google Earth program). (b) High mountains along the horizon from the GS location (Screenshot from Google Earth program). (c) Coordinate reference system established in the spatial position of the antenna rotor center (UTM coordinates: $X = 438473.077$ m; $Y = 4478318.790$ m; $Z = 682.201$ m (orthometric height)).

The software included in the equipment allows the following data post-processing steps; first, the application of the coordinates of the antenna rotor center targeted as the center of the coordinate reference system; second, the translation and rotation (Helmert transformation) of the data set which contains the altimetry profile to the established reference system, and; third, the conversion and output data in the required STK file (azimuth, elevation). Figure 88 shows the graphic result of this file which recreates the scenario surrounding the GS site from the geographic point of view.

Figure 88. Geographic mask calculated from the ETSIT GS site applying the proposed geographic study.

The calculated geographic coordinates of the GS site in the world global system WGS84, $-3^{\circ}43'32''$ E longitude; $40^{\circ}27'11''$ N latitude, complete the data set required by the STK software to simulate the satellite mission. This data set is the antenna elevation mask required by the STK program to create the scenario from the ground segment point of view. The next section describes how the scenario of a particular satellite mission was created, the impact of the calculated mask in the mission analysis, and its comparison with the application of a standard mask in the same mission.

4.1.2.2 Ground station mission scenario simulation

Satellite access times from the GS site are especially important for missions that require a huge download of data, such as the QB50 project. In order to obtain a detailed analysis of the GS coverage to take advantage of every single satellite pass implies; first, creating the mission scenario using the STK program and imposing the calculated geographic mask as a constraint on satellite access to compare different scenarios

(SO3), and; second, reporting the numerical and graphic results of the different scenarios which provide the list of satellite access times (SO4). Figure 89 shows the analysis applied to develop the mission simulation process for these specific objectives.

Figure 89. Process developed for the satellite mission simulation.

When analyzing the problem statement, the antenna minimum elevation can be considered as the factor to be analyzed as this determines the satellite FOV from the GS site. For an efficient use of the satellite visibility along the mission this factor should be considered before the GS installation. To determine the satellite visibility times from the entry to the exit in each satellite pass along the mission, the height and position of the antenna, and the altimetry profile surrounding the GS site must be updated. To discuss the results from the different scenarios analysis which impose constraints such as the orbit height, the spatial vehicle or the antenna elevation mask, the STK program provides the mission analyst with several functions in order to compare specific mission requirements. Hence, this allows him to take a decision in the planning stage in relation to the system communication designed requirements (the amount of download data in each satellite pass along the mission, the GS coverage from the selected location, etc.).

Figure 90(a) shows the screenshot obtained from the STK program in the scenario set-up process of the Xatcobeo, the first Spanish nano-satellite launched in February 2012

(Aguado, 2009), which was used to analyze the results from the different scenarios created imposing the calculated geographic mask and the 5° standard mask, respectively. Figure 90(b) shows the 2D view of the mission simulation using the STK program on a specific day (15th May 2013) applying the antenna calculated elevation mask obtained from the geographic study. The lines (cyan color) are the satellite passes along this day and represent the orbit lengths visible from the ETSIT GS.

(a)

(b)

Figure 90. Satellite Xatcobeo mission simulation applying the STK program. (a) Scenario set-up from the ETSIT GS location. (b) Simulation imposing the antenna calculated elevation mask in specific mission day.

The following figures show the results of applying two antenna elevation masks in the Xatcobeo mission simulation: first, a 5° standard mask (Figure 91(a)) and; second, the calculated mask obtained from the geographic study (Figure 91(b)). These graphics represent the number of visible passes during a specific day (double red line) and the access time in each one (width between double red lines). The UTCG (Gregorian Coordinate Universal Time), and in particular the current ITU version, was selected to determine the time duration in each satellite pass.

(a)

(b)

Figure 91. Access reports obtained from the STK program simulating the Xatcobeo mission on a specific day (15th May 2013). (a) Applying a 5° standard mask. (b) Applying the calculated mask.

Figure 91(b) evidences a new satellite pass between the 3th and 4th pass and the increase in width (access time) in the others satellite passes. When applying the antenna calculated elevation mask from the updated cartography, the geometry of the satellite FOV from the GS site increases and in consequence the satellite visibility times. The following figures show the results in relation to azimuth, elevation and range. Figure 92(b) shows the increase in range (blue line) between the satellite entry and exit over the horizon and, in consequence, the contact times between the satellite and the GS.

Figure 92. AER reports obtained from the STK program simulating the Xatcobeo mission on a specific day (15th May 2013). (a) Applying a 5° standard mask. (b) Applying the calculated mask.

The analysis of the results obtained from the mission simulation in different scenarios provides relevant information in the planning mission, both from the ground and space segments point of view. In this case, the results evidenced the usefulness of the antenna calculated elevation mask for telemetry operations as it increased the satellite FOV from the current GS site. Table 2 shows the available access times in each satellite pass and a new pass. Taking into account the satellite visibility duration of 8 min as a reference value for typical science missions, this fact had a great relevance in the amount of data download in the QBit mission from the ground segment point of view.

Table 2. Time duration of the Satellite passes in the specific day analyzed applying the calculated antenna elevation mask.

Pass	Start Time	Stop Time	Duration (min)
1	00:45:36.009	00:53:40.558	8.706
2	02:20:59.724	02:38:04.221	17.075
3	04:03:36.514	04:19:20.517	15.733
new	05:51:30.166	05:59:38.571	8.140
4	11:06:23.965	11:13:54.037	7.501
5	12:47:38.370	12:57:16.857	9.641
Total			66.796

Considering the fixed parameters from the space and ground segments point of views, and the antenna height as a constraint in the system communication design, the 3D digital process of the GS scenario was the proposal to analyze the problem statement of the satellite FOV. The following section describes this process as the solution for the optimal GS site selection taking into account nearby obstacles surrounding the GS site and the facility constraints on building roofs.

4.1.2.3 3D digital model of the ground station scenario

During the data capture process, nearby obstacles from the antenna site were mapped. These obstacles, which were higher than the antennas, included the top of the

stairs and the elevator of the building. Moreover, these facilities located north of the GS site decreased the satellite FOV in this geographic area. Due to the facility constraints imposed by the facility manager such as the maximum antenna height and a required flat area for GS installation, the following 3D digital model of the GS location was the proposed solution. This includes: first, capture of the clouds of points (x, y, z) and pixel using the laser scanning technology to compose the realistic view of the GS scenario (SO5) and, second, modeling of the selected entities for the scenario analysis by applying the 3D tools (SO6). Figure 93 show the analysis applied to develop the 3D digital model process to achieve these specific objectives.

Figure 93. Process developed for the 3D digital model of the GS scenario.

The Trimble TX5 3D laser equipment and the Real Works Survey software provided by Geotronics (www.geotronics.es) were used. These enabled: first, capturing the cloud of points which allow creating the real 3D view and the 3D geometry of the GS location, and second, modeling the entities which allow analyzing the 3D scene of the satellite FOV from the GS site. This technology allows massive data capture in a short period of time (few minutes per scan) with high accuracy. In addition, the laser software provides a swift data post-processing as it joins the cloud of points in few hours, and allows obtaining graphic deliverables in CAD format, and object modeling using the 3D tools.

In this case, the final accuracy obtained from the data capture process and post-processing was of 7 mm considering a range maximum of 32.23 m in the scanning process (Contreras, 2014). Figure 94(a) shows the screenshot during the fusion process of the cloud of points which provided the real 3D view and the 3D geometry of the GS location. Each orange point corresponds to a different scan site. The viewer program allowed extracting specific information: by taking measurements from the current GS site (see Figure 94(b)) and between different entities within the location and, by visualizing the GS scenario and site proposals considering constraints for installation and mission requirements imposed by the facility manager and the GS engineers, respectively (see Figure 94(c)). Data capture was performed on May 2013.

(a)

(b)

(c)

Figure 94. Laser scanning processes applying the 3D laser TX5. (a) Cloud of points fusion applying the Real Works software to obtain the 3D real view and geometric of the GS scenario. (b) Measurement functions available to measure ranges between the antenna site and obstacles. (c) Antenna site proposal considering the facility constraints and the maximum satellite FOV.

Taking into account the 3D digital model of the GS scenario as the expected result, the next step was the modeling of the selected entities: the roof platform, the outdoor components of the GS and the nearby obstacles. Applying the geometry modifier tools allowed fitting geometric figures (plane, cone, cylinder, sphere, etc.) to the 3D polyhedral models from the scanning process. Figure 95(a) shows screenshots during this process in the particular case of the outdoor components when fitting the main elements to a cylinder figures. For the satellite FOV analysis, the 3D scene of the GS location was created modeling all the selected entities (see Figure 95(b)) using the joined cloud of points (see Figure 95(c)).

(a)

(b)

(c)

Figure 95. Modeling processes applying the Real Works Survey software. (a) Outdoor components modeling using geometric modifier tools. (b) 3D view of the GS site from the clouds of point joined. (c) 3D model scene of the GS site with the entities selected for the satellite FOV analysis.

4.1.3 Results

This section describes the results obtained when applying the proposed theoretical model and particularly the developed processes to solve the problem statement in the case study at UPM University.

The following figure compares both elevation masks: the resulting antenna elevation mask obtained by applying the updated geographic information and the 5° standard mask, which is the minimum mask used in urban environments. This evidences that when using the 5° standard mask there is a loss in visibility times (blue area in Figure 96). However, the calculated mask must not be considered in the satellite link analysis but in the telemetry operations along the mission as it increases the satellite contact times and hence maximizes the data download per day.

Figure 96. Geographic study results: standard mask versus calculated mask.

The satellite Xatcobeo mission simulation performed on a specific day (15th May 2013) by applying the calculated mask evidenced a new pass and an increase in the visibility times in each satellite pass along this day. This fact had a great relevance because it increases the amount of data download in the satellite passes per day in the QBit mission. This new pass and the increase in the time duration for each pass resulted in a 10.633 Megabyte increase in data download compared to that obtained when applying a standard mask. The conversion into Megabytes was done using a bit rate of 9600 bits

per second, (see Table 3).

Table 3. Satellite passes applying a 5° standard mask and the calculated mask (Duration (D) in minutes (min)).

	Standard Mask			Calculated Mask		
	Start Time	Stop Time	Dmin	Start Time	Stop Time	Dmin
1	00:46:50.543	00:52:49.190	5.99	00:45:36.009	00:53:40.558	8.71
2	02:22:31.243	02:37:44.495	15.22	02:20:59.724	02:38:04.221	17.07
3	04:05:11.145	04:18:55.506	13.74	04:03:36.514	04:19:20.517	15.73
				05:51:30.166	05:59:38.571	8.14
4	11:07:43.955	11:13:26.970	5.72	11:06:23.965	11:13:54.037	7.50
5	12:48:36.040	12:56:15.401	7.66	12:47:38.370	12:57:16.857	9.64
Total Passes Duration			48.33			66.79

The 3D modeling process of the GS site using the laser scanning technology and the 3D scene created by applying 3D tools, provided the facility manager and the GS engineers with real time visual and geometric information. This ranged, from the problem statement of the GS current site by analyzing its impact in the satellite mission requirements and in the facility constraints, to the digital modeling process by analyzing the GS scenario to select the optimal site. Figure 97 shows the 3D digital model.

Figure 97. Screenshot of the 3D digital model of the GS location site, including the roof platform, nearby obstacles and the antenna digital model.

In this particular case, the geometric information regarding the antenna orthometric height and the obstacles on the roof was exported in the specific extension file to after import from the CAD program. Once considered the facility constraints, a new GS site was proposed. This reduced the impact of the obstacles in the satellite FOV by 85% (see Figure 98(b)) compared to the current GS site (see Figure 98(a)).

(a)

(b)

Figure 98. Visibility perimeters (cyan color area) obtained from the ETSIT GS site applying the CAD program. (a) Current site. (b) Proposed site to reduce the impact of the obstacles in the satellite FOV.

These results validate the theoretical model proposed for a given GS installation scenario as the implemented framework solves the problem of the amount of download data required for the satellite QBito mission, since it provides; first, the antenna

customized elevation mask for telemetry operations, and; second, the optimal antenna site within the building roof increasing the satellite FOV.

4.2 Case study at Cal Poly University, California (US)

This is the case study of the new GS at Cal Poly University, which corresponds to the international stay of this thesis from November 2013 to February 2014.

The main mission of the GS will be the tracking of the nano-satellite ExoCube. This project is supported by NSF (National Science Foundation) and it will take measurements of the density of oxygen, helium and nitrogen in the high layer of the atmosphere. In addition, new transmission techniques have been included in the nano-satellite and hence the new GS will include new communication and control systems to decode the satellite signals. Since the first CubeSat CP1 launched in July 2006 to the last ExoCube in January 2015, the PolySat Team have designed and built ten small satellites with different science missions such as the CP8 supported by JPL and the CP10 in collaboration with NASA GSFC (Goddard Space Flight center) (www.polysat.calpoly.edu). The success of these missions which correspond to low cost projects has led to a major attention in the efficient use of the GS. In this sense, the new GS will be able to download more data than the other current GSs. Figure 99(a) shows the laboratory building where the current GSs are installed on the roof. Figure 99(b) shows the first CubeSat CP1 and the last nano-satellite ExoCube.

Figure 99. PolySat Team laboratories. (a) Current GSs located on the laboratory roof. (b) CP1: 1 CubeSat unit; ExoCube: 3 Cubesat units (www.polysat.calpoly.edu).

4.2.1 Case study analysis

The selected location for the new GS will be the Engineering building n° 192 which is one of the highest buildings at Cal Poly University, where the PolySat Team has their facilities which are located on the first floor. Figure 100 shows the selected location area (red circle) within the building roof platform.

Figure 100. Location area selected for the new GS on engineering building roof (Screenshot from Google Earth program).

The designed GS contains two yagi antennas with the same rotor which will be installed on top of a metal mast and, also low noise amplifier equipment which will be embraced to this mast. The radio equipment has been designed by the PolySat Team and it will be same as that included in new satellites. This innovation will provide the GS with capacity to decode and transmit the signal directly from the GS. Each antenna will be used for transmission and reception, and communication with the satellites will use radio amateur frequency bands: VHF (435-438 MHz) and UHF (144-146 MHz). In addition, the GS engineers were planning to add; an S band antenna, and; the L band in

the communication system, which provides quality communications without interferences and without the need of great accuracy in the satellite spatial positioning.

The main conclusions drawn from the first meeting with the GS engineers to assess the new communications systems were; first, that the communication system design must take into account the few minutes per satellite pass in LEO mission given the short data storage on-board, and; second, that the optimal site selection must consider the surrounding altimetry profile and the facility constraints for installation on building roof. Taking into account the above, the proposed solution was to select the optimal site considering the satellite FOV and others factors which affect the communication links as well as the imposed security constraints by the facility office and the GS mission requirements. The proposal for the optimal selection included the in-situ simulation of the antenna elevation mask in the mission frequency band. The research objectives of this simulation were; first, to analyze the presence of potential signal interference sources in urban environments, and; second, to design the required measurement set-up in order for the geographic and electromagnetic data fusion to compose the antenna customized elevation mask from the virtual GS site on the building roof.

4.2.2 Framework implementation

The model approach included how to optimize the GS site selection within the location area on the building roof; first, by creating the basic digital model of the building roof platform in order to select the site proposals taking into account the facility constraints within the location area; second, by taking measurements using survey equipment to get the altimetry profile surrounding the site proposals and comparing the results to select the optimal one; third, by taking measurements using the spectrum analyzer equipment to analyze the presence of signal interference sources in the mission frequency bands, and; finally, by applying a further electromagnetic study from this site with a directional antenna to provide the mission analyst with the antenna elevation mask customized for the selected mission frequency band.

Figure 101 shows the theoretical model applied, which includes the specific objectives and the expected results for analysis of the optimal site. This model allows testing the

mission requirements before the GS installation stage and taking a decision in the GS site selection process which takes into account: the updated geographic and electromagnetic information surrounding the location area, the GS requirements for the satellite mission, and the imposed constraints for the GS facilities.

Processes	Specific objectives (SO)	Results
Geographic Study	SO1. Capturing the geographic map of the building roof using GNSS technology. SO2. Capturing the altimetry profile from the site proposals using survey equipment.	Geographic Map Optimal Site
Electromagnetic Study	SO3. Targeting the signal interference sources surrounding the GS location using the spectrum analyzer equipment. SO4. Capturing the signal power spectrums from the interference source positioning the directional antenna in different elevations from the established horizon plane.	Signal Interference Sources Electromagnetic Mask
Geographic and Electromagnetic Data Fusion	SO5. Targeting the antenna minimum elevation in the azimuth range of the source signal beam for a clear communication using using an inclinometer. SO6. Post-processing of the electromagnetic data to complete the calculated geographic mask.	Antenna Elevation Mask in the Mission Band

Figure 101. Theoretical model proposed to analyze the GS case study at Cal Poly University.

4.2.2.1 Geographic study

In this case study, the geographic map of the building roof platform was required for the selection of the site proposals within the selected location area. This map allowed to draw the security ranges established by the facility manager for specific entities on the roof, and hence, to visualize the available sites for the GS installation. To achieve the specific objectives and therefore the expected results, a process analysis was

developed to solve the problem statement in this particular case (see Figure 102). This implied; first, capturing the geographic map using GNSS technology (SO1), and; second, capturing the altimetry profile from each site using survey equipment (SO2)).

Figure 102. Process developed for the geographic study. (a) Geographic map to target the site proposals within the building roof area. (b) Geographic mask from the GS location site proposals.

According to the developed process, the required data set contained the basic geographic map of the building roof and the altimetry profile surrounding from the GS site proposals. This data set was obtained taking into account the orthometric height of the virtual antenna rotor center as the antenna horizon plane. The GNSS equipment built in the engineering department was used for the data capturing processes, and the coordinate reference system was established applying the OPUS (Online Positioning User Service) positioning service which provides high accuracy in the reference system NSRS (National Space Reference System) (www.ngs.noaa.gov). Table 4 shows the coordinates of the base station. Data capture was performed on November 2013.

Table 4. Base station coordinates resolved using OPUS positioning service.

LAT:	35 18 11.74626	0.009(m)	EL HGT:	70.377(m)	0.037(m)
E LON:	239 20 8.29770	0.006(m)	ORTHO HGT:	104.973(m)	0.043(m)
W LON:	120 39 51.70230	0.006(m)	[NAVD88 (Computed using GEOID12A)]		

The next step was to obtain the drawing using the CAD program, which was done by importing the cloud of points from the capture processes using total station equipment. Figure 103(a) shows the resulting geographic map of the building roof area needed to analyze the optimal GS site. Figure 103(b) shows the antenna site proposal taking into account the following facility constraints: a 6 m security radius from the mast position, and a 2 m range from the building perimeter. Figure 103(c) shows the 3D virtual view.

Figure 103. Geographic study processes. (a) Geographic map of the building roof. (b) Optimal site which accomplish the facility constraints. (c) Virtual view of the future antenna installation within the 3D basic map.

The results obtained when implementing this stage in the case study at Cal Poly University show the usefulness of the described geographic study as this allows representing the scenario of the installation area, selecting the optimal site between the proposals, and drawing the facility constraints such as the established security ranges to the walkway on the roof. In addition, the 3D basic map representation of the site proposal including the virtual GS, allowed visualizing the installation impact on the building roof (see Figure 103(c)). This fact was of great relevance to obtain the installation permit as it enabled to visualize the impact of the outdoor components and the connections to the control room.

Following the developed process, the next step was to capture the altimetry profile from the site proposals using the total station provided by University. The resulting geographic masks from each site provided the satellite FOV, a relevant factor for GS engineers to consider when taking a decision in the site selection.

Results in Table 5 indicate the visibility percentage of the elevations over the antenna horizon plane, which reduce the satellite pass length along the horizon from the virtual antenna rotor center. The worst result was in site “A” as this was close to high entities on the roof. Results for the other two sites were very similar. Site “C” was finally selected by the agreement between the facility manager and the GS engineers, considering the facility constraints and the GS requirements, respectively.

Table 5. Analysis factors for the optimal GS location site selection.

Analysis Factors	Site Proposals		
	A	B	C
Satellite FOV from the antenna rotor center	65%	70%	70%
Constrain of 2 m from the building perimeter	Si	No	Si
Constrain of 6 m radius from the mast position	Si	No	Si
Constrain of not crossing the walkway	No	Si	Si

Once selected the optimal site, the final step was the capture of the altimetry profile with major accuracy.

Figure 104 shows the geographic mask obtained from the virtual antenna rotor center in the selected optimal site.

Figure 104. Geographic mask obtained from the optimal GS site.

In addition, the geographic coordinates of the GS site calculated in the world system WGS84 (-120°66'44 E longitude and 35°30'32 N latitude) and a 107.15 m of orthometric height completed the required data set for the satellite mission simulation software. This data set determined the antenna elevation mask to create the GS scenario from the geographic information point of view.

The next section in this case study describes the research relative to the presence of signal interference sources in urban environments which affect the GS scenario from the electromagnetic point of view.

4.2.2.2 Electromagnetic study

As the GS acts as a sensor for receiving and transmitting radio waves and the potential interference sources surrounding the location site could emit in the same frequency bands, the spectrum analyzer equipment is the most adequate data capturing sensor to achieve the following objectives; first, targeting the signal interference sources which radiate in the mission frequency bands, surrounding the GS location using the spectrum analyzer equipment (SO3), and; second, capturing the signal power spectrums from the interference source located in certain azimuth directions by positioning the directional antenna in different elevations (SO4).

Figure 105 shows the process developed in order to achieve the expected results.

Figure 105. Process developed for the electromagnetic study.

Considering the purpose was to in-situ simulate the antenna elevation mask from the electromagnetic point of view and the required measurement data, azimuth and elevation, a measurement set-up and a hardware set-up were designed for the data capture processes. A directional antenna support which included an inclinometer in the vertical plane (see Figure 106(a)), was designed to simulate the spatial position of the directional antenna during the signal spectrums capture (see Figure 106(b)).

Figure 106. Antenna support designed for the electromagnetic study with the directional antenna. (a) Built process. (b) Experimental process.

Figure 107 shows the designed hardware set-up for the electromagnetic study processes.

Figure 107. Hardware configurations for the Electromagnetic Study with the spectrum analyzer Anritsu S412E (www.anritsu.com) provided by the University. (a) Omni directional antenna. (b) Directional antenna.

In this case study the spectrum analyzer equipment used was that available at the PolySat laboratory. The designed hardware set-up included: a portable computer for the measurement data configuration and for the in-situ visualization of the signal spectrum results, an Omni directional antenna connected to the equipment for the detection of the interference sources, a directional antenna for the data capture of signal spectrums in the azimuth direction of the interference sources, and an extendable tripod to simulate the virtual antenna height. The selected frequency bands ranges were those assigned in the ITU recommendations for CubeSat projects in the last 10 years, such as the nano-satellite Delfi C3 in VHF band and the Xatcobeo in UHF band (Klofas & Leveque, 2012). In addition, the study included the S band in the frequency range 2.400-2.450 MHz and the L band in the frequency range 1.260-1.270 MHz.

To describe the process, both the VHF band and a signal interference source which emitted in this frequency band were selected.

The first step in the proposed electromagnetic study was the study with the Omni directional antenna, which detected the presence of potential interference sources in the

VHF band surrounding the selected antenna site. In this process, the measurement set-up consisted in the signal spectrums capture using the Omni directional antenna using the spectrum analyzer equipment without a preamplifier and in different periods of time during the day along one week.

The MST (Master Software Tools) program, provided by Anritsu (www.anritsu.com) was used; first, for the measurement data configuration and; second, for the analysis of the captured data set. The main measurement parameters used were: a minimum sweep time of 300 seconds, a frequency span of 3.000 MHz, a resolution bandwidth (RBW) of 30 kHz, an input attenuation of 10 kHz, and a video bandwidth (VBW) of 10 kHz.

Figure 108 shows the 3D view of this data set in relation to the frequency, the time and the amplitude, by applying the peak power and spectrogram functions. These functions are the most frequently used to visualize the received signal peaks during a period of time and hence very useful to verify the presence of potential interference sources.

Figure 108. Signal spectrums processing applying the MST software from the data capturing process with the Omni directional antenna in the VHF frequency band; peak power and spectrogram functions applied in the data set captured along one week.

The next step was to apply the spectrogram function by configuring frequency filters in order to analyze the measurement data, and to establish a signal amplitude threshold detecting signal interferences which could affect the radio links between the GS and the satellite. In the particular case of the data set captured during every morning along that week, a signal peak power was observed in a specific day.

Figure 109 shows the graphic representation of the data set analysis when applying the average function, targeting a signal peak of -55.216 dBm in the frequency range between 145.0 and 145.2 MHz.

Figure 109. Graphic result of the data set captured in a specific day (5th February 2014) applying the average function.

In order to characterize this signal interference detected around the 145 MHz signal frequency, the peak frequency function was applied. This function provided graphical and numerical information relative to the periods of time during which the signal interference source radiates.

Graphic results determined the level of influence in the communication links in the VHF band between the satellite and the virtual spatial position of the GS. These can be

seen in Figure 110. In addition, the same figure shows the 3D graphic obtained when applying the spectrogram function which allows visualizing the signal interference domain.

(a)

(b)

Figure 110. Graphic result of the data set captured in a specific day (5th February 2014) applying MST functions. (a) Peak Frequency. (b) Spectrogram.

This study was applied in the selected frequency ranges. Results evidenced the presence of signal interference sources that emitted in the mission frequency bands such as industrial machinery, a wireless mobile antenna, a radio amateur antenna, and electronic devices installed on the building roof (see Figure 111(a)). In the developed process, the goal of this study was the geographic location of these interference sources surrounding the GS site. This was done following three stages: detection, identification, and location. Once the main interference sources were identified, their azimuth directions from the antenna site were targeted using total station equipment (see Figure 111(b)).

Figure 111. Azimuth directions of the interference sources located from the selected GS site. (a) Panoramic view. (b) Top view.

The location of these sources was targeted in the same coordinate reference system applied in the geographic study. This fact was of great relevance to develop the study process with the directional antenna. This is described in the next section, and in particular, the designed hardware set-up when using different data capturing sensors.

4.2.2.3 Electromagnetic study with the directional antenna

The measurement system consisted in the signal spectrums capture in different elevations (from 0° to 90°) using the spectrum analyzer equipment with the directional antenna. A radio amateur antenna located in the 120° azimuth direction was selected to describe the proposed measurement set-up (see Figure 112(a)). Measurements were taken: in different periods of time during the day along one week, and applying the same measurement parameters used in the study with the Omni directional antenna. This antenna emitted and received every day, during different periods of time and, in the particular radio amateur frequency ranges; 435-438 MHz, in the UHF band, and; 144-146 MHz, in the VHF band. To describe the applied measurement set-up along this section, the VHF band was selected, and the measurement data was reduced to antenna elevations between 0° and 40° . Figure 112(b) shows a data capture moment for a 10° antenna elevation.

Figure 112. Electromagnetic study with the directional antenna. (a) Top view of the radio amateur azimuth direction from the selected site. (b) Hardware set-up which includes: an extendable tripod, the designed antenna support, the directional antenna, and the spectrum analyzer equipment.

When applying the peak power function included in the MST software, the graphic result describes a poly-line with the signal power maximum received in each directional antenna elevation (0° , 10° , 20° , and 40°). Extracting the measurement data on a specific day (5th February 2014) and applying this function, the graphic result evidenced an increase in the signal power received as the antenna elevation decreased, from 40° to 0° , particularly 32 dBm from 20° to 10° antenna elevations (see Figure 113).

Figure 113. Analysis of a particular signal interference source: graphic result applying the peak power function, in a specific period of time.

The proposed analysis was to target the antenna minimum elevation to start the communications with the satellite, considering a Tx threshold and a minimum signal power range. In this case, a threshold of -80 dBm was selected as a typical Tx for a CubeSat mission, and a signal power range of 10 dBm to establish a clear communication link.

The red point on the following figure determined a 16° antenna minimum elevation in the interference source azimuth direction. However, a 13° antenna elevation (blue point on the previous graphic) should be considered to start the communication in particular

telemetry operations, thus maximizing the communication times with the satellite (see Figure 114 (a)). Figure 114(b) shows these elevations represented on the geographic mask graphic and their signal power received from the radio amateur antenna located in the 120° azimuth direction.

Figure 114. Graphic results of the electromagnetic study proposed with the directional antenna in the interference source azimuth direction. (a) Further analysis proposed to target the directional antenna elevation to start the communication with the satellite. (b) Graphic representation of the geographic mask including the antenna minimum elevation in the azimuth direction of the radio amateur antenna.

Applying both geographic and electromagnetic studies, results provide the mission analyst with the best estimation of the antenna minimum elevation along the horizon

visible from the GS site, and specific antenna elevations in certain azimuth directions due to the presence of signal interference sources in the mission frequency band.

The next section describes the second step in the proposed electromagnetic study; first, completion of the electromagnetic mask in the azimuth range affected by the interference source beam and; second, the proposed data fusion process of both the geographic and electromagnetic data sets.

4.2.2.4 Simulation of the ground station antenna elevation mask

The purpose of the electromagnetic study with the directional antenna was to target a best estimation of the antenna minimum elevation to start communications with the satellite once the signal interference source has been located in a specific azimuth direction. Taking into account that the signal interference sources emitted radio waves, the next objective was to target the antenna minimum elevation in the azimuth range of the source signal beam for a clear communication by using an inclinometer (SO5). Figure 115 shows the panoramic view from the GS site of the azimuth range where the radio amateur antenna was located in the 120° azimuth direction. In addition, this view provides the main elevations targeted from the geographic study which are contained in the resulting geographic mask.

Figure 115. Geographic elevations in the azimuth range where the radio amateur antenna was located.

The azimuth range, which was affected due to the signal interference beam, was considered to complete the electromagnetic mask information. Taking into account the azimuth direction of the interference source as the central axis of the area affected, the next step was the analysis of the signal power received in the azimuth directions, 90° and 150°. Table 6 shows the results obtained by applying the same measurement system as in the azimuth direction of the radio amateur antenna to determine the signal peak power profile in the azimuth range affected by the interference source.

Table 6. Results of the signal peak power received using the spectrum analyzer with the directional antenna in the elevations 0°, 10° and 20°.

Antenna elevation [°]	20	-103,48	-103,31	-103,60
	10	-98,92	-71,74	-103,62
	0	-103,48	-61,64	-103,60
		90	120	150
Azimuth direction from the antenna site [°]				

The results evidenced the decrease of the signal power received as the directional antenna turns away from the center of the source signal beam (see Figure 116).

Figure 116. Graphic analyses for a best estimation of the azimuth range affected using the proposed measurement setup to complete the antenna elevation mask.

The application of a 20° antenna elevation was quite enough to establish a clear communication link. However, the application of a 10° antenna elevation determined a

narrower azimuth range affected by the signal beam. To ensure a stable satellite link, it is important to steer the antenna beam towards the satellite position in order to avoid excessive pointing losses that may degrade the signal reception under specified limits. In this sense, a further electromagnetic analysis between antenna elevations of 10° and 20° was considered to target a best estimation of the antenna elevation in the interference source azimuth direction. Figure 117 shows the antenna minimum elevation between those limits considering the interference source azimuth direction as the center of the azimuth range affected. These elevations correspond to the threshold established for starting the communications with the satellite.

Figure 117. Graphic result of the electromagnetic study proposed with the directional antenna in the interference source azimuth range affected.

The geographic information of the antenna site and surrounding environment is of great importance in order to increase the effectiveness of the acquisition and tracking operations from the satellite entry to the exit along the horizon from the GS site. In addition, the electromagnetic information surrounding the antenna site is even more relevant to estimate the increase in the antenna elevation, as this in turn improves the AOS and LOS of the satellite passes.

The core of this process was the post-processing of the electromagnetic data since, thanks to the use of the same reference system as in the geographic study and the designed antenna support targeting the antenna elevation when the signal power

received reaches the established Tx threshold, the geographic mask was completed (SO6). Table 7 shows the field required by the STK program which also requires the geographic coordinates (North, East) in the WGS84 system and the orthometric height of the spatial position of the antenna rotor center. The data set in red color represents the azimuth range affected by the source signal beam.

Table 7. Azimuth-Elevation Mask (AzElMask) field in specific extension (.txt), required by the STK program, which contains azimuth directions (first column) in each change of horizon elevation (second column).

stk.v.10.0		192.8	1.0	276.3	4.0
BEGIN AzElMask		193.8	0.5	278.9	4.2
NumberOfPoints 80		195.1	0.3	280.6	2.6
BEGIN AzElMaskData		199.5	1.7	281.9	2.5
0.0	8.3	206.6	4.6	282.3	2.9
1.5	8.3	207.9	4.7	283.3	2.4
3.2	7.5	213.3	6.1	288.5	2.4
4.5	7.6	213.9	5.7	292.6	1.6
11.0	6.5	216.1	5.6	298.9	1.1
17.9	7.7	222.6	4.0	302.2	1.8
20.9	6.1	227.8	4.0	307.6	0.8
25.8	6.3	227.8	1.9	311.2	1.1
32.1	9.1	229.0	1.7	314.0	1.3
39.2	8.3	229.2	1.7	315.9	1.5
44.5	5.2	229.6	1.6	317.2	1.9
47.6	5.8	230.2	1.6	318.4	1.9
54.7	5.6	230.4	1.6	319.7	1.6
68.4	10.2	230.8	1.6	321.1	1.6
75.7	9.7	231.0	1.7	322.4	1.5
86.3	10.3	231.3	1.6	326.9	3.1
98.0	8.5	231.7	1.7	330.8	4.8
100.0	10.0	231.7	2.6	335.8	5.0
110.0	12.0	246.1	2.6	339.9	4.7
120.0	13.0	251.0	3.1	346.8	7.2
130.0	12.0	257.3	2.5	354.9	9.1
142.0	10.0	263.9	5.7	357.1	8.4
148.0	2.5	268.6	6.9	END	
172.9	3.0	272.7	4.3	AzElMask	
172.9	1.2	275.1	3.7		

If the described data fusion process is applied to all the targeted signal interference sources which emit in the VHF frequency band, the antenna elevation mask from the geographic information will be completed just in the azimuth directions where these sources are located from the GS site. It can be applied to any threshold between 5° and 20° like those used in real missions.

4.2.3 Results

This section describes the results obtained when applying the proposed theoretical model to solve the problem statement in the case study at Cal Poly University. Particularly, the following proposals: creating a 3D basic model of the GS location for the installation planning, designing an electromagnetic study process for locating signal interference sources in certain azimuth directions from the GS site, and developing a data fusion process of both electromagnetic and geographic data set to complete the antenna elevation mask information.

An optimal site was proposed using the geographic map created by the geographic study process, which considered the facility constraints for the GS installation and the satellite FOV as the main mission requirements. Figure 118 shows the 3D basic model of the building roof applying the CAD program. The 3D basic model was very useful in the approval request for installation; as it provided the facility manager with the view of the GS facilities impact, and GS engineers with specific measurements for the GS components set-up and connections to the control room.

Figure 118. Graphic result of the geographic study proposed to create the 3D basic model for the optimal GS site selection.

The proposed electromagnetic study from the GS site selected, provided a customized mask which reduced the signal noise ratio just in the azimuth range affected by the interference source. Figure 119(a) shows the analysis of the antenna elevation mask

from the GS site selected, which determin the visibility times lost (orange area) when applying the minimum antenna elevation mask (5°) to reduce the signal interferences from man-made noise and the most frequent mask (10°) used in built-up areas in comparison to the mask calculated by applying the proposed geographic study.

Figure 119(b) shows the antenna elevation mask which resulted of applying the proposed geographic and electromagnetic data fusion process. This solution mitigates the noise just in the azimuth range affected by the interference source, and maximizes the satellite visibility times along the horizon from the antenna site.

Figure 119. Analysis of the antenna elevation mask from the selected GS site. (a) Graphic result of the comparison between the calculated mask and the standard masks. (b) Graphic result of the antenna elevation customized mask.

A measurement set-up was designed to in-situ simulate the antenna elevation mask in the mission frequency band (see Figure 120). This design provided a swift process of geographic and electromagnetic data fusion thanks to the use of the same coordinate reference system in both studies. This was possible by using an extendable tripod and by applying the designed antenna support since this set-up established the same virtual antenna rotor center as that in the geographic study. In addition, this set-up allowed transforming the signal spectrum measurements from the interference source into antenna elevation data by using an inclinometer which was included in the vertical plane of the designed support.

Figure 120. Measurement set-up proposed to in-situ simulates the antenna elevation mask in the mission frequency band applying the antenna elevation mask concept.

These results validate the theoretical model proposed for a given GS location scenario, as the implemented framework solves the problem of the optimal site selection by considering the constraints for installation and the GS mission requirements.

4.3 Case study at CUA University, Washington D.C. (US)

This is the case study of the installation proposal of the first GS at CUA University, and corresponds to the first professional activity related to this research.

The main mission of the GS will be the acquisition and tracking of future projects of CubeSat missions and balloons in collaboration with Universities and government organizations such as NASA and NSF.

The CUA team is very interested in starting an aerospace program to test technological instrumentation, and in science missions related to Astronomy, Astrophysics, and Earth sciences (www.iacs.cua.edu).

Currently, projects at CUA University are guided by the IACS (Institute for Astrophysics & Computational Sciences). First, the SmartSat project (see Figure 121(a)), includes Three CubeSat units based on improvements in primary propulsion (technology patented by NASA agency) and, innovations in communication systems between the satellites and the GS computation center. Its main mission will be to test new CubeSat capabilities. Second, the Balloon project whose aim is to study the low atmosphere, which has been built by students (see Figure 121(b)).

Figure 121. CUA University Projects (a) SmartSats 3 3U CubeSat Concept (Clark, n.d.). (b) Screenshot extracted from the video of a balloon project launching (Verner, 2013).

The main interest in the GS installation at CUA campus was the tracking of its own science projects developed by student teams. In addition, these multidisciplinary projects are framed in the “learning by doing” principle, the main objectives being: first contacts between students and the aerospace industry, and interactions between other national and international professionals and students. However, the case study is limited to the analysis of the GS site proposals and the proposed solution to solve the selection of the optimal site within the campus area.

4.3.1 Case study analysis

In this case, the proposed location for the GS installation was chosen as the result of the analysis of the different location proposals within the campus area. These were proposed by the project team on February 2014, and they included specific considerations both from the facility manager and the GS team, that is: constraints for installations on building roofs and, the few minutes per satellite pass in LEO mission associated to the CubeSat short data storage on board, respectively. Figure 122 shows the proposed locations for the GS site.

Figure 122. Location proposals within the campus area for the GS installation on building roofs (Top view of the campus area obtained from the Google Earth program).

The main conclusions from the first meeting with the project team and the facility manager about the selection of building roofs were; first, the need for a flat area for the GS facilities to provide for the safety system required for the GS installation and for future works of maintenance; second, the need for minimum presence of interference sources in the frequency bands selected for the satellite mission, and; third, the need for maximum satellite FOV. This last was suggested by the GS engineers as a relevant factor in the site selection, once fulfilled the facility rules. In this sense, a preliminary analysis for the optimal selection site between the selected buildings roofs was proposed to complete the report requested by the facility manager for the installation permit.

4.3.2 Framework implementation

The model approach was the determination of the optimal location site through the analysis of the proposals taking into account the factors established by agreement with the project team and the facility manager. Figure 123 shows the developed theoretical model for this case study, which takes into consideration the implemented frameworks in the case studies at UPM and Cal Poly universities.

Processes	Specific objectives (SO)	Results
Analysis Factors Definition	SO1. Providing GS engineers and facility manager the most relevant factors for the analysis. SO2. Determining the valuation criteria (coefficient) between the analysis factors.	Analysis Factors
Preliminary Analysis of the Location Proposals	SO3. Applying the specific processes to obtain the factor results in each location proposals. SO4. Analyzing the locations by an objective comparison to select the optimal GS location. SO5. Reporting the information of the GS location selected to complete the GS installation request by the project team.	Optimal GS Location GS Site Report

Figure 123. Theoretical model proposed to analyze the GS case study at CUA University.

The processes described in the previous two case studies were very useful as they determined the specific process for this theoretical model. This was defined as the preliminary analysis process between location proposals for the GS selection site within a location area. This process includes the analysis factors described in the following section and includes definition of the specific objectives and the expected results.

4.3.2.1 Analysis factors definition

This section describes the selection process of the analysis factors included in the theoretical model developed for this case study. This process requires determining the analysis factors, their definition, and assigning the relevance coefficient between them.

In order to determine the main analysis factors, the required data set to simulate a satellite mission analysis from the ground segment point of view was established as the framework. In addition, interaction with GS teams and facility managers at UPM and Cal Poly universities allowed determining the impact of other factors on the optimal selection site. In this sense, the first meeting for the selection of the analysis factors was successful as it provided GS engineers and the facility manager with the most relevant factors for the preliminary analysis and its definition (SO1). These factors included considerations regarding the facility constraints on building roofs and the satellite mission requirements in CubeSat-LEO missions, such as; the outdoor and indoor components of the designed GS and its connections; the available and required facilities for installation on building roofs, and; the antenna elevation mask from each location which includes the basic studies of the satellite FOV and of the presence of signal interference sources in the mission bands. From the experience in the previous case studies, this last factor was targeted as the most relevant in the GS site selection, and should therefore be considered in the system communications design for the GS mission to succeed.

However, installation approval depended on the permit issued by the facility manager. Thus, determining the valuation criteria (coefficient) between the analysis factors (SO2) was necessary for the GS engineers and the facility manager to reach an agreement.

This fact was of great relevance, as this coefficient assignation was added to the selection process offering objective results to the proposed theoretical model.

Table 8 shows the selected analysis factors, agreed between the GS engineers and the facility manager, for the preliminary analysis of the location proposals and the coefficient (value between 0 and 1) assigned to each factor.

Table 8. Analysis factors: assigned coefficient and description.

Analysis Factors	Coefficient Assigned
➤ GS facilities	1.00
➤ Safety systems	1.00
➤ Satellite FOV	0.75
➤ No signal sources	0.75
Description	
<p>GS facilities: is the viability of the GS installation from the components point of view, considering the platform available and the area connections to the control room.</p> <p>Safety systems: is the availability of facilities from the safety point of view, considering the installation and future works of maintenance.</p> <p>Satellite FOV: is the maximum visibility from the horizon plane point of view, considering the altimetry profile surrounding the location.</p> <p>No signal sources: is the minimum presence from the man-made noise point of view, considering the mission frequency band.</p>	

The following table was proposed to show the visualization of results for each location providing a simplified comparison between them, where the results of each analysis factor will be shown in percentage values. The first column will include the results obtained without applying the specific coefficients and the final column applying the respective coefficients (see Table 9).

Table 9. Table proposed to represent the factor results in percentage values.

Factors	Location	Coefficient	Result
GS facilities	- %	1.00	- %
Safety systems	- %	1.00	- %
Satellite FOV	- %	0.75	- %
No signal sources	- %	0.75	- %

The next section describes the analysis process applied for each location, using the proposed table to represent the results of the selected analysis factors.

4.3.2.2 Preliminary analysis of the location

This process included in the proposed theoretical model, allowed GS engineers and the facility manager to take a decision on the optimal location selection, by applying the specific processes in order to obtain the results of the analysis factors for each location proposal (SO3). These processes, extracted from the experience obtained in the previous study cases at UPM and Cal Poly universities, were re-designed to obtain results in a short period of time for specific data capture processes which use data capturing sensors for the analysis of the *Satellite FOV* and *No signal sources* factors.

The first step was the selection of the adequate process which included; the data capture procedure to establish the expected results; the resources necessary to obtain the data accuracy required taking into account the available budget, and; the in-situ information regarding the facility constraints and the GS requirements provided by the professionals involved in the project. This last item was an improvement in the process analysis as it solved in-situ technical specifications and it increased the efficiency in the analysis of the results. In this sense, the role of the technical specialist proved successful as it facilitated interaction between the different professionals from the analysis of the problem statement to the optimal selection site decision.

Figure 124 shows the scheme of the process selected for each analysis factor, including the resources (R) and the expected results (ER).

Analysis Factors	Processes Applied	Professionals Involved
GS facilities	Project Planning R. Project documents and EDM Laser. ER. Installation area and connections between GS facilities.	GS Engineers
Safety systems	Safety Planning R. Internal rules, Project documents and EDM Laser. ER. Safety facilities available and the viability for systems required.	Facility Manager
Satellite FOV	Geographic Study R. Survey equipment with GNSS technology. ER. 3D basic map and altimetry profile surrounding the location.	Technical Specialist
No signal sources	Electromagnetic Study R. Spectrum analyzer equipment with Omni directional antenna. ER. Interference sources map in the mission frequency band.	Technical Specialist

Figure 124 . Scheme of the processes applied in the preliminary analysis of the locations.

Once the provisional locations to start the preliminary analysis had been suggested by the facility manager, the next step was to provide him with the following information:

- The dimensions of the outdoor components (antennas)
- The roof protection system.
- The connections between the GS facilities and the control room. The information regarding the connections included the routes of an Ethernet link and a power connection.

Figure 125 shows the dimensions of the future antennas configuration (see Figure 125(a)) and the proposed roof protection system (see Figure 125(b)), which are similar to the GS facilities at UPM and Cal Poly universities.

Figure 125. Technical specifications of the GS outdoor components at Cal Poly University. (a) Antenna dimensions. (b) Roof protection system.

The next step was the analysis of the factors in the proposed location.

Figure 126 shows the selected location site on the Hannan building roof, within the campus area.

Hannan building

Figure 126. Location site proposed at Hannan building. (a) Site proposal on the building roof. (b) Top view of the building (yellow circle) obtained from the Google Earth program.

The results obtained by applying the proposed processes, *Project Planning* and *Safety Planning*, evidenced the viability with minor constraints for the GS facilities. Figure 127 shows the analyzed items; first, the existence of a flat area for the outdoor components installation on the roof platform; second, the existence of a cable duct to the floor just below used for the in-situ installed antennas; third, the existence of a perimeter wall which will allowed the installation of a fence to increase the safety during installation and for future works of maintenance, and; fourth, the existence of a roof access which complied with safety rules.

Figure 127. Location site proposed at Hannan building. (a) Selected area within the Roof platform. (b) Roof access.

Regarding the analysis factors relative to the antenna elevation mask, *satellite FOV* and *No signals sources*, the results evidenced the prescence of nearby buildings higher than the Hannan building in the southwest quadrant and the presence of signal interference sources, those being the two antennas installed in the selected roof area and the electronic equipments on the floor just below. Applying the proposed *Geographic Study*, the 3D basic map of the building roof and the altimetry profile surrounding the selected site in the roof area were obtained by using survey equipment. This equipment provided by Topcon (www.topconpositioning.com) included the GNSS technology which allowed targeting the geographic coordinates and the orthometric height of the virtual antenna rotor center that was the center of established coordinate reference

system for the data capture processes (see Figure 128(a)). Figure 128(b) shows the top view of the roof area selected for the study. Data set capture on April 2014.

Figure 128. Geographic study of the roof platform at Hannan building Location. (a) Total station and GNSS technology equipment. (b) Top view of the building roof area obtained from the Google Earth program. (c) 3D geographic map of the building roof obtained using 3D CAD program.

Figure 128(c) shows the 3D basic map created by applying the CAD program to the captured data set, and represents the virtual view of the building roof scenario. This allowed:

- Inquiring specific measurements relative to the project planning.
- Further analysis of the *GS facilities* and the *Safety systems* factors once the location was selected from the analyzed proposals.

The next step was the data capturing of the altimetry profile surrounding the location by targeting the geographic elevation in each azimuth direction. Figure 129(a) shows the panoramic views of the main elevations from the Hannan roof and the resulting geographic mask which represents the minimum elevations in each azimuth direction from the virtual height targeted from the future antenna rotor center (see Figure 129(b)).

Figure 129. Geographic study of the Hannan building roof. (a) View of the McMahon building and the Basilica. (b) View of the Caldwell building. (c) Geographic mask from the spatial position established as the center of the coordinate reference system (UTM coordinates: $X=326733.56\text{m}$, $Y=4311561.73\text{m}$ and; an orthometric height of 89.10m).

The interference sources map in the mission frequency band was obtained by applying the proposed *Electromagnetic Study*. In this study, the spectrum analyzer equipment provided by Tektronics (www.tek.com) included GNSS technology which allowed estimating the geographic location of the signal interference sources within the campus area.

In the proposed *Electromagnetic Study* an Omni directional antenna was used to simulate the future antenna height by using an extendable tripod, the same as that used in the geographic study (see Figure 130(a)). Figure 130(b) shows the instrumentation set-up used which included a computer connected to the spectrum analyzer equipment for the in situ processes: measurement set-up, data capture and data basic post-processing.

Figure 130. Electromagnetic study applied from the Hannan building roof using Spectrum Analyzer equipment. (a) Hardware set-up in the geographic study. (b) Measurement set-up for the electromagnetic study, establishing the center of the coordinate reference system using the extendable tripod.

The next step was the selection of the frequency ranges for the analysis of the mission bands. Table 10 shows the frequency ranges selected for the measurement process.

Table 10. Frequency ranges selected for the GS mission bands.

Bands	Frequency range (MHz)
UHF	400 - 401
UHF	435 - 438
S	2.400 – 2.450

This table includes the UHF band range between 400-401 MHz because this was of great interest to GS engineers as this was used in the following satellite missions: Formosat for the study of the atmosphere and, Akenono for the study of the

magnetosphere and the ionosphere (Yue et al. 2014; Ishikawa et al. 2013). The other two frequency ranges analyzed, were suggested by the technical specialist; the frequency range in the UHF band, 435-438 MHz, that assigned for small satellite projects in the last ten years (Bouwmeester & Guo, 2010; Dankov et al. 2012), and; the frequency range in the S band, 2.400-2.450 MHz, that assigned by the ITU organization in radio amateur transmissions in short distance communications, and proposed for future satellites operations (Cakaj & Malaric, 2007; Yamaguchi, 2004).

The next step was the data capture process considering the location of potential interference sources in the mission bands within the campus area and in particular those close to the selected site on the building roof. In this sense, this process was programmed to take measurements on different days and during different periods of time along each day. In addition, different spectrum analyzer functions were applied to extract further information from the signal spectrum captures in each frequency range. Figure 131 shows the main results obtained when applying functions which were used in this preliminary analysis of the *No signal sources* factor.

Figure 131. Signal spectrums obtained in the UHF band (frequency range between 400-401 MHz) applying the DPX function.

The application of the DPX function represents how consistent the shape of the trace was during the capture process in the selected frequency range. A -80 dBm signal threshold is the minimum necessary to establish a satellite communication in CubeSat platforms, therefore the persistence of the signal interference sources in this frequency range should be considered in the system communications design.

Figure 132 shows one of the results of applying the iMap function. This allowed the estimation of the geographic locations of the potential interference sources in the selected frequency band. This figure shows the particular result through the spectrum analysis in the frequency range between 435 MHz and 438 MHz, where two signal sources appeared close to the roof site. These corresponded to:

- The electronic equipments for the control of the building climate and the elevators.
- An installed antenna on a building roof which emits in the UHF band, probably a radio amateur to the southeast of the roof site.

Figure 132. Signal spectrums in the UHF band (frequency range between 435-438 MHz) applying the iMap function.

Results in Figure 133 evidenced the presence of signal interference sources in the S band analysis when applying the average function. Clear communication between the GS and the CubeSat platforms was established below the -100 dBm threshold.

Figure 133. Signal spectrums in the S band (frequency range between 2.400-2.450 MHz) applying the average function.

Table 11 shows the results in percentage values of the factors.

Table 11. Results of the preliminary analysis applied at Hannan building.

Factors	Location	Coefficient	Result
GS facilities	80.00 %	1.00	80.00 %
Safety systems	90.00 %	1.00	90.00 %
Satellite FOV	85.00 %	0.75	63.75 %
No signal sources	40.00 %	0.75	30.00 %

McMahon building

Figure 134. Location site proposed at McMahon building. (a) Site proposal on the building roof. (b) Top view of the building (yellow circle) obtained from the Google Earth program.

Figure 135 shows the selected location site on the McMahon building roof. In this proposal the results from the analysis of the *GS facilities* and *Safety Systems* factors evidence; first, a limited roof area for installation of the outdoor components which required a project planning re-design (see Figure 135(a)), and; second, the existence of an installed safety system close to the roof access, which will allow the installation of the outdoor components by extending the installed safety fence (see Figure 135(b)). In addition, there is a free area available on the floor just below for the control room facilities.

Figure 135. Location site proposed at McMahon building. (a) Roof platform. (b) Installed safety systems and available area connections.

Regarding the analysis factors relative to the antenna elevation mask, *satellite FOV* and *No signals sources*, the following results were obtained; first, when applying the geographic study results evidenced an increase in the elevation of the altimetry profile in the southwest-northwest quadrant due to visibility blockage by the Basilica building and by the building roof (see Figure 136(a)), and; second, when applying the electromagnetic study, results evidenced the same interference sources maps as in the Hannan case, but without the presence of potential interference sources in the building. Figure 136(b) shows the two antennas installed on the building roof area selected for the GS facilities that just received in the UHF band.

(a)

(b)

Figure 136. Location site proposed at McMahon building. (a) Panoramic view from the selected site of the visibility blockage of the Basilica building and the building roof. (b) Panoramic view of the building roof from the site proposal and the two installed antennas.

Table 12 shows the results in percentage values of the analysis factors.

Table 12. Results of the preliminary analysis applied at McMahon building.

Factors	Location	Coefficient	Result
GS facilities	75.00 %	1.00	75.00 %
Safety systems	85.00 %	1.00	85.00 %
Satellite FOV	65.00 %	0.75	45.00 %
No signal sources	60.00 %	0.75	30.00 %

McGivney building

Figure 137. Location site proposed at McGivney building. (a) Site proposal on the building roof. (b) Top view of the building (yellow circle) obtained from the Google Earth program.

Figure 137 shows the selected location site on the McGivney building roof, within the campus area. The results obtained by applying the proposed processes, *Project Planning* and *Safety Planning*, evidenced viability for the GS facilities, but with more constraints than in the other proposals.

Figure 138 shows the existence of flat areas for the outdoor components in the north roof area (see Figure 138(a)) and for the indoor components on the floor just below (see Figure 138(b)).

Figure 138. Location site proposed at McGivney building. (a) Roof platform. (b) Control room.

From the safety point of view the GS project required; first, the installation of a roof access and a fence to surround the roof platform, and; second, the installation of several cable ducts routing the power connection to the GS facilities including an Ethernet link and the connections to the control room. Regarding the processes relative to the antenna elevation mask, *Geographic study* and *Electromagnetic study*, the results evidenced this proposal as the worst option. Most of the surrounding buildings are higher than the McGivney building and the altimetry profile indicated a minimum antenna elevation between 5-10° along the horizon visible from the established virtual antenna rotor center. In addition, the electronic equipments installed between the roof and the selected control room area and the presence of surrounding terrestrial links increase difficulties in the design of the system communication due to the presence of potential interference sources in the mission bands.

Table 13 shows the results in percentage values of the analysis factors.

Table 13. Results of the preliminary analysis applied at McGivney building.

Factors	Location	Coefficient	Result
GS facilities	70.00 %	1.00	70.00 %
Safety systems	85.00 %	1.00	85.00 %
Satellite FOV	60.00 %	0.75	45.00 %
No signal sources	40.00 %	0.75	30.00 %

4.3.3 Results

This section describes the results obtained by applying the proposed theoretical model for the optimal GS location site in the case study at CUA University. These results include the analysis factors selected by agreement between GS engineers and the facility manager, and the data capture processes regarding the antenna elevation mask.

Selection of the optimal GS location (SO4) using objective results once the selected factors were analyzed for each location proposal. These results were obtained from the

analysis of the selected factors for each location proposal. Figure 139 shows the table of results for each location and the graphic comparison between them.

Figure 139. Graphic result obtained from the preliminary analysis of the locations proposed for the GS site selection.

By applying this preliminary analysis between the location proposals, the optimal site selected was the Hannan building. Although the *No signal sources* factor was worse than in the other proposals several solutions are available in order to reduce the signal disturbance which radiates from electronic equipment such as the installation of a copper mat between the base of the antennas and the roof. Because of this disturbance, a further electromagnetic study was recommended; first, to scan for interfering signals (frequency and power) with the Omni directional antenna for a week, and; second, to target, with the directional antenna, the antenna minimum elevation to start the satellite communications just in the azimuth directions of the interference sources.

Another important result was the compilation of the information regarding the GS location selected. This information completed the GS installation requested by the project team (SO5) in the GS site report, as it included not only the above mentioned recommendations, but also the visual impact of the GS facilities (antennas) in the building roof as another analysis factor to be considered for the preliminary analysis between location proposals. The virtual view from different points of view provided the facility manager with information regarding the impact of the future GS installation within the campus area, which was of great relevance in the final decision. Figure 140 shows the visual impact from the McMahon building (see Figure 140(a)), from the roof floor just below (see Figure 140(b)) and from the street (see Figure 140(c)).

(a)

(b)

(c)

Figure 140. Visual impacts of the virtual view of the GS facilities at Hannan building. (a) View from McMahon building. (b) View from the roof floor just below. (c) View from the street.

These results validate the theoretical model proposed for a given location area scenario to select the optimal GS location site. It follows that the implemented framework solves the problem of specific constraints imposed by the facility manager for the installation of GS facilities on building roofs, and the GS mission requirements determined by the GS project team.

The analysis of the results obtained by the implementation of the theoretical model to solve the problem in these three case studies has made it possible to develop the analysis model presented in this thesis.

5 CONCLUSIONS

This chapter presents a summary of the case studies carried out along this thesis, as well as the most important conclusions derived from them. From the initial motivation to the writing of this work, the most important part of this academic project has been the achievements obtained during the research period of the cases studies. As the initial approach to solve the problem statement in each case, fundamental knowledge and concepts related to the RE process, were applied. These developed throughout the research period enabling amongst others the acquisition of knowledge and techniques in Geomatics and Telecommunication Engineering in order to be able to provide a best solution.

Besides conclusions specifically related to each case study, those related to the analysis model proposed in this thesis have been included. Considering, both requirements and constraints from other professionals involved in the GS project, the developed theoretical models to analyze each case as an engineering project in a multidisciplinary scope were a success. The experience acquired thanks to the relationship with GS

engineers and facility managers provided the opportunity to develop an analysis model in which adding the customized antenna elevation mask was the main factor to take into account in the location analysis factor, without disregarding others which also affect the GS project from the location point of view.

Finally, results from experimentation in each case study lead to propose the validation of the analysis model as the research objectives have been achieved. Final reflections from the implementation of the analysis model in the possible case scenarios have provided the opportunity to plan future lines of work related to this thesis, ranging from the application of different procedures of both data capturing and post-processing processes by the integration of new technologies and techniques, to innovations performed in the measurement set-up even, something possible even when using capturing sensors related to other scopes.

5.1 Conclusions related to the case studies

As above mentioned this section presents the conclusions of the following case studies analyzed in this tesis:

1. Case study at UPM University in Madrid (Spain)
2. Case Study at Cal Poly University in California (US)
3. Case study at CUA University in Washington D.C. (US).

5.1.1 Case study at UPM (Madrid, Spain)

This case study was the starting point of the research, and was made possible thanks to the integration of new technologies of data capturing sensors as the solution to solve the problem scenario of the GS location in built-up areas.

The main conclusion drawn from the research experience in this case study was the success in the interaction with GS engineers which providing them with another approach, that from the GS spatial location point of view, to solve the data download problem in the future QBito nano-satellite mission.

In this case study two other specific conclusions can be drawn from the obtained results:

- The first conclusion, relative to the analysis of the problem statement, is the determination of the antenna elevation mask and the spatial position of the future antenna rotor center as the two relevant factors in the GS site selection. The required data set obtained through satellite tracking was used to simulate the mission using software in order to create the scenario from the ground segment point of view. Hence, the calculated mask provides the antenna minimum elevation for each obstacle azimuth direction, and opens discussion, from the point of view of the satellite communications in built-up areas, since the application of a standard mask not only reduces obstacles but also the satellite FOV.
- The second conclusion, relative to the 3D digital model of the GS scenario, is the usefulness of the RE tools and techniques used to create the real 3D scene of the GS location. Hence, 3D digital surveying techniques, and in particular laser scanning technology, are an innovative solution to analyze GS scenarios on building roofs: first, by capturing massive information about the GS location; second, by creating the digital scene which contains the spatial position and pixel of each point analyzed, and; third, by modeling objects without physical contact to create the 3D model of the particular problem. This enables to make proposals for the site selection by analyzing the obtained 3D digital model.

5.1.2 Case study at Cal Poly (California, US)

This case study was the core of this research, as it enabled the analysis of other location factors in the scenario of the GS location in built-up areas, and in consequence resulted in the design of a measurement set-up to provide a best solution.

The main conclusion in this case study regarding the analysis of the problem statement, is that signal interference sources located in certain azimuth directions from the GS site affect the communication links, and in consequence, satellite mission analysts should consider them in the system communications design along the mission.

Derived from this, two specific conclusions can be drawn:

- The first conclusion, relative to the proposed electromagnetic study from the GS site, is the targeting of the antenna minimum elevation to start the communication with the satellite in the selected mission frequency bands. In built-up areas, the presence of signal interference sources is of great importance in the system communications design as they reduce the signal quality in the communication outage, decreasing the effective use of communication times from the GS site in each single pass along the satellite mission. In the particular case of CubeSat-LEO missions this fact is even more important due to the few minutes per satellite pass and the few kilobits per second of power transmission on-board.
- The second conclusion, relative to the proposed geographic and electromagnetic data fusion process, is the usefulness of the antenna customized elevation mask for the GS site, as this provides effective use of the available communications times per satellite pass along the mission. Application of a standard mask reduces the amount of data download per satellite pass in a science mission. Given that, as the altitude of the satellite decreases the opportunities to track or communicate with it from the antenna become more restricted, the customized elevation mask increases these opportunities and thus maximizes data download. Due to the importance of this fact, the satellite FOV obtained from a customized mask application should not be considered as a link budget parameter but as one that increases the amount of telemetry data in downlinks with minimum possible elevations.

5.1.3 Case study at CUA (Washington, US)

This case study which was both a professional activity and part of the research, allowed the experimentation of the analysis model proposed to solve the problem scenario of the GS location in built-up areas.

The main conclusion drawn from the research experience in this case study was the usefulness of the application of the preliminary analysis to different location proposals

for the provisional GS site selection, in which other factors apart from the antenna elevation mask were taken into account.

Derived from this, two specific conclusions can be drawn:

- The first conclusion, regarding other factors to be taken into account in the GS location analysis, is the previous analysis of the GS project impact on a building roof considering constraints for installation and safety systems. These were extracted from meetings between GS engineers and the facility manager.
- The second conclusion, regarding the selected factors, is the need to define the impact of the analysis factors, and the valuation criteria between them. Results from this analysis method allow making an optimal decision by comparing objective results from each GS location proposal.

5.2 Conclusions related to the analysis model

This section presents the conclusions derived from the analysis of the research problem which established the approach of this thesis, and the conclusions related to the analysis model designed from the analysis of the case studies.

5.2.1 Conclusions of the research problem

This research aimed to optimize the GS location in built-up areas, as in these environments physical obstacles and signal interference sources surrounding the GS site affect satellite communications. These are even more relevant in tracking GS missions of small space platforms in low orbits due to the limited power transmission on board and the few minutes per satellite pass.

To achieve the research aim, critical points from the analysis of the GS scenario were identified, and the available solutions were analyzed.

From the GS location analysis point of view, this research mainly discusses that the application of a standard antenna elevation mask would typically guarantee adequate conditions to establish a satellite radio link in built-up areas as this would avoid most of

the surrounding obstacles and interferences. However, obstructions which cannot be avoided often hinder such a standard mask from ensuring an optimal satellite radio link, and reduce the available satellite communication times. In this sense, this thesis analyses the application of an antenna customized elevation mask to solve the problem by optimizing the available satellite communication times from the selected GS site as this customization takes into account updated geographic and electromagnetic information surrounding the GS site.

In consequence, this research concludes that this customized mask should be considered as the most relevant factor in two case scenarios; first, in the selection of the GS site before the installation stage, and; second for a given GS site, to implement mitigation techniques either in its re-design or re-location.

5.2.2 Conclusions of the analysis model

This thesis presents an analysis model to optimize the GS locations in built-up areas as a contribution in the satellite communications scope in these environments.

From the analysis of the case studies it was possible to design and to propose a new model, the stages of which have been validated in each case study. The model stages based on the developed framework achieve the research objectives, as described below:

Objective 1. To recreate the GS scenario by updating the available satellite visibility times from the antenna site, and by generating the 3D digital model of the GS location platform.

Results obtained by implementing the analysis model, and in particular the framework based on RE tools, allow further analysis in the GS location site (Stage 3) thanks to the true view and geometry obtained from the digital model of the selected site. Results obtained from the 3D tools applications provide relevant information to take a decision regarding the optimal site versus site re-design (Stage 6), and the impact of the GS facilities on the building roof. This is very useful as it makes it possible to finally take a decision when different professionals are involved in the project (see Figure 141).

Stage 1	Mission requirements & constrains for installation	
Stage 2	Preliminary analysis of the location proposals	
Stage 3	Further analysis in the location site	
Stage 4	Antenna elevation mask in the mission band	
Stage 5	Analysis using the satellite mission software	
Stage 6	Optimal site versus site re-design	
	O6.1. Optimal site	R6.1. Final report
	O6.2. Site re-design	R6.2. Stage 3

Figure 141. Relationship between the research objective 1 and the analysis model stages.

Objective 2. To analyze the current state of the available communication links from the GS site using the satellite mission software.

Results obtained by implementing the analysis model, and in particular the framework based on technologies of data capturing sensors and simulation software, provide a preliminary analysis of the location proposals (Stage 2) by updating information related to the GS site and nearby signal obstructions, and the analysis performed by the satellite mission software (Stage 5) (see Figure 142).

Stage 1	Mission requirements & constrains for installation	
Stage 2	Preliminary analysis of the location proposals	
Stage 3	Further analysis in the location site	
Stage 4	Antenna elevation mask in the mission band	
Stage 5	Analysis using the satellite mission software	
Stage 6	Optimal site versus site re-design	
	O6.1. Optimal site	R6.1. Final report
	O6.2. Site re-design	R6.2. Stage 3

Figure 142. Relationship between the research objective 2 and the analysis model stages.

Objective 3. To develop a swift data post-processing for an in-situ preliminary analysis of the GS site.

Results obtained by implementing the analysis model, and in particular the framework based on a measurement set-up, provide the antenna elevation mask in the mission band (Stage 4) applying the in-situ capture of the required data set

from the mission simulation software in the same parameters, and in the same coordinate reference system (see Figure 143).

Stage 1	Mission requirements & constrains for installation	
Stage 2	Preliminary analysis of the location proposals	
Stage 3	Further analysis in the location site	
Stage 4	Antenna elevation mask in the mission band	
Stage 5	Analysis using the satellite mission software	
Stage 6	Optimal site versus site re-design	
	O6.1. Optimal site	R6.1. Final report
	O6.2. Site re-design	R6.2. Stage 3

Figure 143. Relationship between the research objective 3 and the analysis model stages.

Objective 4. To develop a preliminary analysis process for selection of the provisional site taking into account the location factor analysis.

Results obtained by implementing the analysis model, and in particular the framework based on the location factor analysis, provides a comparative analysis between the mission requirements and constrains for installation (Stage 1). This is obtained from the analysis of the main location factors and the valuation criteria established by the professionals involved in the GS project (see Figure 144).

Stage 1	Mission requirements & constrains for installation	
Stage 2	Preliminary analysis of the location proposals	
Stage 3	Further analysis in the location site	
Stage 4	Antenna elevation mask in the mission band	
Stage 5	Analysis using the satellite mission software	
Stage 6	Optimal site versus site re-design	
	O6.1. Optimal site	R6.1. Final report
	O6.2. Site re-design	R6.2. Stage 3

Figure 144. Relationship between the research objective 4 and the analysis model stages.

The conclusion derived from the relationship between the research objectives and the results is the validation of the model stages, as the research objectives established from

the analysis of the research problem have been achieved in the possible case scenarios analyzed.

5.2.3 Final conclusions

This thesis concludes in the usefulness of the analysis model implementation to optimize the GS location in built-up areas as a particular GS scenario which requires a further analysis in the site selection. In particular, a designed measurement set-up which takes into account: first, the required measurement data related to presence of nearby obstacles and signal interference sources in certain azimuth directions from the GS site; second, the adequate selection of data capturing sensors for both measurement data, geographic and electromagnetic, and; third, the data fusion process to in-situ simulate the antenna horizon elevation in the mission frequency band.

Other conclusion and by no means least, is the usefulness of geomatics techniques and tools integration in specific stages of the analysis model. By applying RE concept and using specific 3D modeling sensors this analysis model achieves a successful interaction between the GS engineers and the facility manager, taken into account the GS mission requirements and the facility rules on building roofs, respectively: from the real view of the GS scenario to be analyzed to the visual impact of the GS facilities in the selected site.

Finally, this thesis concludes in the validation of the analysis model as the applied stages accomplish the research objectives and achieve the expected results (see Figure 145), based on:

- First, establishing the research objectives from the problem definition and the analysis of the new GS scenario in built-up areas.
- Second, developing the model stages by implementing the most adequate framework from the exploration of the geomatics techniques and tools to others in the telecommunications scope involved.
- Third, analyzing the implementation of the analysis model in the possible case scenarios.

- Fourth, verifying the obtained results respect to the expected results established from the research objectives.

Figure 145. Validation proposal of the analysis model.

5.3 Future works

This section shortly describes future lines of work related to this thesis, which were sketched out during the research period in each case study and are now planned to be carried out.

As regards the improvements in the presented analysis model:

- Implementation of others link budget parameters related to the ground segment performance in the processing software for the electromagnetic mask study.
- Software programming to maintain the proposed swift process for the data fusion when the amount of data increases, and to provide the customized mask in the different mission frequency bands simultaneously.
- Automation of the designed antenna support for its remote control by computer programs and a mechanical solution to calibrate the vertical plane of the antenna support which includes the inclinometer (Patent in process).

Regarding the adaptability of the analysis model in other case scenarios:

- Validation of the designed measurement set-up for higher antennas which includes; first, replacing the tripod for an extendable mast; second, using a modeling sensor with integrated digital camera, and; third, establishing a wireless connection for both data links, input and output.
- Measurement set-up experimentation in extreme conditions within the location (access, obstacles, safety, etc) using other technologies of data capturing sensors such as specific Tablets and Drones.

Regarding the applications of the analysis model within spectrum congested areas:

- HUMSAT project: Optimal location site for the data collection sensors (Project in process).
- CUA GS Project: Ground system design (Project in process).

Regarding the GS antenna design for installation on building roofs:

- Antenna box project (Patent in process).

5.4 Final reflections

The CubeSat era has marked a new way of pursuing challenges in space and Earth sciences by the scientific community. The number of missions by international space agencies and the interest for technology development by the industry has increased. Both from the educational and research points of view, this small cube has been revolutionary giving hands-on experience in building, launching and operating space platforms. Being a multidisciplinary project it has given the opportunity to students and researches from different scopes involved in the project of establishing relationships enabling specific contributions in both space and ground segments missions.

This thesis is an example of the contribution of geomatics in these multidisciplinary projects. It is a new approach to increase the effectiveness in the use of the satellite communication times, particularly from the ground segment point of view. In addition, this thesis opens a discussion on the usefulness of the in-situ simulation of the antenna elevation mask before the GS installation providing an optimal location. This simulation

takes into account facility constraints and mission requirements, and even allows for antenna re-design for a given GS or for antenna re-location for a given site.

Finally, “Learning by doing”, a principle which has been the best lesson learnt during the research period at UPM, CUA and Cal Poly Universities. The relationship with other students and engineers involved in the GS projects; the use of equipment and programs from different scopes, such as the spectrum analyzer and the satellite mission simulation software to achieve the specific objectives proposed by the theoretical model, and; specially, personal development in the design and building of a directional antenna support, included in the designed measurement set-up.

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Measurement of the Horizon Elevation for Satellite Tracking Antennas Located in Urban and Metropolitan Areas Combining Geographic and Electromagnetic Sensors

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ABSTRACT

In urban and metropolitan areas presence of nearby obstacles and signal interference sources surrounding tracking antenna locations reduces satellite communication times. In low orbit missions these obstructions are even more relevant due to a few minutes per satellite pass. In this scenario a best estimation of the antenna elevation mask in the mission frequency band is proposed to test the antenna design for a given site by applying mission simulation software before the installation stage. If needed, to improve efficiency in satellite tracking operations, mitigation techniques will be proposed either in the redesign or relocation of the antenna.

This paper describes a methodology for deriving the horizon elevation diagram, which includes a measurement setup when different data capturing sensors are used: geographic and electromagnetic. Application results which have contributed in the selection of the antenna location can be seen in the case study of the new CubeSat-LEO tracking antenna at Cal Poly University.

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1. Introduction

Emergence and increase in the number of LEO (Low Earth Orbit) nano-satellite projects such as the QB50 project [1] and their development at universities and research centers in the last years, have conditioned the geo-location of the satellite tracking antennas in urban and metropolitan areas. Despite the great advantage of LEO orbits being the short distance the radio signal must pass through which in turn reduces transmission power requirements and minimizes the propagation delay [2], it is becoming necessary to increase the operational quality of the antenna. Critical points identified are: visibility times of a few minutes in each satellite pass per day, assembly adaptability to any direction in azimuth and elevation, accuracy of the initial orientation derived from the position of the satellite and the antenna, and effectiveness of satellite tracking through a continuous system in order to avoid possible signal losses. To improve the performance of the antenna design there are several solutions: the use of azimuth-elevation pedestals to minimize tracking losses [3], the antenna size selection to achieve the desired gain margin [4], and the antenna

positioning system using stepper motors [5]. Moreover, in urban and metropolitan areas obstructions caused by buildings and interference sources become another critical point as they reduce the FOV (Field of View) and disturb the signal communication between the satellite and the antenna. In particular AOS (Acquisition of Signal) and LOS (Loss of Signal) along the horizon in certain azimuth directions, since above mentioned critical points in the tracking antenna operations increase. In this scenario for LEO tracking antennas, mission analysts must take into account the quality link and the mission concept when analyzing the link budget. Link budget analysis takes into account in situ analysis of external noise caused by radio electric emissions from the earth and the atmosphere, extraterrestrial sources, and man-made noise [6]. In this sense, measurements presented by Leferink et al. [7] confirm that different interference sources coming from industrial production plants, cars and trains affect radio links in UHF (Ultra High Frequency) and in VHF (Very High Frequency) bands. For LEO tracking antennas locations on building roofs, parameters such as the antenna gain in relation to its size and the noise temperature at in relation to spectrum congested antenna sites [8] are of great relevance in the link budget analysis in order to establish a robust communication link. From the link quality point of view, applying a standard antenna elevation mask with a fixed minimum elevation of 10° would guarantee adequate conditions for the satellite

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communication links, as this would avoid most of the surrounding obstacles and interferences [9]. However, from the mission concept point of view the above mentioned standard mask reduces the amount of data download per satellite pass in a science mission. This is further reduced as the altitude of the satellite decreases, the opportunities to track or communicate with it from the antenna become more restricted further complicating satellite scheduling [10]. In this scenario, a best estimation of the antenna elevation mask would increase the satellite FOV (field of view) and in consequence would maximize science data download. In this sense, results presented by Gill et al. [11] do not consider the satellite FOV as a link budget parameter but for the amount of telemetry data in downlinks with minimum possible elevations.

This paper analyzes the tracking antenna scenario associated to a new generation of nanosatellites called CubeSat [12]. These small satellites reduce the link budget margin available in LEO missions, adding short lifetime and limitation of available signal power on board as specific link budget parameters. In order to reach an optimal solution, considering the above mentioned points of view, a balance between them and the limited resources in CubeSat missions, a methodology to simulate the horizon elevation from the selected antenna site is proposed.

2. Methodology

This methodology has been developed taking into account the data set required by the satellite tracking software from the antenna location point of view. From the measurement data analysis, a measurement setup has been designed to finally select the most adequate equipment for data capturing processes.

2.1. Measurement data

The tracking software with information of the satellite orbit is engaged to the antenna rotor controller to start the tracking process when the satellite is in view (satellite entry) over a predefined elevation. The rotor controller governs the operation of the antenna rotors to generate the required voltages to steer the antenna in the correct angular position. Then, the antenna comes to stow position once the satellite goes below the minimum elevation (satellite exit). These programs, such as Orbitron [13] used to predict when and in which direction the satellite is available to

communicate with it, or STK (Satellite Tool Kit) [14] used to analyze the satellite missions, require a data set from the antenna location point of view: first, to simulate and analyze the satellite mission, and; second, to control the positioner to point the antenna in the satellite direction during the tracking mission. [15]. The data set contains both the geographic coordinates and the orthometric height of the antenna rotor center, and the antenna elevation mask or altimetry profile surrounding the antenna site. In urban and metropolitan areas, this mask should also contain information about antenna minimum elevations to avoid physical and electromagnetic obstructions caused by nearby obstacles and signal interference sources which affect the communication links in certain azimuth directions from the antenna location site. Fig. 1 shows the simulation of this scenario in which nearby obstacles (white dots) surrounding the antenna site reduce the satellite FOV, and a radio amateur antenna that emits in the same frequency band also reduce the communication time between the satellite and the antenna in the azimuth direction of the satellite entry.

This required measurement data is twofold: geographic and electromagnetic. Considering the STK file required to create the scenario the data must be exported with the same parameters (azimuth, elevation) from each software used. In addition, the electromagnetic and geographic data fusion requires data capture in the same coordinate reference system.

2.2. Measurement setup

Considering that the purpose is to in situ simulate the tracking antenna elevation mask and the measurement data required, a measurement setup has been designed when using different data capturing sensors to provide in situ quick results by a swift process of data fusion. Data capturing sensors for each procedure have been selected for each procedure analyzing the data set required. Fig. 2 shows the scheme of the measurement setup designed which contains the procedures followed to obtain each mask, geographic and electromagnetic. In the first procedure, the *Geographic study*, the main purpose is to establish the spatial position of the antenna rotor center as the center of the coordinate reference system by using GNSS (Global Navigation Satellite System) technology. This reference system will be used for the acquisition of the altimetry profile data by using topographic instrument. The reference system will also be used in the second procedure, the *Electromagnetic*

Fig. 1. Simulation of a tracking antenna scenario in a particular satellite pass.

Fig. 2. Scheme of the designed measurement setup by applying the data set analysis and the adequate selection of the data capturing sensors in each procedure.

study, for the acquisition of signal transmission data from the interference sources by using spectrum analyzer equipment.

The hardware setup designed takes into account the use of different data capturing sensors. An antenna support was designed for the electromagnetic study to establish the same reference system for the data acquisition process as in the geographic study. This support was designed considering how a theodolite works, replacing the viewfinder by a cylinder to insert the directional antenna. This cylinder is contained in the vertical plane and includes an inclinometer which allows targeting elevations during the data acquisition by using a spectrum analyzer in a specific azimuth direction. In addition, the designed measurement setup has been adapted so it can be used for higher antennas: first, by replacing the tripod for an extendable mast; second, by using a topographic instrument with digital camera integrated, and; third, establishing a wireless connection for both data links, input and output.

The core of the measurement setup is the software configuration both in input and output data before the data acquisition processes. In particular, the output data setup in the parameters required to simulate the antenna horizon elevation (azimuth, elevation), provides a quick data fusion process by a basic calculation program. In the geographic study, selecting output data in angular coordinates by the portable controller, and; in the electromagnetic study by the antenna support oriented in a specific azimuth direction, and targeting the antenna minimum elevation by the inclinometer integrated for a specific signal threshold. Further description of both procedures and result by applying the data fusion process will be described in the experimental setup applied in the case study at Cal Poly University.

3. Case study at Cal Poly University

The proposed measurement setup has been experimented in the future installation site of the Cal Poly's third antenna. The antenna will be able to track CubeSat-LEO in VHF and UHF bands and it will be capable of achieving significantly higher data rates than Cal Poly's two other antennas, Marconi and Hertz [16].

3.1. Geographic study

The main purpose in the study application is the antenna selection site within a location area by comparing the available visibility times between site proposals. In this case study, for a given antenna site, the first step was the analysis of the most adequate data acquisition process to update the geographic information surrounding the antenna location. By applying the geographic data fusion of the altimetry profile and information of nearby obstacles a best estimation of the satellite FOV is obtained considering the satellite FOV loss when applying a 10° elevation mask (see Fig. 3 (a)). To establish the accuracy of the required measurement data the standard antenna rotation is 0.5° and an antenna rotor center 2.20 m high was used. The second step was to establish this antenna point as the center of coordinate reference system (see Fig. 3(b)) by capturing its spatial position and orthometric height using GNSS technology. The OPUS (Online Positioning User Service) system [17], which provides coordinates in the NSRS (National Space Reference System), was used. The third step was the capture of the altimetry profile (azimuth, elevation) from this position, once the measurement data setup of the topographic controller

Fig. 3. Geographic study (a) Satellite FOV loss (orange area) when applying a 10° elevation mask; (b) Antenna elevation mask concept; (c) Geographic mask which includes the geographic coordinates (35.30N latitude, –120.66E longitude) and the orthometric height (107.15 m) from the antenna rotor center. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

was done. Fig. 3(c) shows the graphic result which contains antenna minimum elevations along the horizon visible from the antenna site. This data set (azimuth, elevation) and the spatial position of the antenna rotor center compose the geographic mask, which is required by the satellite tracking programs to simulate the mission, from the point of view of the visibility times.

3.2. Electromagnetic study with the directional antenna

The main purpose in the study application is completing the geographic mask information from the point of view of the interfering signals surrounding the antenna site. The presence of signal interference sources which emit in the mission frequency bands, reduce the available visibility times along the horizon from the antenna site to establish satellite communication links. Within a selected location area to install the antenna, an omnidirectional antenna can be used for a preliminary detection of interference sources surrounding the site proposals, and by seeking the strongest signal in the mission frequency bands can be very useful for the antenna site selection with low interfering signals. In this case study, for a given antenna site, the purpose was then the electromagnetic study with the directional antenna to complete the antenna elevation mask obtained by applying the geographic study. The first step was the geo-location of the interference sources in the frequency ranges of the mission bands by targeting the azimuth directions from the antenna site. The second step was the simulation of the antenna spatial position in the azimuth range

affected by a specific interference source, by targeting the antenna minimum elevation in order to establish a satellite radio link under a predefined signal threshold.

3.2.1. Geo-location of signal interference sources

The process proposed in the methodology consists in the geo-location of signal interference sources by following three stages; detection; identification and; location [18]. In this scope, the most efficient solution proposed is to analyze mapped signals from export field strength measurements obtained using GNSS technology based location information, and transfer it to PC-based mapping programs [19] which can be then displayed by the Google Earth application. Due to equipment available at the University, spectrum analyzer equipment without integrated GNSS technology, the proposed geo-location solution was achieved by combining visual inspection and information given at the facility manager's office. Once the main interference sources were identified, their azimuth directions from the antenna site were targeted using topographic equipment. Fig. 4 shows the azimuth directions of the interferences sources identified.

Following the proposed procedure, the next steps were to setup both hardware and software for the electromagnetic study. First, adjustment of the spatial position of the antenna rotor center in the antenna support applying the same coordinate reference system as in the geographic study was performed. Second, the frequency band ranges assigned by International Telecommunication Union-Recommendations (ITU-R) in CubeSat mission projects

Fig. 4. Top view (source: Google Earth) of the building geo-location which includes the azimuth directions of the signal interference sources identified, 0°, air conditioning devices and industrial machinery; 90°, wireless mobile antenna; 120°, radio amateur antenna; 210°, satellite tracking antennas; 240°, building climate device.

during the last 10 years in UHF and in VHF band [20] were selected. Finally, the measurement parameters as applied were: a minimum sweep time of 300 s, a frequency span of 3.000 MHz, a resolution bandwidth (RBW) of 30 kHz, an input attenuation of 10 kHz and, and a video bandwidth (VBW) of 10 kHz [21]. In addition, to verify presence of other signal sources during the data capturing process this was completed by analyzing signal transmissions, each 30° along the horizon (see Fig. 4). No relevant results were obtained.

Fig. 5(a) shows the designed hardware setup considering the spatial position established in the geographic study thanks to the use of the designed antenna support and an extendable tripod. To describe next step, the *Electromagnetic mask*, a radio amateur antenna located in the 120° azimuth direction, which emits in VHF band, was selected as a particular case of a signal interference

Fig. 5. Hardware setup for the electromagnetic study with the spectrum analyzer equipment with the directional antenna.

source which affects the AOS in this specific azimuth direction (see Fig. 6).

3.2.2. Electromagnetic mask

The purpose of the measurement setup is to capture the electromagnetic mask by the simulation of the antenna spatial position in the azimuth range affected by a specific interference source, and to target the minimum antenna elevation to establish a satellite radio link under a predefined signal threshold. Results evidences how the signal power transmission decreases as the antenna elevation is increased from 0° to 20° (see Fig. 7), considering a threshold of -80 dBm as the standard CubeSat power transmission, and a signal power range of 10–15 dBm to mitigate the disturbance. An antenna elevation of 20° was established for a clear communication link with the satellite in this specific azimuth direction (see Fig. 7(d)). The proposed measurement setup can be applied to any minimum elevation threshold between 5 and 20 degrees as used in real missions.

The azimuth range which is affected by the signal interference beam should be considered to complete the electromagnetic mask information. Taking into account the azimuth direction of the interference source as the central axis of the affected area, the next step was the analysis of the signal power received in 90° and 150° azimuth directions. Table 1 shows peak power results of the signal received, applying the same measurement system as in the azimuth direction of the radio amateur antenna to determine the signal power profile in the azimuth range affected by the interference source.

Fig. 8 shows the area of the geographic mask, including the main elevations from the antenna site, which is affected in the VHF band by the radio amateur antenna located in the 120° azimuth direction. Curves in Fig. 9, represent the signal peak power received between 90° to 150° azimuth directions in specific antenna elevations (0°, 10° and 20°) and, how the signal power decreases as the antenna turns away from the center of the source signal beam source. The resulting area represents the electromagnetic mask which completes the geographic information in this azimuth range, and allows establishing the antenna minimum elevation to start communication with the satellite in the VHF band [22,23].

Electromagnetic measurements in other frequency bands require the adaptation of the measurement setup. For instance, interference detection in the 2 GHz band with the presence of

Fig. 6. Top view (source: Google Earth) of the building geo-location which includes the antenna site (orange line) and the azimuth direction (white line) of the radio amateur antenna from the antenna spatial position. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 7. Electromagnetic study with the directional antenna. (a) Signal spectrum with a 0° antenna elevation. (b) Signal spectrum with a 10° antenna elevation. (c) Signal spectrum with a 20° antenna elevation. (d) Graphic representation of the measurement data by the signal power function.

Table 1
Results of the signal peak power (dBm) received in the azimuth range established.

Elevation [°]	20	-103.48	-103.31	-103.6
	10	-98.92	-71.74	-103.62
	0	-103.48	-61.64	-103.6
		90	120	150
Azimuth [°]				

802.11 and/or 802.15.4 networks (2.4–2.4835 GHz) requires the filtering of the particular frequency channel used by the satellite downlink to avoid confusion between the interference in the frequency channel with interference in a neighbor frequency channel. Thus, appropriate bandwidth and central frequency parameters in the spectrum analyzer must be selected.

3.3. Fusion of the geographic and electromagnetic masks

Fusion of both masks, geographic and electromagnetic, gives the expected result for the in situ simulation of the tracking

Fig. 8. Measurement setup applied in the azimuth range affected where the radio amateur antenna was located.

Fig. 9. Graphic representation of the measurement data captured from the spectrum analyzer with the directional antenna in the VHF band.

Fig. 10. Graphic representation of the tracking antenna elevation mask customized in the VHF band, from the future location site at Cal Poly University.

Fig. 11. Graphic representation of the further analysis proposed for a best estimation of the antenna elevation to start communications in a 10–20° elevation range.

antenna elevation mask in the VHF band from the selected site. The swift data fusion process including application of a basic calculation program was possible through the hardware setup by establishing the same reference system when using different capturing sensors and, through software setup by transforming the output data in the parameters required, azimuth and elevation, in both studies. Fig. 10 shows the graphic representation of the antenna elevation customized mask in the VHF band from the proposed site. This mask combines the geographic mask information (see Fig. 3(c)) and the electromagnetic mask information, captured in the azimuth range affected by radio amateur antenna (see Table 1).

4. Conclusions and future works

As initially stated, a standard antenna elevation mask would typically guarantee adequate conditions to establish a satellite radio link in urban and metropolitan areas, as this would avoid most of the surrounding obstacles and interferences. However, obstructions which cannot be avoided often hinder such a standard mask from ensuring an optimal satellite radio link. In this sense, this paper concludes that a customized mask which takes into account the updated geographic and electromagnetic information surrounding the antenna site optimizes the satellite communication times which are available.

In the analyzed case study for CubeSat-LEO missions, the conclusion drawn is the usefulness of simulating the horizon elevation for a given site before antenna installation to test the antenna design. This provided relevant information for the implementation of mitigation techniques either in the redesign or relocation of the

antenna to maximize the amount of telemetry data in downlinks as each of them would have the minimum possible antenna elevation.

The conclusion drawn from the experimented measurement setup is the swift data fusion process using geographic and electromagnetic data capturing sensors. This is the result of previously configuring the software and hardware setup. In particular, the design of a directional antenna support in the hardware setup which allows the simulation of the antenna spatial position, azimuth and elevation, in the electromagnetic study.

Finally, there are several follow on issues that lead towards a generic method to measure the horizon elevation for satellite tracking antennas located in urban and metropolitan areas. These can be inferred from the proposed measurement setup. First, the implementation in the processing software for the electromagnetic mask of others link budget parameters relative to the earth station and satellite performance. Second, experimentation in other frequency bands which requires the adaptation of the proposed measurement setup. Finally, a further analysis of the electromagnetic mask, using a mechanical solution to calibrate the antenna support which includes the inclinometer. Fig. 11 shows why this improvement in the antenna support would determine a best estimation of the antenna minimum elevation to establish a radio link between an earth station and a satellite.

Conflict of interest

The authors declare no conflict of interest.

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