UNIVERSIDAD POLITÉCNICA DE MADRID

Escuela Técnica Superior de Ingenieros de
Caminos, Canales y Puertos

APPLICATION OF DIFFERENTIAL SYNTHETIC APERTURE RADAR INTERFEROMETRY (DINSAR) TO THE MONITORING OF GROUND AND STRUCTURE MOVEMENTS

TESIS DOCTORAL

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Ingeniero Aeronáutico

MADRID, 2019

UNIVERSIDAD POLITÉCNICA DE MADRID

ETSI Caminos, Canales y Puertos
Laboratorio de Topografía y Geomática

Doctorado en Ingeniería de Estructuras, Cimentaciones y Materiales

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“Exploration is really the essence of the human spirit.”

Frank Borman

ACKNOWLEDGEMENTS

En primer lugar me gustaría agradecer a mis directores de tesis Miguel y Beatriz por su continuo apoyo en el guiado de esta tesis. También me gustaría agradecerle todo su apoyo a Rubén. Muchas gracias a los tres por adaptaros a mis circunstancias laborales y por motivarme cada viernes a seguir investigando y estudiando. Es un hecho objetivo que esta tesis no habría sido posible sin vuestra dedicación y comprensión. Juntos, y con la ayuda de Sergio Álvarez, habéis conseguido que el laboratorio de Topografía y Geodesia sea mi segunda casa. Me gustaría también agradecerle a Geocisa y, especialmente, a Carmen González el proporcionarnos los datos de validación que han aportado un enorme valor a este trabajo.

El trabajo que aquí se presenta es el resultado de una carrera de fondo que comienza hace 28 años y en la que, por fortuna, muchas personas han contribuido. Me gustaría aprovechar este momento para agradecerlos todo el cariño y apoyo que me habéis dado.

María del Mar, Rubén, Alberto, Carlos y Mónica muchas gracias por acogerme de forma tan increíble en vuestra familia. Me hacéis sentir como uno más y eso se traduce en más ganas para seguir aprendiendo y creciendo.

Justo y María Jesús, no se puede pedir más a unos padres que han dado (y siguen dando) más de lo que deberían. Los dos sois un ejemplo para mí. Ojalá pueda darle a mis hijos el cariño, la paciencia, la comprensión y el amor que vosotros me habéis

dado desde el día que os enterasteis de que yo existía (De acuerdo, no lo recuerdo desde el minuto 1 pero la extrapolación siempre fue un método estadístico válido). Aldari tu ejemplo me ayudó a aprender lo más difícil, el esfuerzo y el trabajo. Sin ti, el camino habría sido más aburrido y abrupto. Gracias por ser mi hermana. Rober, a pesar de tu mal gusto futbolístico, eres para mí como un hermano. Eva, no miento si digo que esta tesis es mayor que tú, y, aún así, ya me has ayudado con tu sonrisa a buscar fuerzas para terminar este trabajo. Tengo toda la vida por delante para devolverte el favor.

No me gustaría olvidarme de mis Abuelos, de las que están, Hermelina y Petra y de los que ya no, Jesús y Justo. Vuestro orgullo siempre ha sido y siempre será mi mayor premio. La persona que soy hoy es sin duda alguna resultado de todo lo que me habéis enseñado. Para mí, siempre seréis los que más sabéis de la vida. ¡Gracias!

Me gustaría también agradecerle a mi segunda familia, mis amigos, todo su apoyo durante todos estos años.

Y... lo mejor para el final. Sara, has dejado el listón muy alto en tus agradecimientos, a ver si llego a la altura acompañante de vida (Sara, 2019). Tu pasión se contagia y gracias a ti esta tesis ha sido mucho más sencilla. Tengo que confesar que he disfrutado compartiendo tardes y noches en Berna y en la universidad estudiando contigo. Mentiría si no te digo que todos los días levanto la vista del ordenador, te miro y sonrío pensando: ¿Cómo se puede tener la suerte de conocer a la mejor persona del mundo en un avión? Éste es el primero de muchos retos que superamos juntos acompañante de vida. Gracias por todo Pai.

RESUMEN

Durante las últimas décadas, la teledetección basada en radar de apertura sintética (SAR) se ha desarrollado y optimizado en el mundo académico con la implementación de algoritmos y metodologías que permiten el aprovechamiento de la información satelital en numerosas aplicaciones. Sin embargo, en muchas de estas aplicaciones, la transición del mundo académico al mundo profesional y operacional aún no se ha producido. La falta de una normalización de las prestaciones y limitaciones de la tecnología SAR ha limitado su completa aplicación comercial en la monitorización de construcciones civiles. El objetivo de esta tesis es arrojar luz sobre este problema.

Este trabajo propone una innovadora metodología para aprovechar el archivo de 25 años de datos radar de distintos sensores para desarrollar mapas de deformación histórica. El desarrollo de esta metodología proporciona la posibilidad de llevar a cabo un análisis comparativo de las características de los distintos algoritmos y sensores. Esta información tiene el objetivo de proporcionar criterios de selección de la mejor combinación sensor-algoritmo a un usuario.

Asimismo, se ha llevado a cabo un profundo trabajo de validación de la aplicabilidad de la interferometría de puntos persistentes (PSI) satelital al control de trabajos de soterramiento y tunelación. Los trabajos de construcción de la M-30, que supusieron el soterramiento de 50 km de carreteras, son el escenario empleado

para la validación. Las deformaciones estimadas mediante PSI son comparadas contra las deformaciones medidas por los instrumentos usados durante el periodo de construcción. La validación demuestra que prestaciones milimétricas pueden obtenerse con los últimos algoritmos basados en PSI. Por otro lado, las limitaciones de la técnica como la latencia con la que las estimaciones son actualizadas y la disponibilidad de estimaciones precisas en áreas decorreladas son detalladas. Como resultado del análisis, se propone una solución de monitorización óptima basada en la integración de la tecnología SAR satelital y un número reducido de instrumentos en tierra para cubrir la monitorización de los elementos que requieren una gran frecuencia de control.

Se ha analizado la aplicabilidad de la técnica PSI al escenario urbano más complejo, el centro histórico de una ciudad. Estas zonas se caracterizan por tener una mayor decorrelación que otras áreas urbanas debido a la peculiaridad de sus tejados y fachadas y de la aglomeración de personas en las calles que impide obtener puntos coherentes en las zonas de paso. Se han analizado los trabajos de construcción del túnel ferroviario que une Chamartín y Atocha y la ampliación de los andenes de la parada de metro de Sol. Las limitaciones de disponibilidad de la técnica se muestran claramente en el hecho de que algunos edificios no muestran puntos coherentes. No obstante, se demuestra que la técnica PSI puede complementar la instrumentación convencional proporcionando datos de deformación sobre grandes áreas.

Por último, el escenario del centro histórico de Madrid se ha empleado para la definición y validación de unos índices de clasificación que permiten una interpretación objetiva de la técnica PSI y reducen la dependencia de los resultados de las características del algoritmo y sensor empleados en el procesado.

ABSTRACT

During the last decades, satellite-based Synthetic Aperture Radar (SAR) technology has been fully developed in the academic world with the implementation of the algorithms and methodologies that allow the exploitation of satellite-based radar information. However, in some applications, such as the monitoring of ground civil structures, the transition between the academic and the professional work is far from being complete. The lack of a clear standardization of the potential and limits of the technique along with the limited amount of ground truth data from actual constructions work have slowed down the common operational use of satellite-based SAR sensors in the monitoring of construction works. This thesis aims at shedding light to this matter.

An innovative approach is proposed to exploit the long data archives with data from more than 25 years from different sensors generating historical deformation maps. This scenario also provides the opportunity of carrying out a benchmarking analysis pointing out the characteristics of the main frequency bands and the outcomes of different algorithms. This can provide an end user with valuable information to select the best combination of sensor and processing algorithm.

A concise validation effort of the application of satellite-based Persistent Scatterer Interferometry (PSI) to the monitoring of tunneling works is carried out. The construction works of the M-30, which implied the underground of up to 50 km of

roads, represent the validation scenario. The estimated PSI deformations have been compared against the data from actual instruments used during the construction period. This validation work proves that high accuracies of a few millimeters can be achieved with the state of the art PSI algorithms. In addition, the limitations of the technique, such as the latency of the estimations update, and the limited availability of coherence points in decorrelated areas are detailed. As a result of this analysis, an optimal monitoring process is proposed based on the integration of satellite-based and a reduced amount of on-ground instruments for the assets that require high frequent estimation updates.

The applicability of the PSI technique to the most challenging urban scenario, a city center, is assessed. These areas have higher decorrelation statistics than other urban areas due to the characteristics of the facades and rooftops and the crowded streets that prevent from obtaining coherent points in transit areas. The tunneling works of the railway between Atocha and Chamartín and the enlargement of the waiting areas of the Sol metro stations are the scenarios used. The availability limitations of the technique are clearly seen in this scenario since some of the building affected by the construction works are not covered by coherent points. Nevertheless, it has been shown that PSI can complement conventional instruments providing deformation estimations over large areas.

Finally, the city center scenario is also used for the definition and validation of a set of classification indexes that allow an objective interpretation of the PSI results and reduce the dependency of the results on the algorithm and sensor used in the processing.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	iii
RESUMEN	v
ABSTRACT	vii
LIST OF FIGURES	xiii
LIST OF TABLES	xvii
ABBREVIATIONS	xviii
SYMBOLS	xx
1 INTRODUCTION AND BACKGROUND	1
1.1 Introduction	1
1.1.1 Objectives	5
1.2 Thesis roadmap	6
1.3 List of publications and communications	9
1.4 Theoretical background	10
1.4.1 Satellite-based SAR principles	10
1.4.2 SAR Interferometry	16
1.4.3 Time series Analysis algorithms	24

2	SAR SENSORS BENCHMARKING. APPLICABILITY OF SAR DATA ARCHIVES TO HISTORICAL DEFORMATION	31
2.1	Evolution of urban monitoring with radar interferometry in Madrid City: performance of ERS-1/ERS-2, ENVISAT, COSMO-SkyMed, and Sentinel-1 products	32
2.1.1	Abstract	32
2.1.2	Introduction	33
2.1.2.1	Related work	35
2.1.3	Material and methods	37
2.1.3.1	Area of study and rationale	37
2.1.3.2	Satellite datasets	38
2.1.3.3	Analyses description	41
	Analysis 1: Historical deformation through the evolution of sensors imagery	41
	Analysis 2: Historical deformation using different algorithms	43
2.1.4	Results and discussion	44
2.1.4.1	Dataset validation	44
2.1.4.2	Analysis 1: Historical deformation through the evolution of sensors imagery	50
2.1.4.3	Analysis 2: Historical deformation using different algorithms	53
	Case study: M-30	55
2.1.5	Conclusions and future work	58
2.2	Historical monitoring of urban subsidence based on long-term SAR data archives	60
2.2.1	Abstract	61
2.2.2	Introduction	61
2.2.3	Material and methods	63

2.2.4	Results and Discussion	65
2.2.4.1	Validation results	65
2.2.4.2	Historical deformation map	65
2.2.5	Conclusions	67
3	INTEGRATING GEOTECHNICAL AND SAR DATA FOR THE MONITORING OF UNDERGROUND WORKS	68
3.1	Abstract	69
3.2	Introduction	69
3.2.1	Validation scenario	72
3.3	Material and methods	74
3.3.1	Control instruments and reference data	74
3.3.2	PSI processing	75
3.3.3	Validation process	81
3.4	Results of the PSI validation in Madrid tunneling works	82
3.4.1	Global results of the PSI validation	82
3.4.2	Limits of the PSI technique in tunneling works	83
3.4.3	In-depth case studies	84
3.4.3.1	M-30 sector 5	85
3.4.3.2	M-30 sector 10	87
3.5	Discussion	88
3.6	Conclusions	90
4	STRUCTURAL HEALTH MONITORING THROUGH SAR- DERIVED CLASSIFICATION INDEXES	93
4.1	Abstract	94
4.2	Introduction	94
4.2.1	Area of study: Atocha	97
4.2.2	Area of study: Puerta del Sol	98
4.3	Material and methods	99

TABLE OF CONTENTS

4.3.1	PSI processing	101
4.3.2	On ground measurements	102
4.3.2.1	Case study: Atocha	102
4.3.2.2	Case study: Puerta del Sol	103
4.3.3	Ground-truth validation process	103
4.3.4	Building health assessment	104
4.4	Results	107
4.4.1	Case study: Atocha	107
4.4.1.1	Ground-truth validation	108
4.4.2	Case study: Puerta del Sol	108
4.4.2.1	Ground-truth validation	109
4.5	Discussion	111
4.6	Conclusions	114
5	GENERAL DISCUSSION	116
6	CONCLUSIONS AND FUTURE WORK	124
6.1	Future work	128
	REFERENCES	131
	APPENDIX A	154
	APPENDIX B	156
	APPENDIX C	158
	APPENDIX D	160
	APPENDIX E	162

LIST OF FIGURES

1.1	Interferogram of the Landers earthquake. Image from (Ferretti et al., 2007a).	3
1.2	Thesis methodology workflow. The chapters where the different points area addressed are included.	8
1.3	Sentinel-1 acquisition representation. Image from (European Space Agency (ESA), 2019).	11
1.4	Real part of an SLC image over the area of Madrid from Envisat satellite.	13
1.5	Impact of the terrain geometry on the SAR image. Section 1 shows the nominal scenario with flat terrain. Section 2 shows the foreshortening effect. Section 3 shows the layover and section 4 the shadowing effect.	14
1.6	Illustration of different SAR operation modes. (a) Stripmap. (b) ScanSAR. (c) Spotlight. Image from (Moreira et al., 2013).	15
1.7	SAR techniques that allow the exploitation of the satellite-based radar information.	17
1.8	Illustration of the DInSAR concept.	22
1.9	DInSAR phase generated with two SLC Envisat images over the Madrid area.	23
1.10	Perpendicular and temporal baselines of the SLC images. The optimal master of the dataset is highlighted.	28
1.11	PSInSAR dataflow process.	29

1.12	LOS deformation velocity in the area of Madrid derived from a Sentinel-1 PSI processing.	30
2.1	Area of interest of the study. The location of the validation GNSS stations is marked with blue squares.	38
2.2	Coverage map of the different datasets used in this work. (a) CSK, (b) ENVISAT (SPN), (c) ENVISAT (PSP), (d) ERS-1/2, and (e) Sentinel-1 A/B.	39
2.3	Circular buffer considered around IGNE station for the deformation estimation.	46
2.4	SAR geometry	47
2.5	PS and GNSS estimated cumulative vertical displacement for the validation GPS stations. (a) 3CAN, (b) IGNE, (c) LEGA , (d) MER2, (e) VILL.	49
2.6	PS density of the different missions for Corine Label 1 Classes. . . .	51
2.7	PS density of the C-band missions for Corine Label 2 Classes. . . .	53
2.8	PS density of Envisat datasets for Corine Label 2 Classes.	54
2.9	M-30 working area. The M-30 tunnels and metro lines are presented. The sector of interest is highlighted in blue.	55
2.10	Estimated transversal subsidence of sector 5 of M-30 works. The deformation derived from the combination of both datasets is also included along with a sketch of the twin tunnels and the theoretical deformation.	57
2.11	PS distribution of Envisat datasets over the area of interest.	58
2.12	Historical deformation map of the area of Madrid. The cumulative displacement from April 1992 to May 2017 is shown. The metro stations and tunnels are included. The deformation of a point of interest is shown.	66
2.13	Deformation time series of the point of interest highlighted in Figure 2.12.	66

3.1	Sketch of the geological profile of the area of interest	73
3.2	Area affected by the M-30 works. The zone has been divided into 12 sectors. The two sectors of interest are highlighted. The location of the leveling and strip measurements used for validation purposes is shown.	74
3.3	Area of the PSI processing. The location of the reference point and the area of interest of this study, the M-30 works, is indicated. . . .	77
3.4	LOS velocity map obtained from the SPN processing. The area of study is highlighted in blue.	79
3.5	LOS velocity map obtained from the PSP processing. The area of study is highlighted in blue.	80
3.6	RMS of the PSI displacement error as a function of the maximum displacement rate between acquisitions measured from the on-ground instruments at the control points. The average of the control points per interval is plotted in the histogram.	85
3.7	Area of sector 5 corresponding to Legazpi Square. The location of the Persistent scatterers and the on-ground data used as reference is shown.	86
3.8	Time series deformation of the 5 m buffer around the M-30's north tunnel axis	87
3.9	Area of Sector 10 corresponding to Ciudad de Barcelona Street. The location of the on-ground data used as reference and the PS is shown. The area is mainly affected by the secondary pipe included in the Figure. The building of interest is highlighted in blue.	88
3.10	Time series deformation of the building of interest highlighted in Figure 3.9.	89
4.1	Atocha construction work area. The location of the TBM when there was a malfunction is shown as Section 0 + 382 m. The buildings included in the monitoring activities have been highlighted.	98

4.2	Puerta del Sol construction area. The trace of the underground activities is highlighted in green. The black line shows the location of section A-A'.	99
4.3	Sketch of Puerta del Sol works. It represents the construction works at section A-A' of Figure 4.2. a) Status prior to the construction works. b) Status after the construction work with the waiting area and enlarged platform.	100
4.4	Comparison of the deformation time series of the levelling points and the PSI deformations. PS deformations are joined by a dashed line. When different behaviours are identified different line colors are used.	109
4.5	Comparison of the deformation time series of the strips and the PSI deformations of the odd buildings of Atocha Street. PS deformations are joined by a dashed line. When different behaviours are identified different line colors are used.	110
4.6	Comparison of the deformation time series of the strips and the PSI deformations of the even buildings of Atocha Street. PS deformations are joined by a dashed line.	111
4.7	Comparison of the deformation time series of the strips and the PSI deformations of SOL 11 (a) and SOL 12 (b) buildings.	112
5.1	Comparative illustration of the characteristics of the different monitoring methods analysed in this work.	122

LIST OF TABLES

2.1	Summary of the characteristics of the 5 SAR datasets used in this work.	42
3.1	Temporal and perpendicular baselines of the radar images used in the PSI processing.	78
4.1	Temporal and perpendicular baselines of the radar images used in the PSI processing.	102
4.2	Completeness of Information Index as a function of the PS deformation velocity.	105
4.3	Conservation Criticality index as a function of the PS deformation velocity.	106
4.4	Classification indexes of the buildings affected by the underground activities carried out in Atocha. Refer to Figure 4.1 for the location of each building. The accumulated value is an average of all the analysed buildings.	107
4.5	Classification indexes of the buildings affected by the underground activities carried out in Puerta del Sol. (Refer to Figure 4.2 for the location of each building. The accumulated value is an average of all the analysed buildings).	108

ABBREVIATIONS

2D	2D imensions
A-DInSAR	A dvanced DInSAR
APS	A tmospheric P hase S creen
ASAR	A dvanced S ynthetic A perture R adar
CPT	C oherent P ixel T echnique
CSK	COSMO SKyMed
DGPS	D ifferential G lobal P ositioning S ystem
DGT	D isplacement G radient T ensor
DEM	D igital E levation M odel
DInSAR	D ifferencial InSAR
Envisat	E nvironmental satetellite
EPN	EUREF GNSS P ermanent N etwork
EPOS	E uropean P late O bserving S ystem
ERS	E uropean R emote S ensing satellite
ESA	E uropean S pace A gency
EUREF	R egional RE ference F rame Sub-Commission for EU rope
GNSS	G lobal N avigation S atellite S ystem
GPS	G lobal P ositioning S ystem
HH	H orizontal emit H orizontal receive
IGS	I nternational GNSS S ervice

IM	I mage M ode
InSAR	I nterferometric S ynthetic A perture R adar
LOS	L ine O f S ight
MT-InSAR	M ulti T emporal I n SAR
Pol-InSAR	P olarimetric SAR I nterferometry
PS	P ersistent S catterer
PSI	P ersistent S catterer I nterferometry
PPP	P recise P oint P ositioning
PSIC4	PSI C odes C ross- C omparison A nd C ertification
PSP	P ersistent S catterer P airs
RMS	R oot M ean S quare
RTK-DGNSS	R eal T ime K inematic- D ifferential GNSS
SLC	S ingle L ook C omplex
SAR	S ynthetic A perture R adar
SBAS	S mall B aseline S ubset
ScanSAR	S canning SAR
SeaSat	S ea f aring S atellite
SPN	S t a ble P oint N etwork
SRTM	S huttle R adar T opography M ission
StaMPS	S tan f ord M ethod for P ersistent S catterers
TBM	T unnel B oring M achines
TLS	T errestrial L aser S canner
TEC	T otal E lectron C ont e nt
TOPS	T errain O bservation with P rogressive S can
VV	V ertical emit V ertical receive

SYMBOLS

Symbol	Definition	Unit
$B_{\perp}$	perpendicular baseline	m
$B_{\parallel}$	parallel baseline	m
d	displacement in the LOS	m
D_a	PS density of the surrounding area	—
D_i	Dispersion Index	—
D_m	Limiting PS density	—
D_o	PS density over the building of interest	—
e	displacement in east direction	m
I_{ci}	completeness of information index	m
I_{cc}	conservation criticality index	m
$I_{cc,a}$	conservation criticality index of the surrounding area	m
$I_{cc,o}$	conservation criticality index of the building of interest	m
I_{vd}	velocity dispersion index	m
n	displacement in north direction	m
N	number of electrons	—
R	distance satellite - ground	m
R_{def}	ground deformation	m
R_{tropo}	tropospheric range deformation	m
u	vertical displacement	m

V_{max}	maximum deformation velocity	m
V_{mean}	mean deformation velocity	m
V_{min}	minimum deformation velocity	m
α	LOS elevation	rad
$\delta_{spatial}$	spatial decorrelation	—
$\delta_{Doppler}$	Doppler decorrelation	—
$\delta_{temporal}$	temporal decorrelation	—
$\delta_{thermal}$	thermal decorrelation	—
$\Delta\phi_d$	differential interferometric phase difference	rad
$\Delta\phi$	interferometric phase difference	rad
Δz	height above the reference ellipsoid	m
γ	coherence	—
λ	wavelength	m
μ_a	mean amplitude	—
ϕ	phase deformation	rad
ϕ_0	backscattering phase shift	rad
ϕ_{iono}	ionospheric phase deformation	rad
ϕ_{topo}	topographic phase deformation	rad
ϕ_{tropo}	tropospheric phase deformation	rad
ϕ_{orbit}	orbital phase deformation	rad
ϕ_{def}	ground phase deformation	rad
ϕ_{atmos}	atmospheric phase deformation	rad
ϕ_{noise}	noise phase deformation	rad
σ_a	standard amplitude deviation	—
θ	off-nadir angle	rad
θ	satellite's heading angle	rad

Dedicated to Sara

CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 Introduction

The monitoring of civil structures affected by underground construction works has been formerly carried out by conventional techniques such as levelling, strips, piezometric and extensometers. The technological advances that have been made in the field of the laser, radar and satellite-based systems in recent years have motivated the development of new techniques for the monitoring of movements in civil engineering aiming at easing the control, reducing costs and increasing precision. Some examples whose applicability has been widely analysed are the Differential Global Positioning System (DGPS) and the Terrestrial Laser Scanner (TLS). The DGPS allows continuous monitoring of the receiver locations with an accuracy that, in the most optimal conditions, can be in the order of the millimeter (although nominally it is in the order of the centimeter ([Teunissen and Montenbruck, 2017](#))). TLS, with a precision in optimal conditions of 3 millimeters, allows campaign based measurements

of a complete structure. Both of them can be integrated along with the traditional methods in order to achieve the most optimal monitoring. A detailed assessment of both techniques can be found in [APPENDIX A](#). These methods require the installation of expensive instrumentation in the area of study which represents a major limitation in the auscultation of wide areas. The exploitation of satellite-based active monitoring techniques, such as those based on Synthetic Aperture Radar (SAR) ([Bamler and Hartl, 1998](#)) could allow the monitoring of civil structures with no on-ground instrumentation and independently of the weather conditions.

The first satellite with SAR technology, Seafaring Satellite (SeaSat), was launched in 1978 ([Jordan, 1980](#)). It demonstrated the capabilities of the technique for operational monitoring activities, proving that land, ice and sea surface could be monitored at the cost of the signal processing and an unconventional geometry when compared to optical imagery ([Bamler and Hartl, 1998](#)). Although the basic principle that allows the generation of interferograms, which is detailed in section [1.4](#), dates from the 1970s ([Graham, 1974](#)), the first application to satellite-based SAR data appears in the early 1990s ([Gabriel et al., 1989](#); [Zebker and Goldstein, 1986](#)). However, these early applications were founded on the limited amount of data available from SeaSat at that time and, therefore, the outcomes of the studies were not conclusive.

The launch of the European Space Agency (ESA) satellites ERS-1/2 in 1991 and 1995 ([Bamler and Hartl, 1998](#)) provided an enormous amount of SAR information that motivated the development of Interferometric SAR (InSAR or IFSAR) and Differential InSAR (DInSAR) algorithms. In this line, the earthquake of Landers, which occurred in June 1992 close to the city of Los Angeles ([Ferretti et al., 2007a](#)), provided the first scenario for the demonstration of the radar interferometry capabilities. The interferometric analysis carried out by [Massonnet et al. \(1993\)](#) exceeded

popularised the ‘fringes’ as a new way to look at ground deformation with coloured, and sometimes shaky, contour lines, each amounting to 3 cm or so of additional deformation.

CHAPTER 1: INTRODUCTION
 The interferometric image of Figure 1.1 provides a striking collision of scales: it shows the central part of the 100 km by 300 km area under study, where displacements are recorded with millimetre accuracy, from 800 km away in space. The ratio of the width of the scene and the potential accuracy is 10^8 . The ratio of the ‘fringes’ as the colored representation of contour lines of the displacement in the image is 10^6 , accounting deformations of 3 cm (Figure 1.1).

FIGURE 1.1: Interferogram of the Landers earthquake. Image from (Ferretti et al., 2007a).
Figure 3-F: The Landers Earthquake of 18 June 1992

Different studies further refined and extended the work of Massonnet et al. (1993), first, in the same scenario (Feigl et al., 1995; Hernandez et al., 1997; Massonnet et al., 1993; Zebker et al., 1994) and, later, studying other events such as the earthquake of Atacama in Chile in 1995. Although not published at that time and only reported

a decade later ([Ferretti et al., 2007a](#)), the earthquake of Latur in India in 1993 also pointed out one of the main limitations of the technique, the coherence loss. The rapidly changing conditions of the area, mainly agricultural and with heavy rainfalls, limited the interferometric analysis of this earthquake.

The next milestone in the evolution of the satellite-based interferometry is the development of the Persistent Scatterers Interferometry (PSI) technique ([Ferretti et al., 2001](#)). This technique, which is deeply assessed in section 1.4.3, aims at estimating the deformation in the pixels that remain coherent over a set of SAR images of the same area. In this line, the correlation related errors are reduced and the accuracy of the estimation is highly increased. Different formulations were proposed in the following years ([Crosetto et al., 2016](#)) whose applicability was tested with data from Envisat satellite (2002-2012) in C-band. ERS 1/2 and Envisat data was recently made publicly available by ESA. Moreover, the open data strategy was followed by the recent launch of Sentinel 1A and Sentinel 1 (illustrated in Figure 1.3) in 2014 and 2016 respectively, ensuring the future of the C-band SAR remote sensing ([Li et al., 2016](#)). In addition, X-band SAR data, which provides higher resolution, is also covered by the tandem TerraSAR-X and COSMO-SkyMed (CSK), although their data is not publicly available. The combination of data from different sensors feeds a data archive of more than 30 years of SAR data which, up to now, has not been jointly exploited.

In recent years PSI algorithms have achieved a great maturity level leading to an open source methodology based on SNAP and StaMPS ([Foumelis et al., 2018](#)). As a result, current and future efforts should focus on the assessment of the capabilities and limitations of the technique in different scenarios to motivate the standardization of the technique. This is a costly step since external validation inputs are usually difficult to obtain. This is the investigation line which founds this thesis.

1.1.1 Objectives

The monitoring of civil structures affected by underground construction works has been formerly carried out by conventional techniques: levelling, strips, piezometric and extensometers. This scenario could benefit from the application and integration of SAR technology with traditional tools. However, the uncertainties linked to the PSI technique, i.e., the accuracy and the maximum Line of Sight (LOS) velocity that can be detected, require that the actual performance and limitations of the technique on the specific application are investigated.

Although the PSI technique has proven its applicability in most urban areas, the old city centers represent a great challenge for the technique due to the fact that the area is usually crowded, which increases the spatial decorrelation. In addition, in order to avoid the facades alteration, most of the rooftops of the historical buildings are full of air conditioning systems increasing the thermal residual noise. Therefore, the applicability of the PSI technique in this environment, which represents the most challenging scenario, should be assessed.

The interpretation of the PSI results is usually unclear and depends on the selected algorithm and sensor. In order to remove this dependency and ensure an objective assessing of the PSI results in the monitoring of underground works, a set of classification indexes should be defined.

In this context, the objectives of this work are derived from the previous open points and are specified below:

1. Conduct a benchmarking of the performance of the most common frequency bands (C and X) and the influence of the PSI algorithms.

2. Confirm that Sentinel-1 A/B ensures the continuity of C-band free-of-charge SAR data and that can be exploited by PSI techniques to derive ground deformations.
3. Investigate if the long data archives of SAR images of different sensors and processed by different means can be used to derive the historical deformation of a given area of interest.
4. Investigate the applicability of the PSI technique to the monitoring of underground works.
5. Refine the potential and limitations of the PSI technique when applied to the monitoring of construction works.
6. Address the integration of PSI techniques with conventional monitoring instruments in order to achieve an optimal monitoring in terms of coverage and cost.
7. Analyse the performance and limitations of the PSI technique when applied to the most challenging urban environment: historical city centers.
8. Propose a set of classification indexes that ensure an objective and dataset independent interpretation of the PSI results.

1.2 Thesis roadmap

This work is divided into 6 different chapters including a general introduction, three case studies, a general discussion, and the conclusions. The case studies have been prepared following a twofold objective, they are self-contained with a specific state of the art and discussion of each application since they are based on paper publications

and they also ensure the continuity of the dissertation. A summary of the content of the different chapters is listed below:

- Chapter 1, the current chapter, includes the introduction, the technological background that supports this thesis and it specifies the objectives and contributions of this work.
- In Chapter 2 five different datasets covering more than 25 years of SAR monitoring are used to cover the objectives 1 to 3. The chapter is divided into two sections whose content has been published in journal articles. The first one carries out an analysis of the performance of the C and X bands sensors. These datasets also allow the assessment of the combination of different datasets and algorithms to assess historical deformation. The second section represents a step forward in the exploitation of long data archives developing a historical deformation map that allows the interpolation of data even in areas with a medium density of PS. In both cases, the area of Madrid is used as a testing scenario.
- Chapter 3 aims at addressing objectives 4 to 6 and its content has been published in a journal article. The M-30 works, which implied the underground of up to 50 km of roads, is the perfect scenario for the assessment of the applicability of the SAR data to the monitoring of underground works. Moreover, the availability of the outputs of the conventional instruments used in the monitoring allows meeting two objectives. First of all, the limitations of the technique in the monitoring of underground works can be identified. Moreover, the integration of SAR data with traditional monitoring can be investigated.
- Chapter 4 covers objectives 4, 7 and 8 and its content is under review as a journal article. The historical city center of Madrid is the perfect scenario for

the assessment of the performance of the PSI technique in the most challenging urban scenario. Two underground construction works, the enlargement of Sol metro station and the underground of the railway in Atocha, for which the actual monitoring data is available, are exploited in this work. Moreover, a set of classification indexes is proposed that allow the objective assessment of the PSI results both in term of the magnitude of displacement and the confidence in the results.

- Chapter 5 contains the general discussion of the applicability of the PSI to the monitoring of ground civil infrastructures.
- Finally, Chapter 6 contains the conclusions and future work.

Figure 1.2 illustrates the workflow followed in this thesis.

FIGURE 1.2: Thesis methodology workflow. The chapters where the different points area addressed are included.

1.3 List of publications and communications

As a result of the work carried out in this thesis, several journal articles and conference communications have been submitted and published. Hereafter, the journal articles are listed:

- M. Bakon, M. Marchamalo, Y. Qin, **A.J. García**, S. Álvarez, D. Perissin, J. Papco, R. Martínez, Madrid as Seen from Sentinel-1: Preliminary Results, *Procedia Computer Science*, Volume 100, 2016, Pages 1155-1162, ISSN 1877-0509, DOI: <https://doi.org/10.1016/j.procs.2016.09.269>.
- **A. J. García**, M. Bakon, R. Martínez & M. Marchamalo (2018) Evolution of urban monitoring with radar interferometry in Madrid City: performance of ERS-1/ERS-2, ENVISAT, COSMO-SkyMed, and Sentinel-1 products, *International Journal of Remote Sensing*, 39:9, 2969-2990, DOI: <https://doi.org/10.1080/01431161.2018.1437299>
- **A. J. García**, L. Ramos Alcázar, D. Galán Martín, M. Marchamalo & R. Martínez (2018) Nuevas técnicas aplicadas a la auscultación de movimientos en Ingeniería Civil, *Revista Mapping*, Vol. 27 188 36-39, ISSN: 1131-9100.
- **A. J. García**, M. Marchamalo, R. Martínez, B. González-Rodrigo, C. González, Integrating geotechnical and SAR data for the monitoring of underground works in the Madrid urban area: Application of the Persistent Scatterer Interferometry technique, *International Journal of Applied Earth Observation and Geoinformation*, Volume 74, 2019, Pages 27-36, ISSN 0303-2434, DOI: <https://doi.org/10.1016/j.jag.2018.08.025>.
- **A. J. García**, R. Martínez, B. González-Rodrigo, M. Marchamalo, Building Health Monitoring in the old town of Madrid: Applicability of SAR Imagery

to the monitoring of underground works through classification indexes, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 2019. Under review.

Hereafter, the conference publications are listed:

- M. Bakon, M. Marchamalo, Y. Qin, **A. J. García**, S. Álvarez, D. Perissin, J. Papco, R. Martínez, Madrid (2017) Sentinel 1 potential for monitoring large urban areas: Madrid case study, Fringe 2017, 5-9 June 2017, Helsinki, Finland. Poster presentation
- **A. J. García**, M. Bakon, S. Álvarez, B. González-Rodrigo, R. Martínez & M. Marchamalo (2018) Historical monitoring of urban subsidence based on longterm SAR data archives, Centeris/SARWatch 2018, ISBN 978-989-97433-9-7, pp.241-245.
- **A. J. García**, R. Martínez, B. González-Rodrigo, M. Marchamalo (2019) Monitoring underground works in the Madrid urban area: DInSAR vs conventional techniques, Living Planet Symposium 2019, 13-17 May 2019, Milan, Italy. Poster presentation. Refer to [APPENDIX E](#).

1.4 Theoretical background

1.4.1 Satellite-based SAR principles

Satellite-based SAR technology consists of a moving radar sensor that provides high-resolution images independently of the weather conditions and daylight conditions allowing continuous remote sensing of the Earth's surface. As any radar-based system, an electromagnetic pulse is emitted from the SAR emitter. This pulse travels

through the atmosphere and penetrates the Earth’s surface. Then, the electromagnetic echoes are received on the SAR sensor ([Kampes, 2006](#)). The intensity and phase of the received echo depend on the relative geometry between the sensor and the backscattering element as well as on the properties of the reflecting element ([Moreira et al., 2013](#)) and, therefore, this information can be exploited to obtain information of the ground surface. Figure 1.3 shows a representation of satellite-based SAR sensor, Sentinel 1, imaging through a cloud area.

FIGURE 1.3: Sentinel-1 acquisition representation. Image from ([European Space Agency \(ESA\), 2019](#)).

The SAR principle receives the name of ‘Synthetic Aperture Radar’ from the capability of combining the echoes of electromagnetic pulses emitted at different positions as part of the sensors’ movement. The combination of the different pulses allows the emulation of a virtual aperture which corresponds to a bigger physical antenna. The size of the image is defined by the swath width and the length, which depends on the time during which the electromagnetic pulse is emitted ([Kampes, 2006](#)).

The frequency at which the SAR sensor emits the electromagnetic pulse is selected as the outcome of a trade-off process between the penetration capability and the

sensitivity of the sensor to ground deformations. In this line, shorter wavelengths imply better sensitivity and less penetrability. The most common frequency bands applied to the SAR sensors are L-band, with a wavelength of 24 cm, C-band, with a wavelength of 6 cm and the X-band, with a wavelength of 3 cm. As a result of their wavelengths, X- and C-band pulses cannot penetrate densely vegetated areas. The higher frequency of the L-band allows the penetration of vegetated areas and, therefore, coherent points can be observed in forest areas (Ferretti et al., 2007a) at the cost of a worse sensitivity to ground deformation.

The result of every SAR acquisition is a 2D matrix with complex numbers, also known as Single Look Complex (SLC) image. Each element of the matrix shows a picture element or pixel, and it represents an area of the Earth's surface, which is known as the resolution cell. The rows of the matrix are linked with the azimuth direction and the columns with the slant range direction. The real part represents the amplitude or intensity of the reflected echo which depends on the characteristics of the reflecting surface, i.e., the dielectric properties and the geometry of the terrain with respect to the sensor. A sample of the intensity derived from an SLC image of the area of Madrid has been included in Figure 1.4. The complex part represents the phase which mainly depends on the two-way travel between the sensor and the surface (Ferretti et al., 2007a). In this line, taking into account the almost purely sinusoidal behavior of the emitted electromagnetic wave, the relationship between the phase, ϕ , and the distance satellite-ground, R , can be expressed as:

$$\phi = \frac{2\pi}{\lambda} \cdot 2R + \phi_0 = \frac{4\pi}{\lambda} \cdot R + \phi_0 \quad (1.1)$$

where λ is the sensor's wavelength and ϕ_0 is the phase shift which is generated as part of the backscattering process. Note that, according to Equation 1.1, any integer multiple of wavelengths leads to the exact same phase. This is the so-called

FIGURE 1.4: Real part of an SLC image over the area of Madrid from Envisat satellite.

ambiguity which is of great relevance in SAR applications. This concept is further explained in section 1.4.2.

Apart from the dielectric properties and the surface's roughness the terrain elevation also has an impact on the effective resolution cell (Ferretti et al., 2007a). In this regard, three different distortion scenarios can be found, as it is represented in Figure 1.5. Note that all the segments of the figure have the same length, which allows the visual inspection of the actual resolution cell. The first section shows the nominal scenario with flat terrain. When the slope increases with respect to the LOS, the ground resolution dimension in the range direction is increased, as in section 2. This is known as the foreshortening effect. If the terrain slope is close or higher than the off-nadir angle the image is obtained in reverse order, which is known as layover. This is the case of section 3. Finally, section 4 shows the shadowing effect for which some areas are not covered by the SAR sensor.

The SAR sensors can be classified as a function of the polarization capabilities of the emitter and receiver sensors. Linear polarization sensors emit and receive one channel: Vertical emit and vertical receive (VV), horizontal emit and horizontal receive (HH) or cross-correlated channels (HV and VH). Hybrid-polarity sensors have

FIGURE 1.5: Impact of the terrain geometry on the SAR image. Section 1 shows the nominal scenario with flat terrain. Section 2 shows the foreshortening effect. Section 3 shows the layover and section 4 the shadowing effect.

the capability of emitting a right circular wave and receiving a linear polarization such as vertical or horizontal polarization (RH or RV). Moreover, circular polarizations emit and receive right circular and left circular polarizations (RL, RR, and LL). Finally, quad-polarimetric sensors have the capability of emitting and transmitting different combinations (VV, VH, HV, and VV). Due to the different dielectric properties of the backscattering elements, the SAR images formed from the different available emitted and received channels contain different information. This principle is exploited by the SAR polarimetry.

All the resolution cells are sensitive to the so-called ‘speckle’ problem. It is caused when different elements act as scatterers within the same resolution cell. As a result, the coherent sum of the contributions of the different scattering elements

must be larger than the transmitted chirp bandwidth (assuming 1/C demodulation) according to Shannon's sampling theorem. The same is true in azimuth. However, in this case the sampling rate is equal to the PRF which must be larger than the signal Doppler bandwidth. This can be stated as

$$PRF \geq B_D = \frac{2v}{d_a} \quad (9)$$

the backscattering elements (Ferretti et al. 2000) which can be rearranged in terms of the spatial sample spacing $v \cdot PRI \leq d_a/2$, i.e., at least one sample (pulse transmission event) is required whenever the platform has moved by half of the antenna length.

Common approach to ease the effects of the speckle is multi-look processing. It consists of the formation of multiple images of the same area. Although it increases the visible image resolution

in azimuth and range which also worsens the resolution as seen in the multi-looked SAR images above. (a) Without multi-look. (b) 2×2 multi-look. (c) 4×4 multi-look. (d) 8×8 multi-look. These different modes allow obtain-

FIGURE 5. The effect of speckle can be reduced through multi-look in azimuth and range which also worsens the resolution as seen in the multi-looked SAR images above. (a) Without multi-look. (b) 2×2 multi-look. (c) 4×4 multi-look. (d) 8×8 multi-look. These different modes allow obtain-

ing images with better azimuth resolution or increased swath. The most common operational mode, which is considered as baseline, is the Stripmap mode (Moreira et al., 2013). Other operational modes include the scanning SAR (ScanSAR) which increases the swath width, and the Spotlight mode which increases azimuth resolution. Figure 1.6 illustrates these modes. Other modes include terrain observation with progressive scan (TOPS) (De Zan and Monti Guarnieri, 2006) or the wave mode.

angles corresponding to multiple sub-swaths as shown in Fig. 6(b). Each sub-swath is illuminated by multiple pulses but for a shorter time than in the Stripmap case. The timing is adjusted such that the time-varying elevation patterns repeat cyclically the imaging of multiple sub-swaths. In a processing approach, which yields a wide-swath SAR image, however, the azimuth resolution is decreased. If a better azimuth resolution is required, the Spotlight mode is utilized. Here the antenna pattern is steered in azimuth towards a fixed point to illuminate a given region as shown in Fig. 6(c). The long illumination

FIGURE 6. Illustration of different SAR operation modes which are used to increase the swath width (ScanSAR) or improve the azimuth resolution (Spotlight) compared to the Stripmap mode. (a) Stripmap. (b) ScanSAR. (c) Spotlight. Image from (Moreira et al., 2013).

The capabilities of the SAR imagery can be exploited by three main approaches: interferometry, polarimetry, and tomography. The interferometry is a powerful remote sensing technique that allows the estimation of deformation and subsidence as

well as deriving digital elevation models of wide areas. The principles of this technique, which is the one used in this work, are detailed in the following section. The polarimetry is a technique that allows obtaining quantitative information of land, snow, oceans and urban areas exploiting the different echo reflected by the scatterers at different polarizations as a result of the dielectric properties (Moreira et al., 2013). Lee and Pottier (2009) further explain the basics of polarimetry along with different applications. The polarimetric SAR interferometry (Pol-InSAR) takes advantage of interferograms acquired at different polarizations combining the principles of polarimetry and interferometry. It has been successfully applied to biosphere volume (Kumar et al., 2017; Mette et al., 2004) and snow depth calculations (Manickam et al., 2017; Oveisgharan and Zebker, 2007). The tomography aims at computing the vertical heights of scattering elements exploiting multiple images of the same area taken at different positions. It has been successfully applied to the estimation of biomass, ground topography under vegetation or to detect objects under foliage (Danisor et al., 2018; Tebaldini, 2010). Holographic tomography is the latest advance on this topic which allows obtaining 360° images of scatterers (Fornaro et al., 2012). Figure 1.7 illustrates the different techniques.

1.4.2 SAR Interferometry

SAR intensities are less stable than phase measurements (Wang et al., 2016). Therefore, in order to make the most of the SAR applications, the phase information has to be exploited. The ambiguity associated with the phase component of the SAR images makes it not very informative by itself. However, the difference of the phase component of different images taken in similar geometric conditions and at different times can be directly related to the change in range between the emitter and

FIGURE 1.7: SAR techniques that allow the exploitation of the satellite-based radar information.

the backscattering element. This is the principle of SAR interferometry (InSAR) (Hooper, 2014).

This principle can be exploited in order to obtain digital elevation models of the terrain. In the processing, two images, one usually considered as master and the other one as slave, with similar look direction over the same area can be combined to form an interferogram. The first step for the interferogram generation is the coregistration and resampling of the two images. It consists of a translation and a linear stretch, along with higher-order effects of the slave image in order that the pixels of both images refer to the same area. This step can be carried out in a pixel basis, if accurate satellite orbits and the topography are known, or by the correlation of the amplitudes of the different pixels. Once the coregistration is completed the slave image is resampled into the geometry of the master image interpolating the

amplitudes and phases of the slave images on the points of the master image.

Once the master and slave images have been coregistered and resampled, the interferogram can be generated multiplying, pixel by pixel, the master image by the conjugate of the coregistered slave image. In this line, the amplitude of the obtained interferogram is the multiplication of the amplitudes of the master and slave and the phase is the difference between master and slave. This phase difference can be expressed as the combination of the different sources that contribute to its value (Osmanoğlu et al., 2016):

$$\Delta\phi = \phi_{topo} + \phi_{orbit} + \phi_{def} + \phi_{atmos} + \phi_{noise} \quad (1.2)$$

where $\Delta\phi$ is the interferometric phase difference between master and slave images, ϕ_{topo} is the topographic contribution, ϕ_{orbit} is the contribution of the error of the orbit data, ϕ_{def} accounts for the ground deformation, ϕ_{atmos} is the atmospheric phase contribution and ϕ_{noise} is the noise term which is amplified in the interferogram generation. Depending on the specific application, the term of interest in equation 1.2 can be the topographic for the Digital Elevation Model (DEM) extraction or the deformation one for the deformation estimation.

The topographic contribution is given by:

$$\phi_{topo} = \frac{4\pi \cdot B_{\perp}}{\lambda \cdot R \cdot \sin(\theta)} \cdot \Delta z \quad (1.3)$$

where $B_{\perp}$ is the perpendicular baseline (Figure 1.8), R is the range distance, θ is the off-nadir angle and Δz is the scatterer height above the reference ellipsoid. An additional contribution has to be considered if in the processing a flat earth assumption is made, ϕ_{flat} which is given by:

$$\phi_{flat} = \frac{4\pi \cdot B_{\parallel}}{\lambda} \quad (1.4)$$

where $B_{\parallel}$ is the parallel baseline (Figure 1.8). This step is known as interferogram flattening. Equations 1.3 and 1.4 assume that there is no error in the satellite orbit. Therefore, any error in the orbit information is accounted in the phase orbit error component, ϕ_{orbit} .

The ground deformation contribution can be expressed as:

$$\phi_{def} = \frac{4\pi}{\lambda} \cdot R_{def} \quad (1.5)$$

where R_{def} is the ground deformation, being positive if the distance satellite-ground is increased. Note that the deformation contribution is usually referred to a point of the image for which the displacement is known or for which a stable behavior is assumed.

The atmospheric contribution can be divided into two sources, the tropospheric contribution, ϕ_{tropo} , and the ionospheric one, ϕ_{iono} :

$$\phi_{atmos} = \phi_{tropo} + \phi_{iono} \quad (1.6)$$

The tropospheric phase, also known as atmospheric phase screen (APS) is produced by the different atmospheric conditions at the acquisition times that lead to differences in the refractivity properties of the atmosphere. The tropospheric phase is usually divided into its wet and dry components. It can be either estimated in the processing or using external data or atmospheric models (Hanssen and Feijt, 1997;

[Zebker et al., 1997](#)). The general formulation of this contribution is given by:

$$\phi_{tropo} = \frac{4\pi}{\lambda} \cdot R_{tropo} \quad (1.7)$$

where R_{tropo} is the range deformation due to the tropospheric delay. Lower frequency radars, L-band and lower, are also affected by the different total electron content (TEC) of the ionosphere at the different acquisition times. The ionospheric contribution is given by [Wegmüller et al. \(2006\)](#):

$$\phi_{iono} = 1.69 \cdot 10^{-6} N \lambda \quad (1.8)$$

where N accounts for the number of electrons.

Finally, the phase noise ϕ_{noise} , which accounts for all the remaining uncorrelated phase differences, is usually linked to the local coherence γ . Being 1 the maximum coherence value, there are four different sources of decorrelation:

$$\gamma = 1 - (\delta_{spatial} + \delta_{Doppler} + \delta_{temporal} + \delta_{thermal}) \quad (1.9)$$

where $\delta_{spatial}$ is the spatial decorrelation linked with the horizontal position difference between two satellite acquisitions, $\delta_{Doppler}$ is Doppler centroid decorrelation produced by a different attitude at the acquisition time, $\delta_{temporal}$ the temporal decorrelation related with a change in the cell resolution between the acquisitions such as construction works or vegetation growth and, $\delta_{thermal}$ which accounts for the thermal noise.

InSAR techniques aiming at obtaining the digital elevations try to derive the height of the backscattering points from the topographic contribution. In this line, it is assumed that there is no deformation between acquisitions and, therefore, ϕ_{def} is

0. However, in order to obtain the actual height, the ambiguity associated with the phase component has to be solved. This process is known as phase unwrapping.

Many different unwrapping algorithms have been developed from the initial implementation of [Tribolet \(1977\)](#). These different implementations can be grouped into two different strategies ([Osmanoğlu et al., 2016](#)):

- Path following unwrapping algorithms: Starting from a reference point, for which the phase is known or assumed to be zero, a local unwrapping function is applied pixel by pixel. The path-following algorithms are usually based on sequential paths. The most common implementation is the Goldstein algorithm ([Goldstein et al., 1988](#)) which is the precursor of the branch-cut algorithms. This theory is based on the calculation of the residues introduced by local effects. When a sign change or a residue is detected a branch-cut is placed. Different methods can be applied to compute the residues and place the branch-cuts, some of which include the nearest neighbor, the initial proposal of [Goldstein et al. \(1988\)](#), and a later modification ([Cusack et al., 1995](#)), the minimum cost matching ([Buckland et al., 1995](#)), phase field direction ([Gutmann and Weber, 2000](#)) or the residual vector approach ([Karout et al., 2007](#)).
- Path-independent unwrapping algorithms: These algorithms exploit the fact that there should be a small misfit between the derivatives of two common SAR variables, the unwrapped data and the complex phase of the wrapped data. The most common implementation are the minimum L-p norm and the extended residue-cut algorithms based on network theory, such as the minimum cost flow algorithm ([Costantini, 1998](#)). A complete explanation of the mathematical formulation can be found in ([Ghiglia and Romero, 1996](#); [Ghiglia and Pritt, 1998](#)).

Apart from the DEM extraction, the interferogram information also allows estimating the deformation of ground assets between acquisitions by separating the contribution ϕ_{def} from all the contributions of equation 1.2. The topographic and orbital components can be removed applying an external DEM of the acquisition scene and using precise satellite orbits Prati et al. (2010). This originates the so-called differential InSAR (DInSAR) equation, whose principle is illustrated in Figure 1.8 and which can be written as:

$$\Delta\phi_d = \phi_{def} + \phi_{atmos} + \phi_{noise} = \frac{4\pi}{\lambda} \cdot R_{def} + \phi_{atmos} + \phi_{noise} \quad (1.10)$$

FIGURE 1.8: Illustration of the DInSAR concept.

where $\Delta\phi_d$ is the differential interferometric phase difference. It is computed from $\Delta\phi$ after removing the topographic component (See Figure 1.9). This equation shows that, in perfect conditions, i.e., neither decorrelation nor atmospheric errors,

the sensitivity of the DInSAR technique to measure deformations is limited by $\lambda/2$ given that it generates a deformation phase of 2π .

FIGURE 1.9: DInSAR phase generated with two SLC Envisat images over the Madrid area.

The actual capabilities of DInSAR technique are limited by the temporal and geometric decorrelation (Ferretti et al., 2001). The temporal decorrelation prevents from applying the technique to vegetated areas given that the vegetation growth deals with a dramatic decorrelation. In the same line, the geometric decorrelation sets a limit on the number of interferogram pairs that can be used in order to derive deformation estimations. On top of that, the APS, which has an inhomogeneous behaviour, compromises an accurate deformation estimation. The time series analysis techniques aim at easing this problem.

1.4.3 Time series Analysis algorithms

The time series analysis, also known as Multi-temporal InSAR (MT-InSAR), Advanced DInSAR (A-DInSAR) or PSI, aims at detecting the points that act as permanent scatterers for long periods of time (years) in a series of SAR images (more than 10) over the same area (Osmanoğlu et al., 2016). The Persistent Scatterers (PS) are points that correspond to the backscattering of the main element inside a resolution cell. Therefore, they are most likely smaller than the resolution cell. (Mohammed et al., 2014). These points maintain a coherent reflectivity even from different acquisition angles. Moreover, they are characteristic for not having a random decorrelation due to the temporal and geometric aspects and they can be used to carry out statistical analysis to separate the deformation component from the other sources. In this line, the atmospheric term is highly spatially correlated but uncorrelated with time. At the same time, the deformation term is highly correlated in time and it can be slightly spatially correlated (Prati et al., 2010). Finally, the residual topographic effect after the removal with an available DEM is correlated with the distance from the baseline. These different behaviors can be exploited in order to separate the deformation from the atmospheric and topographic terms. The LOS velocity can usually be estimated with an accuracy of 0.5 mm/yr with high signal to noise ratio if 30 images or more are available (Ferretti et al., 2001, 2007b; Osmanoğlu et al., 2016).

Three different strategies have been traditionally applied for the PS selection (Crosetto et al., 2008):

- *Amplitude Stability*: The selection is based on the standard deviation of the amplitude of the elements acting as scatterers. The points that have a low standard deviation are selected as PS. Note that this approach requires a big number of images (more than 20). For each pixel, the standard amplitude

deviation, σ_a , and the mean amplitude, μ_a , are computed and the Dispersion index, D_i , is derived as follows:

$$D_i = \frac{\sigma_a}{\mu_a} \quad (1.11)$$

Usually, points with a D_i less than 0.25 are selected as PS. This strategy has proved to be very effective in urban areas.

- *Interferometric Coherence*: This method, which is the most suitable when a reduced number of images is available, selects as PS the pixels whose interferometric coherence is bigger than a given threshold.
- *Spectral Coherence*: Keeping the full resolution of the SAR images the PS are selected from the analysis of the spectral coherence. It is only suitable for cases with a small number of images.

From this conceptual approach, four different categories of Time series algorithms can be identified ([Osmanoglu et al., 2016](#)):

- The so-called Persistent Scatterer Interferometry (PSInSAR) proposed by [Ferretti et al. \(2001\)](#). It was the first time series algorithm completed. The process implies the generation of the interferograms after the selection of a master image and the later removal of the topographic component with an external DEM. The master is usually selected as the image that leads to a minimum relative and temporal difference with the complete dataset (Figure [1.10](#)). Note that, until this point, it is the same procedure followed for the classic DInSAR. Then, a preliminary list of PS candidates is selected using usually the amplitude stability method. The network of identified PS is used to estimate a correction of the DEM and to estimate the deformation velocities. In this step, an unwrapping algorithm and a velocity model are applied.

A common assumption is to assume a linear deformation velocity. Then, the APS estimation process is performed in two steps. First, the master APS is computed using a low pass filter and Kriging interpolation since its contribution can be found in all the interferograms. After it is subtracted from all the interferogram pairs. The same procedure is followed on each interferogram pair to delete the APS from each acquisition. The process is illustrated in Figure 1.11. Small variations have been proposed to the initial implementations such as the Stable Point network (SPN) (Crosetto et al., 2008) and the Persistent Scatterer Pairs (PSP) (Costantini et al., 2008, 2011). Both of them are applied in this work.

- Although it is also a variation of the PSInSAR, the Standford Method for Persistent Scatterers (StaMPS) is usually cataloged as an independent time series implementation. It redefines the PS as the points with stable phase (Hooper et al., 2004). It applies the same amplitude dispersion as the PSInSAR for the initial selection of the PS but with a value of D_i of 0.4, on top of a densification algorithm that identifies new PS. It also includes a 3-D unwrapping method. As it has been previously mentioned, the open source strategy of this software is making this implementation the most applied one in recent years (Foumelis et al., 2018). The Coherence Pixel Technique (CPT) can be considered as a variation of both the PSInSAR and the StaMPS (Blanco-Sánchez et al., 2008; Siles et al., 2015).
- Small Baseline Subset (SBAS) algorithms (Berardino et al., 2002; Lanari et al., 2004) combine individually unwrapped interferograms and minimize the perpendicular, temporal and Doppler baselines (Hooper, 2008). The master-slave pairs are selected from the combinations whose estimated correlation is above a certain threshold, which should ensure that no isolated clusters are found. A minimum number of 5 images is required although in order to cope with

the correlation requirements this number can be increased up to 10. Common critical baselines include 1 year and 400 m for the temporal and perpendicular baselines (Osmanoğlu et al., 2016). All the images have to be coregistered to a single acquisition. In this frame, the topographic component can be removed. The atmospheric and orbital components are removed following the same procedure as in the PSInSAR. Different variations of the initial approach have been proposed such as the Small Temporal Baselines Subset (STBAS) which only uses image pairs with short temporal baselines (Hong et al., 2010). This is of great interest to investigate highly variable deformations. SBAS technique is not suitable to detect local deformation phenomena (Crosetto et al., 2016).

- *SqueeSARTM* is indeed an update of the PSInSAR method in such that it exploits the information of not only the PS but also of the distributed scatterers (Ferretti et al., 2011). It is of great interest for rural applications where the traditional PSInSAR technique does not provide a high-density network of PS.

The common outputs of a time series analysis include (Armas et al., 2017) a georeferenced map of the PS distributions with the estimated LOS velocity (Figure 1.12) and the deformation time series, the APS correction of every image, the measurement precision for both the displacement and velocity, the height correction over the input DEM and the cumulative displacement.

As it has been previously mentioned, the different PSI techniques can achieve an accuracy of up to 0.5 mm/yr and 1 mm in the LOS deformation time series (Ferretti et al., 2001, 2007b; Osmanoğlu et al., 2016) under optimal conditions. The optimal conditions of each algorithm are application dependent. Different works have

FIGURE 1.10: Perpendicular and temporal baselines of the SLC images. The optimal master of the dataset is highlighted.

been carried out that compare the results of the different time series implementations under the same conditions. Some examples include the work of [Osmanoğlu et al. \(2016\)](#) that qualitatively compare all the time series implementations and a high-level quantitative comparison of STaMPS, PSInSAR, SqueeSAR, and SBAS algorithms. [Gheorghe and Armas \(2016\)](#) compare the SBAS and PSInSAR implementations in the area of Bucharest and [Mirzaee et al. \(2017\)](#) compare the PSI, SBAS and SqueeSAR methods. Moreover, in recent years, different validation works have been carried out although the capabilities of the technique are far from being standardized. This problem will be addressed in Chapter 3.

FIGURE 1.11: PSInSAR dataflow process.

FIGURE 1.12: LOS deformation velocity in the area of Madrid derived from a Sentinel-1 PSI processing.

CHAPTER 2

SAR SENSORS

BENCHMARKING.

APPLICABILITY OF SAR

DATA ARCHIVES TO

HISTORICAL DEFORMATION

This chapter is divided into two sections. The first one analyses the evolution of the SAR urban monitoring presenting a benchmarking of the available historical SAR data for the monitoring of ground civil structures. The possibility of exploiting the historical data archive of SAR data is assessed. The second section aims at showing a concept proof of the applications of the exploitation of historical datasets over the same area.

2.1 Evolution of urban monitoring with radar interferometry in Madrid City: performance of ERS-1/ERS-2, ENVISAT, COSMO-SkyMed, and Sentinel-1 products

The content of this chapter has been published in the following journal article:

Adrián Jesús García, Matus Bakon, Rubén Martínez & Miguel Marchamalo (2018) Evolution of urban monitoring with radar interferometry in Madrid City: performance of ERS-1/ERS-2, ENVISAT, COSMO-SkyMed, and Sentinel-1 products, *International Journal of Remote Sensing*, 39:9, 2969-2990, DOI: <https://www.doi.org/10.1080/01431161.2018.1437299>.

2.1.1 Abstract

During the last decades, synthetic aperture radar image exploitation has matured with the launch of different satellite missions and the development of different techniques which allow exploiting the capabilities of the radar images. Among these techniques, Persistent Scatterer Interferometry (PSI) has proven to be a powerful tool to derive terrain deformations over urban areas. It is based on the use of a large number of images over wide areas in order to obtain terrain displacements time series. The imagery from the different Synthetic Aperture Radar (SAR) missions has led to an archive with data that covers up to 30 years in the past. Moreover, different methods and algorithms have been proposed in order to perform this complex task. In this line, this work aims at identifying if data from different missions and processed by different techniques can be combined in order to study the evolution

of urban monitoring. Three different PSI techniques are used in order to process data from four SAR missions: ERS-1/2, Envisat, COSMO-SkyMed and the recent Sentinel-1 A/B. The rapidly evolving urban area of Madrid, where numerous underground works have been carried out in the last decade, has been chosen as the testing environment. The density of persistent scatterers, the deformation accuracy validated with Global Positioning System (GPS) displacements and deformation trends are used as the key performance items for the assessment.

2.1.2 Introduction

Synthetic Aperture Radar (SAR) has become one of the most powerful tools for remote sensing. The processing of the imagery provided by the SAR sensors allows the unique capability of identifying deformations and displacements with a high resolution over wide areas. This makes it suitable for the analysis of subsidence ([Bakon et al., 2016a,b](#); [Sillerico et al., 2015](#); [Sousa et al., 2010](#); [Tofani et al., 2013](#)), earthquakes ([Massonnet et al., 1993](#)), volcanic phenomena ([Ferretti and Rocca, 1999](#)), topography definition ([Zebker and Goldstein, 1986](#)), crop control ([Kussul et al., 2014](#)), cultural applications such as archaeological prospection ([Lasaponara and Masini, 2013](#))([Lasaponara & Masini 2013](#)) and many other civil and military uses. Although continuous real time applications are not feasible due to the characteristic revisiting time of the satellites over the same region, near real time applications can be considered such as construction monitoring or early warning systems ([Intrieri et al., 2015](#)).

The state of the art of SAR applications is the usage of persistent scatterers (PS) Interferometric (PSI) algorithms, which have evolved from the original approach proposed by [Ferretti et al. \(2001\)](#) to a wide range of approaches. The different techniques have been carefully reviewed ([Crosetto et al., 2016](#); [Mohammed et al.,](#)

2014; [Osmanoğlu et al., 2016](#)) and their performances have been compared ([Gheorghe and Armas, 2016](#); [Sabater et al., 2011](#); [Sousa et al., 2011](#)) in recent works. A common statement to all the applications is that the sensitivity of the sensors to measure ground displacements depends on the sensor's wavelength. Moreover, the frequency band determines the penetrability of the SAR sensors ([Palmann et al., 2008](#)). In this way, theoretically, X-band sensors with a wavelength of 3.0 cm, almost half of the wavelength of C-band (5.4 cm) and 8 times lower than L-band (24.0 cm), presents a higher resolution. This higher resolution may reduce the number of scenes required in order to acquire reliable estimates of the rate displacements of the scatterer points ([Prati et al., 2010](#)). However, the temporal analysis may be negatively affected by the shorter wavelength when dealing with high rate displacements ([Gatelli et al., 1994](#)). X-band missions reduce this effect with a higher revisiting time being up to 4 days for a full operational COSMO-SkyMed (CSK) constellation ([Covello et al., 2009](#)) and up to 11 days for the German TerraSAR-X against the 35 days revisiting time of ERS-1, ERS-2 and Envisat missions. This enhanced revisiting time along with the reduced number of required scenes provide new opportunities and possibilities such as early warning systems with reduced latency or the detection of deformations without requiring long temporal baselines. The higher revisiting time of C-band Sentinel-1 mission, comparable to those of the X-band missions, represents a new era in the C-band sensors and has motivated different works aiming at assessing the performances of this new mission ([Bovenga et al., 2010, 2013](#); [Herrera et al., 2011](#); [Kouamé et al., 2006](#); [Notti et al., 2015](#); [Prati et al., 2010](#)).

Not only do the aforementioned different missions and frequency bands affect the performances of the PS processes. Their outputs are also determined by the geometrical considerations of the area of interest, such as the angle of incidence, the

acquisition position, the land use along with the PS algorithm selected and the configuration of the process (i.e., time baseline, the number of scenes, Doppler centroid offset).

This rapidly evolving SAR environment has led to a wide data archive which covers up to 30 years with radar information from sensors with different characteristics and whose potential capability for each specific application has to be known prior to using them. This work aims at providing an assessment of the applicability of different sensors to the monitoring of ground displacements over long periods of time and by exploiting different sensors, geometries, and algorithms. Data from 3 different missions which are the natural evolution of the C band sensors: ERS-1/2, Envisat, and Sentinel-1 along with a representative sensor from X-band, CSK, are used in this work for a historical assessment that covers up to 25 years. Moreover, the performance of two different PS algorithms: Stable Point Network (SPN) and Persistent Scatterer Pairs (PSP) and the possibility of combining its results in order to obtain better results are analysed. The validation of the datasets has been carried out with Guidance and Navigation Systems (GNSS) data.

2.1.2.1 Related work

Over the last decade, different works have taken advantage of the combined exploitation of ERS and Envisat imagery in order to monitor ground subsidence and landslides over periods of time covering the operative time of both SAR missions. These works represent the first attempt to exploit the data of different missions in order to carry out assessments over long periods of time. Some examples include the work of [Crosetto et al. \(2008\)](#), who exploited ERS and Envisat datasets to obtain a joint estimation of the deformation in the area of Barcelona, the work of [Tofani et al. \(2013\)](#), who combined the use of ERS and Envisat sensors with both

ascending and descending geometries for the assessment of the landslide problem, the work of [Del Ventisette et al. \(2013\)](#), who exploited all the potential of ERS and Envisat long term datasets to assess the ground deformation problem in different areas, and, a recent work by [Luca et al. \(2016\)](#), who combined imagery of ERS and Envisat with different acquisitions in order to carry out a historical analysis over Ebro Delta.

A step forward in the use of the long term data archive of different SAR missions was carried out by [Ciampalini et al. \(2014\)](#), who addressed the landslide problem over long periods using imagery of bands C and X, not for comparison purposes but to fill any spatial and temporal gaps of a single dataset. In the same line, [Pepe et al. \(2016\)](#) combined the data of ERS, Envisat and CSK missions to monitor ocean reclaimed areas, in this case exploiting Small BAseline Subset (SBAS) technique.

Nevertheless, none of these works introduce the recently launched Sentinel-1 missions, whose applicability to multi sensor historical studies would extend the data archive to the active period of Sentinel-1 mission. Moreover, no multi sensor evolution study has yet been reported that applies this technique to an urban environment and that addresses its applicability to a specific construction work. In addition, it will be shown that an historical evolution of the deformations can be obtained regardless of the algorithms used in the processing and the combination of outputs from different algorithms processing will be assessed. In this line, this work aims at answering these questions, combining data from X and C band missions, including Sentinel-1, and proving the applicability to urban areas and assessing the applicability to the M-30 underground works using different algorithms and imagery from different sensors.

2.1.3 Material and methods

2.1.3.1 Area of study and rationale

The area of interest of this study is located in Madrid and defined by the availability of different datasets. During the last two decades, important works have shaped Madrid such as the tunneling of railroad tracks and roads and metro's expansion. It is of special interest the M-30 Street case, undergrounded with twin tunnels, in the framework of the "Madrid Rio Park" project aiming at transforming an area of 1,210,881 m^2 into a linear park. Therefore, Madrid represents the perfect time evolving scenario in order to assess the SAR sensing capabilities. Figure 2.1 presents the area of the study with the available GNSS stations in blue squares, which will be used for validation purposes. The definition of the land uses provided within the Corine land cover project ([European Environment Agency, 2007](#)) will be used as a reference in order to study the applicability of the conclusions to the different land uses.

The different datasets, which cover the same area for a period of around 25 years, provide the inputs required to assess the possibility of using data from different sensors, taken with different geometry conditions and processed by different algorithms, in the study of subsidence over long periods of time.

The applicability of data from different sensors to historical deformation studies can be measured in terms of the possibility of the identification of the same PS in the area of interest within the different datasets, by applying a resample approach if required, and in terms of the accuracy of the estimated displacement. In this work, the first one will be addressed by computing the PS density over different land uses and the second one will be assessed by two means: the comparison of the results

FIGURE 2.1: Area of interest of the study. The location of the validation GNSS stations is marked with blue squares.

against Global Positioning System (GPS) reference stations and by evaluating the results in the area of the M-30 works.

2.1.3.2 Satellite datasets

For this paper, five different SAR datasets of the Madrid area, previously processed by different means, have been used. These datasets are distributed over 4 different SAR sensors: ERS-1/2, Envisat, CSK and Sentinel-1 A/B and two different frequency bands: C and X. Figure 2.2 (a) – (e) includes the processed areas of the different datasets. The characteristics of the different processes are depicted hereinafter following the labeling of Figure 2.2 (a) – (e):

FIGURE 2.2: Coverage map of the different datasets used in this work. (a) CSK, (b) ENVISAT (SPN), (c) ENVISAT (PSP), (d) ERS-1/2, and (e) Sentinel-1 A/B.

- COSMO-SkyMed: 28 images of 40 x 40 km from May 2011 to January 2012 taken with horizontal transmit and horizontal receive (HH) polarization were processed using the PSP technique ([Costantini et al., 2008](#)). The digital elevation model (DEM) of the Shuttle Radar Topography Mission (SRTM) has been used to remove topographic effects. Images were taken using a left looking mode over a descending orbit. A perpendicular baseline of 168 m, a temporal baseline of 224 days and a maximum relative doppler centroid difference of 250 Hz were used in the processing of the interferometric pairs. The processed area is shown in Figure 2.2 (a).
- Envisat. The first Envisat dataset contains 26 images from the Advanced Synthetic Aperture Radar (ASAR) Image Mode (IM) taken with vertical transmit and vertical receive (VV) polarization. It covers from August 2003 until April 2008 ([Sillerico et al., 2015](#)). SPN algorithm was used for the PS generation being the pixel selection based on the Amplitude stability ([Crosetto et al., 2008](#)). In the elaboration of the interferometric pairs, a perpendicular baseline of 800 m, a temporal baseline of 3 years and a Doppler Centroid difference of 400 Hz were used. The DEM of the SRTM has been used to remove topographic effects. The processed area is shown in Figure 2.2 (b).
- Envisat. The second Envisat dataset contains the same 26 images taken in the IM with VV polarization and also covering from August 2003 to April 2008. The PSP technique was used in the processing. Interferograms were generated from pairs of SAR images with a perpendicular spatial baseline smaller than 800 m, a temporal baseline shorter than 3 years and a relative doppler centroid difference below 400 Hz, for both analyzed periods. The DEM of the SRTM has also been used to remove topographic effects ([Ezquerro et al., 2014](#)). The processed area is shown in Figure 2.2 (c).

- ERS. This dataset has been processed using the same approach as in the previous one: PSP, a perpendicular baseline of 1198 m, a temporal baseline of 2089 days and a doppler centroid difference of 321 Hz. In this case, 50 images taken in the IM and with a VV polarization were processed covering from April 1992 to November 2000. In addition, as in the previous dataset, SRTM has been used to remove topographic effects ([Ezquerro et al., 2014](#)). The processed area is shown in Figure 2.2 (d).
- Sentinel-1 A/B. This dataset contains 88 Interferometric Wide Swath (IW) Single Look Complex (SLC) images with single VV polarization covering from November 2014 until May 2017. These images were processed using a classical PSInSAR methodology ([Ferretti et al., 2001](#)) with a perpendicular baseline of 140 m, a temporal baseline of 548 days and a Doppler centroid difference of 60 Hz. The DEM of the SRTM has been used to remove topographic effects ([Bakon et al., 2016a](#)). The processed area is shown in Figure 2.2 (e).

The radar information from the different datasets and processing modes has been summarized in Table 2.1 and it is extended in [APPENDIX C](#).

2.1.3.3 Analyses description

Two different analyses have been carried out. The first one implies the evolution of sensors and the applicability of their imagery to a historical assessment. The second one aims at investigating if datasets processed by different algorithms can be used together for the deformation estimation. Hereinafter, the methods to carry out both analyses are detailed.

Analysis 1: Historical deformation through the evolution of sensors imagery The data from the different C-band sensors and the X-band CSK mission

SAR mission	Time coverage	Number of images	Orbit type and acquisition looking position	Processing algorithm
ERS 1/2	April 1992 - November 2000	50	Descending - Left	PSP
Envisat	August 2003 - April 2008	26	Ascending - Right	SPN
Envisat	August 2003 - April 2008	26	Ascending - Right	PSP
CSK	May 2011 - Jan. 2012	28	Descending - Left	PSP
Sentinel-1 A/B	November 2014 - May 2017	88	Ascending - Left	PS InSAR

TABLE 2.1: Summary of the characteristics of the 5 SAR datasets used in this work.

allows assessing the feasibility of using datasets from different bands and technologies in the continuous analysis of ground subsidence over time in urban areas. This implies using data from sensors that belong to different technological levels and assessing if the combination of data from different sensors can fill the temporal or spatial gaps of a single dataset.

The different datasets have been processed with slightly different coherence thresholds adapted to the specific dataset conditions and processing algorithm aiming at making the most of each specific dataset. This allows assessing the possibility of combining all of them in the evolutionary assessment of land subsidence under the best conditions. A post processing step has been conducted selecting for all the datasets only the points with a coherence over 0.8, which is the maximum selected coherence threshold for one of the datasets.

The continuous monitoring over long periods of time coping with the evolution of

sensors has been determined by identifying the PS density in the area of interest and by assessing the accuracy of the cumulative deformation estimation combining the use of the different datasets on a set of validation points.

Analysis 2: Historical deformation using different algorithms The Envisat datasets, which were processed over a common area of interest, with the same scenes, and with the same parameter configuration, allow the assessment of the evolution of two algorithms which use different network strategies: a multi master approach, used by SPN and a single master approach used by the PSP ([Osmanoğlu et al., 2016](#)). First of all, the SPN technique ([Crosetto et al., 2008](#); [Duro et al., 2005](#)) provides three methods for the pixel selection depending on how the high stable points are obtained: the amplitude stability, interferometric coherence, and spectral coherence. The amplitude stability, the method used in this work, is based on the availability of a high number of scenes and takes advantage of the amplitude stability of the points in order to perform the pixel selection. Regarding the image processing, SPN differs from the original PS techniques in the fact that it does not define a common master image but it considers different masters which leads to smaller baselines, reducing the decorrelation. Note that this approach is similar to SBAS ([Berardino et al., 2002](#)) with the advantage that exploiting PS makes it less sensitive to geometric correlation. Using as observables the Differential Interferometry SAR (DInSAR) phase of the N number of images, the SPN technique is able to estimate the deformation component, the residual topography and the atmospheric artifacts. A linear deformation is assumed for phase unwrapping. The capabilities of this algorithm have been exploited in different applications: ([Crosetto et al., 2008](#); [Duro et al., 2010](#); [Sillerico et al., 2015](#)).

The PSP method was proposed by [Costantini et al. \(2008\)](#). It is an iterative approach that takes advantage of the information of nearby points connected by arcs

in order to identify PS. An important advantage, which overcomes the capabilities of other techniques, is the fact that deformations do not necessarily need to be assumed as linear. In addition, it does not require a preprocessing step to calibrate the data. PS in natural areas can be obtained and, despite its iterative approach, it is computationally efficient and parallelization is a possibility. However, the algorithm is sensitive to the selection of the initial seed from which the different arcs are iteratively computed. This initial seed must be highly stable points and they have to be well distributed in order to avoid uncovered areas due to a great distance from the initial points. The capabilities of this method have been exploited in different applications: (Costantini et al., 2011; Daraio et al., 2014; Ezquerro et al., 2014; Zhantayev et al., 2014).

In this case, since both datasets have been processed with the same parameters, the points do not need to be filtered to a common coherence threshold for the assessment. Two different assessments have been carried out for the algorithms evolution. First of all, the PS density has been computed in order to assess the identification of PS over the same area of interest and, then, a specific assessment of the performance of both algorithms in the same conditions has been addressed using the M-30 works as verification environment. The feasibility of combining the outputs from both algorithms has also been investigated.

2.1.4 Results and discussion

2.1.4.1 Dataset validation

GNSS measurements of five stations distributed over the area of Madrid, Figure 2.1, were used in order to validate the deformations estimated by the different datasets. The positions of the different stations are routinely computed by the

Nevada Geodetic Laboratory using the Jet Propulsion Laboratory's (JPL's) final orbit and clock products and are made publicly available on their website. These positions, computed on a 24 hours basis, have been used in order to derive the reference deformation time series of the stations.

Due to the reduced spatial resolution and the poor georeferencing accuracy, it is usually difficult to identify the objects that geospatially represent the PS ([Tofani et al., 2013](#)). In addition, the PS output of different SAR processes rarely match those obtained from other analyses or the validation points from which deformation information is available from other sources of information. However, different strategies can be applied in order to overcome this issue. Common approaches are resampling, interpolating or buffering the data from the available PS close to a certain area or a point of interest. These workarounds have been exploited by [Tofani et al. \(2013\)](#) who proposed to resample the PS over a 50 m grid and [Wang et al. \(2015\)](#) who introduced a new approach combining Interferometric SAR and the displacement gradient tensor (InSAR-DGT) to obtain the deformations at a given validation point using a circular area around the point of interest and weighing the deformations of the surrounding points of interest based on their statistics. An interpolation scheme is proposed by [Fuhrmann et al. \(2015\)](#) by exploiting the Ordinary Kriging algorithm and fitting a semivariogram function. A step forward was proposed by [Perissin and Ferretti \(2007\)](#) and [Guccione et al. \(2014\)](#) who showed that the characteristics of the backscattering objects can be inferred from the PS which could be used for the identification of roofs.

A weighting scheme is proposed in this work where the PS close to the receiver antenna are used in order to infer the deformation of the point of interest. The points inside a circular area of 50 m around the validation point will be weighed by its coherence threshold in order to give a bigger weight to the deformations that

correspond to higher coherent scatterers. This approach is also reinforced by the fact that the selected GNSS stations, some of which are included in the Regional Reference Frame Sub-Commission for Europe (EUREF) network, are located in high stable areas, which reduces the interference of outliers introduced by punctual behaviours in the selected grid. Note that the selected area of 50 m approximately represents a few cells for C-band sensors and almost 10 resolution cells for X-band. The same value has been used in both bands in order to ensure that potentially the same persistent targets contribute in all the sensors to the final deformation value of the point of interest. Figure 2.3 contains a sketch with the definition of the area of interest of a validation point for IGNE GNSS station.

FIGURE 2.3: Circular buffer considered around IGNE station for the deformation estimation.

SAR displacements are computed over the satellite-PS line of sight (LOS). Taking into account the SAR geometry described in Figure 2.4, the LOS displacement as a function of East, North and Vertical displacements can be written as (Diao et al.,

2016; Fialko et al., 2001):

$$d = [n\sin(\theta) - e\cos(\theta)]\sin(\alpha) + u\cos(\alpha) \quad (2.1)$$

where d is the displacement in the LOS, n , e and u are the North, East, and vertical displacements respectively, α , is the LOS incidence angle and θ represents the satellite's heading angle (Figure 2.4). Note that a right looking acquisition has been assumed. The left looking formulation can be straightaway derived from the previous formulation (Ng et al., 2011).

FIGURE 2.4: SAR geometry.

At least three independent measurements are required in order to solve the three dimensions displacement vector. As it will be further explained in the following

section, under the assumption of a greater vertical displacement, horizontal displacements can be neglected and the LOS deformation can be directly related to the vertical movement. This, however, cannot be applied to these reference points. Nevertheless, taking advantage of the fact that actual GNSS displacements are known, the horizontal component projected over the LOS can be removed from each PS temporal displacement in order to obtain the vertical displacements. Note that this can be done without influencing the PSI vertical displacement estimation due to the fact that GNSS horizontal and vertical displacements are not correlated. In this line, from Equation 2.1:

$$u = (d - [n\sin(\theta) - e\cos(\theta)]\sin(\alpha))/\cos(\alpha) \quad (2.2)$$

Figures 2.5(a) - (e) contain the historical evolution of the 5 GNSS stations with the PSI displacement estimations of the different datasets. The estimated GNSS and PS trends have also been included. Note that since all the deformations of the PS processes are related to the reference epoch, the deformation corresponding to this image has been corrected adding the respective deformation predicted by the GNSS deformation model. A common assumption made in the GNSS community is the consideration of linear velocities, whose parameters are regularly reviewed by different Analysis Centres such as the International GNSS Service (IGS). However, linear trends fail in the estimation of long periods of time such as the ones considered here. In this line, second order polynomial fits have been considered here.

In the periods of time where a direct comparison between the PS and GNSS estimation can be carried out a great agreement can be observed. It is of special interest the assessment of the results of 3CAN, Figure 2.5 (a) and IGNE, Figure 2.5 (b). In both cases, the GNSS best fit is a linear trend. However, a change in the deformation trend can be observed in the GNSS estimation around the end of

FIGURE 2.5: PS and GNSS estimated cumulative vertical displacement for the validation GPS stations. (a) 3CAN, (b) IGNE, (c) LEGA , (d) MER2, (e) VILL.

2010 although due to the reduced number of points before this date there is no appreciable impact on the estimated trend. On the contrary, the PS estimations of ERS and Envisat prior to 2010 provide the data required for the proper modelling of the station's deformation.

The apparent difference in the polynomic trend of GNSS and PS estimations for VILL station, Figure 2.5 (e), can be explained by the fact that only two datasets cover this station and it is not due to a deviation of the PS estimation which, as it can be checked, matches the GNSS measurements. The GNSS and PS estimated deformations trends of LEGA, Figure 2.5 (c), and MER2, Figure 2.5 (d), stations are in line.

Therefore, it is confirmed that the historical deformation history can be accurately modelled by combining data from different sensors and even from different frequency bands.

2.1.4.2 Analysis 1: Historical deformation through the evolution of sensors imagery

The PS density distributed over the Corine Label 1 Classes of the area of interest (Figure 2.1) has been calculated and the results have been included in Figure 2.6. First of all, it can be seen that artificial land uses are those that provide a higher PS density (Usai, 2000) contrary to water bodies, where no PS can be found (Palmann et al., 2008). Moreover, CSK density is between 10-20 times bigger than in C-band sensors due to the X-band higher resolution and revisiting time, which is in line with previous studies in related works (Bovenga et al., 2012; Prati et al., 2010; Sansosti et al., 2014). It is worth mentioning that this higher density is also found in Forest and semi natural areas where the lower penetrability of X-band frequency may have initially led to a lower PS density due to the decorrelation caused by rapid changes

affecting the vegetation such as the orientation of leaves and the growth of small branches. However, the reduced revisiting time overcomes this initial drawback. Therefore, the applicability of data from different sensors to historical analysis is spatially limited by the lower resolution band used in the analysis.

FIGURE 2.6: PS density of the different missions for Corine Label 1 Classes.

In Figure 2.7 the PS density for Corine Label 2 Classes has been represented for the C-band sensors considered in this work. Note that this more specific classification allows the assessment of the PS densities over the different land uses of the city of Madrid and its surroundings. Envisat is the natural evolution of ERS mission, as well as Sentinel-1, is the natural evolution of Envisat. In this regard, the potential performance of the C-band sensors has been increased along with the evolution of the missions. Nevertheless, there are numerous factors surrounding the PS processing such as the relative satellite-target geometrical conditions, processing algorithms

or coherence thresholds that determine the actual achievable performances of the different sensors.

In this specific case of study, ERS PS density is lower than in the other C-band missions due to the longer temporal baseline and the effect produced by the problem detected on ERS-2 gyroscopes on 7 February 2000 which led to a problem in the attitude control (Fernandez et al., 1999; Meadows and Rosich, 2002). The slightly lower PS density of Sentinel-1 and Envisat PSP dataset is mainly due to the different algorithms used in the processing as well as the different acquisition geometry of the datasets.

For the purpose of this study, a threshold to the spatial applicability of different sensors to historical analysis can be defined. In this line, assuming the combination of datasets with different geometries and processed by different means, it can be set that for high stable areas a density of at least 2 P/ha are required in order to have enough PS to cover a circular area of 50 m radius with at least two PS. Note that two points have been selected as a threshold in order to have the average of at least these two points and reduce the effect of possible outliers. This represents a minimum threshold which allows a general coverage of an area of interest but the distribution of PS and the applicability to each specific application has to be analysed.

Therefore, taking into account the defined minimum threshold, the applicability of different sensors to the study of historical subsidence over a given area can only be applied to urban fabric and Industrial, communication, and transport land uses, as it is derived from Figure 2.7.

FIGURE 2.7: PS density of the C-band missions for Corine Label 2 Classes.

2.1.4.3 Analysis 2: Historical deformation using different algorithms

The PS density distributed over the Corine Label 2 Classes of PSP and SPN has been included in Figure 2.8. Both datasets have been processed using the same images, configuration, including the same coherence threshold, but with two different algorithms. Unlike in the previous analysis, where only the points with a coherence over 0.8 were selected, in this case, all the PS output of the algorithms have been used. This aims at providing a higher PS density for the study of the M-30 works where a smaller buffer will be used.

The results show that the number of PS provided by the dataset processed by SPN is higher than the obtained with PSP, mainly in the urban fabric land use. The multi master approach of SPN reduces the baselines of the interferometric products which reduces the decorrelation. Moreover, PSP final PS density depends on the

FIGURE 2.8: PS density of Envisat datasets for Corine Label 2 Classes.

initial seed which has been selected in order to maximize the trade-off between PS density and accuracy of the deformations obtained.

From the point of view of the applicability of these datasets to the historical monitoring of ground subsidence and, taking into account the spatial threshold of 2 PS/ha defined in this work, a priori both algorithms can be used in stable Urban fabric and Industrial Communications and transport areas but the applicability is limited to the remaining areas. Nevertheless, as it will be analysed in the M-30 case study, the higher density of SPN in urban areas represents a clear advantage in applications where the area of interest does not have a clear homogeneous behaviour as it is the case of underground works.

The different PS algorithms are designed aiming at optimizing a particular application or under specific conditions. In this regard, it is of interest addressing if

the results of different algorithms can be combined in the identification of ground subsidence aiming at making the most of their specific advantages. The M-30 works have been used in order to derive the benefits and drawbacks of this approach.

Case study: M-30 Different underground works have been carried out in recent years in the area of Madrid. It is of special interest the works performed in M-30 Street aiming at building an underground ring. The M-30 works were carried out between 2004 and 2007 and it implied the construction of two unidirectional three-way tunnels, which will be identified as North and South tunnel. North tunnel works were carried out from November 2005 to July 2006 and South tunnel works were conducted between February 2006 and October 2006 using two tunnelling machines. Figure 2.9 shows a sketch of the aforementioned tunnels. For further details of the construction works refer to [Sillerico et al. \(2015\)](#).

FIGURE 2.9: M-30 working area. The M-30 tunnels and metro lines are presented. The sector of interest is highlighted in blue.

This scenario has been used in order to further assess the performance of the two considered algorithms. First of all, the number of PS over the working area for both algorithms is 3221 for SPN and 1631 for PSP. Note that the relation, around 2:1, is in line with the results in Figure 8 for the complete area of interest.

The M-30 working area covers a longitudinal area of 4280 m in the southern tunnel and 3650 m in the northern tunnel (Figure 2.9). The tunnels have been included in green straight lines. The longitudinal working area has been divided into 12 different sectors. It is of special interest the analysis of sector 5, highlighted in blue in Figure 2.9, given that the geometry conditions provide a higher number of PS in this sector. The Metro lines have been included in red color.

The vertical displacements obtained in the transversal direction to the tunnel have been analyzed. In order to average the results, the transversal section has been divided into sections of 7.5 m. Note that this buffer value is the same used in previous studies assessing the M-30 works, (Sillerico et al., 2015), since it provides the resolution required for the identification of the transversal deformation rate. For each buffer, the average subsidence of each sector is computed. Note that, according to Equation 2.1 and, as it has been previously mentioned, the determination of the vertical displacements requires at least 3 independent measurements. However, a common approach performed in the assessment of underground works or mining activities is to assume that horizontal displacements can be neglected when compared to vertical displacements, (Ng et al., 2011). Taking this assumption in Equation 2.1 the vertical displacements are given by:

$$u = d/\cos(\alpha) \quad (2.3)$$

The results have been included in Figure 2.10, where the subsidence derived from the

PSP and SPN datasets have been represented along with the subsidence computed by the combination of both datasets weighing the different points by their coherence. The theoretical curve has also been added to the assessment of the results. The displacement of the north tunnel is correctly modelled by both algorithms and, as a consequence, also by the combined solution. However, the South tunnel is not correctly modelled by neither the PSP algorithm nor the combined solution. This can be explained by the reduced number of PS provided by the PSP algorithm, which is especially noticeable in the area between the two tunnels where only 2 PS are available, as presented in Figure 2.11.

FIGURE 2.10: Estimated transversal subsidence of sector 5 of M-30 works. The deformation derived from the combination of both datasets is also included along with a sketch of the twin tunnels and the theoretical deformation.

It is important to note that non symmetrical deformations have been obtained. This is explained by the fact that both tunnels have not been built at the same time and also by the fact that two metro lines cross close to the south tunnel.

FIGURE 2.11: PS distribution of Envisat datasets over the area of interest.

The aforementioned analysis shows that the advantage of combining the outputs of both datasets is the increased density which allows filling the spatial gaps of using one single dataset. However, the analysis of the results of the south tunnel also provides an example of the main problem derived from the combination, which is the possible contamination of one of the datasets. In this regard, it can be stated that the combination of data processed by different means is of great interest but its application has to be carefully considered. A possible approach to overcome this drawback motivated by the increased density is the application of an outliers filter.

2.1.5 Conclusions and future work

In this study over the Madrid urban area, an assessment of the possibility of combining data from different SAR missions for studies of the evolution of ground

subsidence in urban areas has been conducted. Five different datasets containing data from Envisat, ERS-1/2, Sentinel-1A/B and CSK sensors have allowed assessing the evolution of urban deformation covering a period up to 25 years over the area of Madrid.

Two different conditions have been identified as key elements for the applicability of datasets taken with different sensors and acquisition geometries and/or processed with different algorithms: the possibility of modelling the deformation over the same area, which can be measured by the PS density and the quality of the measured deformations, which can be assessed by different techniques.

An approach to overcome the difficulty of identifying the same exact points in different datasets due to the anisotropy of the scatterers has been proposed. It implies using an area of 50 m around the point of interest and weighing the contribution of the different PS inside the area. Taking this approach into account a threshold of $2\ PSha^{-1}$ has been defined as the minimum density of PS over a stable area in order to be able to use a dataset for the assessment of the evolution of the subsidence.

The validation of the deformations measured by the different datasets has been carried out using the GPS deformations of different stations distributed over Madrid. The combined use of the different datasets for the evolution of the deformation provides a great agreement with respect to the GNSS stations.

In addition, the case study of the M-30 works has been used in order to assess the possibility of combining data from different algorithms processing the exact same imagery. The PS inside longitudinal buffers 7.5 m width parallel to the M-30 tunnel axis have been used in order to assess the subsidence effect of the M-30 underground works. SPN and PSP algorithms have been used in the processing. The combined solution of both algorithms has been worsened by the fact that the low density of PS in the PSP datasets has led to an error in the deformation estimation.

The heterogeneous datasets used in this study, in terms of sensors, acquisition geometries and processing algorithm prove that historical assessments can be conducted using any imagery available and processed by any algorithm.

In this work different future investigation lines have been opened. A performance index per dataset measuring the applicability of datasets to historical assessment, able to weight the different parameters assessed in this work, could be defined considering more datasets from different missions and for different areas of interest. The definition of this performance index could follow the recent research by [Notti et al. \(2015\)](#). Secondly, the availability of data from different sensors in the same period opens the possibility of post processing and combining the PSI results obtained from them as it has been proposed by [Tofani et al. \(2013\)](#) for ERS and Envisat sensors, in order to fill any spatial gap. Moreover, the increased PS density derived from the combination motivates future assessments of different outlier filters.

The increasing availability of series of 3D SAR displacements over large urban areas as Madrid, ([Fialko et al., 2001](#); [Hu et al., 2010](#); [Wang et al., 2015](#)), opens a wide range of monitoring and control applications. Post processing techniques, such as the proposed by [Bakon et al. \(2017\)](#), which represent an interesting approach in order to enhance the accuracy of the datasets, should also be combined with the evolution assessment of ground subsidence.

2.2 Historical monitoring of urban subsidence based on long-term SAR data archives

The content of this chapter has been published in the following journal article:

Adrián Jesús García, Matus Bakon, Sergio Álvarez, Beatriz González-Rodrigo, Rubén Martínez & Miguel Marchamalo (2018) Historical monitoring of urban subsidence based on longterm SAR data archives, Centeris 2018, ISBN 978-989-97433-9-7, pp.241-245.

2.2.1 Abstract

Civil engineering works represent a key end user of the Synthetic Aperture Radar (SAR) archives. The great amount of SAR data collected over the last 30 years allows the generation of historical deformation maps for target areas of interest. A concept proof of the potential of historical deformation maps is presented using the Madrid urban area as a testing environment. For this purpose, 3 different C-band SAR datasets from ERS, Envisat and Sentinel-1 and 1 X-band dataset, COSMO Sky-Med, are used in this work covering 25 years. The data of the considered SAR datasets have been processed with different Persistent Scatterer Interferometry (PSI) algorithms. The outputs have been combined over a grid buffering the contributions of the different PSI in the area obtaining a historical deformation map. The PSI outputs have been validated against GNSS measurements.

2.2.2 Introduction

The exploitation of the Synthetic Aperture Radar (SAR) technology from space sensors has proven to be a reliable source of remote sensing data. The use of the high resolution scenes produced by the different SAR missions has proved its applicability in the analysis of the ground deformations (Du et al., 2017; Infante et al., 2018; Liu et al., 2018a,b; Sarychikhina et al., 2018). The launching of the European Remote Sensing (ERS) mission represented a key event in the development of the SAR based

activities due to the fact that its data motivated and pushed forward the refinement of the SAR based exploitation techniques [Way and Smith \(1991\)](#).

The ERS mission was followed by a wide variety of missions that exploited the capabilities of C-band, L-band and X-band wavelengths such as the Environmental Satellite (Envisat) mission in C-band, the COSMO-SkyMed (CSK) mission in X-band or the recently launched Sentinel-1 A/B mission also operating on band C. These missions cover more than 25 years with almost continuous SAR data.

The persistent scatterer interferometry (PSI), which is based on the generation of interferometric pairs from a high number of complex SAR images, is the cornerstone algorithm in the estimation of ground deformations from SAR acquisitions. Introduced by [Ferretti et al. \(2001\)](#), it provides deformation accuracies up to 1 mm ([Ferretti et al., 2007b](#)). Different implementations of the PSI algorithm have been proposed such as the Stable Point Network (SPN) approach ([Crosetto et al., 2008](#)) or the Persistent Scatterer Pairs (PSP) ([Costantini et al., 2008](#)) which are the ones used in this work. Nevertheless, refer to ([Osmanoğlu et al., 2016](#)) for a complete description of all the available techniques and their potential applications.

As a result of the continuously evolving SAR satellite-based technology, a data archive from different missions of more than 25 years is available. In addition, a variety of algorithms can be used by the end users in order to process this data. Although data from different missions cannot be processed within the same PSI process due to the phase unwrapping limitations the data for the different missions can be indeed combined. Recent works have introduced the idea of using this archive of data to historical deformation analysis ([Armas et al., 2017](#); [Del Ventisette et al., 2013](#); [García et al., 2018](#)).

In this work, a historical deformation map of the Madrid urban area is computed and presented and a proof of concept of its potential applications is shown. In

this regard, data from 5 different datasets that cover the area of Madrid over more than 25 years is used in this study. The results are validated against the GPS deformations computed over the GNSS stations located over the area of study.

The area of interest, Madrid (Figure 2.1), represents a unique scenario for the assessment of the SAR technique capabilities since numerous underground activities have been carried out in recent years (Bakon et al., 2016a; García et al., 2018; Sillerico et al., 2015).

2.2.3 Material and methods

Five different SAR datasets have been processed using different PSI algorithms. This aims at ensuring that a historical deformation map can be computed with datasets processed by different means. Table 2.1 describes the characteristics of the 5 PSI processes. The same reference point, a stable point, has been used in the processing of all the datasets. In all of them, the topographic component has been removed by using the Digital Elevation Model (DEM) obtained from the Shuttle Radar Topography Mission (SRTM). Moreover, a manual correction step has been conducted in order to reduce the georeferencing error of all the datasets. The coherence thresholds have been defined trying to get the best trade-off between the density of points and the accuracy of the results.

The main challenge in the generation of a historical combined map is the fact that the points that act as scatterers are not consistent in the different datasets. Moreover, it is usually difficult to identify the actual feature that acts as scatterer. In order to overcome this problem, a common approach is to use a buffer around the specific point for which the deformation wants to be investigated, averaging or weighting the contributions of all the PS included in the buffer. This approach is

in line with similar works ([Crosetto et al., 2010](#); [García et al., 2018](#); [Tofani et al., 2013](#)) which use buffers from 10 to 50 meters.

In order to compute the historical deformation map, the urban area of Madrid has been divided into cells of 100 x 100 meters and the deformations for each cell have been computed at the centroid of each square. A buffer of 50 meters has been selected. Only the points for which at least one PS for all the SAR missions has been found have been included in the historical deformation map. The time gaps between dataset have been filled assuming a linear deformation with the previous dataset. Since, for the area of interest and for the analyzed period of time, the horizontal movement can be assumed as negligible with respect to the vertical movement, as a first approximation, the vertical displacement has been derived from the line of sight displacement applying the cosine of the incidence angle.

For validation purposes, the deformation time series has been also computed for the locations of the Global Navigations Systems (GNSS) stations in the area of Madrid whose data is publicly available. Similarly, a buffer of 50 meters has been used and the different PS contributions have been weighted by the coherence of each PS. The positioning solution for the Global Positioning System (GPS) measurements has been obtained from the Nevada Geodetic Laboratory which computes a daily position of each GNSS station by means of a Precise Point Positioning (PPP) algorithm using Jet Propulsion Laboratory orbits and clocks as inputs. The evolution of the capabilities of the C-band SAR missions has been addressed in terms of the accuracy of the obtained deformations, assessed through the comparison of the deformations against the GNSS deformations, and the PS density of the processed PS datasets per land use.

2.2.4 Results and Discussion

2.2.4.1 Validation results

Figure 2.2 (a-e) shows the comparison of the vertical GNSS deformations, which are used for the validation of the deformation map, and the vertical displacements obtained from the PS datasets. It can be seen that there is a great agreement between the deformations estimated from GNSS and SAR data. On the one hand, it can be seen that the vertical PSI estimations present less noise than the GNSS ones. On the other hand, a position can be estimated from the GNSS data at almost the desired rate due to the continuity of data meanwhile for the PSI estimations only at the acquisition times an estimation of the deformation can be computed.

2.2.4.2 Historical deformation map

Figure 2.12 shows the historical deformation map obtained from the 5 datasets. The cumulative deformation from April 1992 to May 2017, which is the covered period of the processed datasets, is presented. The figure shows the metropolitan area of Madrid where a cumulative displacement of up to 55 mm has been measured in the considered period. Note that the inspection of higher deformations has been classified as outliers since they are points affected by temperature oscillations. The temporal series of the PS marked in Figure 2.12 has been represented in Figure 2.13. This point has been selected since the scatterers that have contributed to that point of the grid corresponds to features above a metro station. The vertical deformation in the period 1997 - 1998 can be explained by the underground works of the Metro line 10 whose tunnels have also been included in Figure 2.12 and the metro station remodeling works.

FIGURE 2.12: Historical deformation map of the area of Madrid. The cumulative displacement from April 1992 to May 2017 is shown. The metro stations and tunnels are included. The deformation of a point of interest is shown.

FIGURE 2.13: Deformation time series of the point of interest highlighted in Figure 2.12.

Not only does the computed deformation map allow the assessment of the impact of a given construction work but it can also be used in numerous civil engineering applications. Proactive maintenance activities based on the historical evolution or the provision of a first order estimation of the stability of an area are examples of the wide range of applications.

2.2.5 Conclusions

Data from up to 25 years and 4 different sensors have been processed in order to generate a historical deformation map in the area of Madrid. This map can be applied by an end user interested in a first-order estimation of the deformation evolution of a specific area. The results have been validated with GNSS deformations. Proactive maintenance activities based on the historical evolution or the provision of a first order estimation of the stability of an area are examples of the wide range of applications of this historical deformation map.

The results presented here highly motivate future activities including post-processing algorithms that can remove outliers from the historical deformation map. In addition, a completely three-dimensional map could be obtained by processing both ascending and descending acquisitions of the same datasets.

CHAPTER 3

INTEGRATING GEOTECHNICAL AND SAR DATA FOR THE MONITORING OF UNDERGROUND WORKS

The content of this chapter has been published in the following journal article:

Adrián Jesús García, Miguel Marchamalo, Rubén Martínez, Beatriz González-Rodrigo, Carmen González, Integrating geotechnical and SAR data for the monitoring of underground works in the Madrid urban area: Application of the Persistent Scatterer Interferometry technique, International Journal of Applied Earth Observation and Geoinformation, Volume 74, 2019, Pages 27-36, ISSN 0303-2434, DOI: <https://doi.org/10.1016/j.jag.2018.08.025>.

3.1 Abstract

The Differential Interferometric Synthetic Aperture Radar (DInSAR) is a powerful deformation control technique for civil engineering applications. However, the performance definition and limitations of the technique in tunneling works are far from being standardized. This work presents a thorough validation effort of the applicability of the Persistent Scatterer Interferometry (PSI) technique to the Madrid's M-30 tunneling works. A set of 26 Envisat images, covering from August 2003 to April 2008, were processed with two PSI techniques and the results were validated with on-ground measurements from leveling benchmarks and strips. The comparison of the deformations of more than 1500 control points has led to a global deformation difference of 2.6 mm RMS and 3.5 mm RMS with a coverage of the area of interest with persistent scatterers of 65% and 34% for the two PSI algorithms used. The limitations of the PSI technique when using SAR missions with low revisit time were shown. PSI has proven the potential to complement on ground monitoring techniques in tunneling works as soon as the limitations are overcome.

3.2 Introduction

The Persistent Scatterer Interferometry (PSI), the most developed differential Interferometric Synthetic Aperture Radar (DInSAR) technique, is a powerful remote sensing technique that allows the estimation of Earth surface's deformation with an accuracy of up to 1 mm/yr in optimal conditions ([Armas et al., 2017](#); [Castellazzi et al., 2017](#); [Cigna and Sowter, 2017](#); [Wang et al., 2018](#)). From the initial approach of [Ferretti et al. \(2001\)](#), different algorithms have been proposed that exploit the phase information contained on a set of radar images taken over the same area and with the same sensor ([Costantini et al., 2008](#); [Duro et al., 2005](#); [Perissin and Wang,](#)

2012). Concise reviews of all the currently available techniques were carried out by [Osmanoğlu et al. \(2016\)](#) and [Crosetto et al. \(2016\)](#) using as inputs the different works that have been conducted in the line of the PSI exploitation.

Although the potential and capabilities of the PSI technique have been shown in numerous applications in the last decade ([Crosetto et al., 2010](#)), the actual limits of the technique are far from being standardized. Uncertainties such as the deformation rates that can be observed, the geocoding error, the assumption of a linear deformation and the sensitivity to phase noise have limited the application of the SAR-based monitoring techniques to operational subsidence control systems. In order to put the PSI techniques at the level of the geodetic and geotechnical deformation measurement techniques, a concise and deep validation effort for each specific application has to be conducted. The outcome of this validation process should be a clear definition of the scenario and specific conditions under which PSI can be used as a reliable deformation control technique in tunneling works.

Different validation efforts have been carried out in the recent years aiming at validating the applicability of the PSI techniques to specific applications. Two main important validation works were carried out in the frame of the Terrafirma and the Persistent Scatterer Interferometry Codes Cross-Comparison And Certification (PSIC4) projects. The Terrafirma project, funded by ESA, aims at creating a European ground hazard information service. The validation activities carried out within the project were divided into two main parts: the process validation ([Adam et al., 2009](#)), and the product validation ([Hanssen et al., 2008](#)). The first one implied the assessment of the intermediate products, removing the impact of the geocoding error and allowing the assessment of errors comparing different processing chains. The product validation implied the comparison of the geocoded PSI products of 5 teams from business and academic groups against leveling measurements. Two

areas were studied, Amsterdam, an urban area, and Alkmaar, an area characterized by gas exploitation. The assessment of the urban area was limited by the fact that no important construction works took place in the studied period of time and, therefore, the results can only be extrapolated to test areas with a zero or moderate deformation rates ([Crosetto et al., 2010](#)). The PSIC4 project implied the inter-comparison of the PSI results of 8 different teams without a priori knowledge of the testing environment: a mining area ([Raucoules et al., 2009](#)). The fact that no a priori information of the area was used was of great interest for the comparison of the different techniques and approaches followed by different teams. However, it does not represent the common scenario for an end-user for commercial purposes, who usually has available the historical deformation trends of the area of interest.

Other recent validation works include the work of [Armas et al. \(2016\)](#) who carried out a validation activity in Bucharest using GNSS measurements, although no specific construction work was used as validation scenario. In the same line, [Herrera et al. \(2009\)](#) conducted a validation work of the PSI technique in the area of Murcia, which is affected by a slow subsidence, comparing the results against a limited number of extensometers. Moreover, [Ferretti et al. \(2007b\)](#) and [Quin and Loreaux \(2013\)](#) conducted an experimental validation with a controlled movement of corner reflectors establishing the theoretical submillimeter accuracy that can be achieved under optimal conditions. Finally, [Perissin \(2008\)](#) conducted a validation work of the Digital Elevation Models (DEM) that can be derived from the outputs of a PSI processing.

Therefore, it can be inferred that the applicability of PSI processing, especially when applied to the monitoring of construction works, is far from being validated and the limitations standardized. In this work, a validation of the PSI technique, from the point of view of an end-user, is carried out using as the testing environment the

urban area of Madrid during the construction works of the M-30 tunnel, which were conducted from November 2005 to October 2006. The outputs of a PSI processing are compared against the on-ground geotechnical techniques used during the construction work. Moreover, it will be assessed if the geotechnical measurements could have been combined with the outputs of the PSI process. Note that, in this work, it is assumed that geotechnical data refers to the on-ground measurements taken in a local reference system, such as the benchmark leveling and strip measurements used in this study. In this line, the aim of this work is the combination of these geotechnical measurements, referred to local reference systems, with the SAR data, which has a global reference system.

Two commonly available techniques, Stable Point Network (SPN) ([Duro et al., 2010](#)) and the Persistent Scatterer Pairs (PSP) ([Costantini et al., 2008](#)), are used here since they are representative techniques that are available to a general end-user. A formal comparison of all the available PSI techniques is left out of the scope of this work.

3.2.1 Validation scenario

The continuously growing urban area of Madrid over the last two decades led to traffic and mobility problems which had the maximum indicator in the M-30 beltway which, at the beginning of 2003, was on the brink of collapsing due to the heavy traffic. In order to ease this problem, the Madrid Council projected the remodeling plan of the M-30 implying the underground of up to 50 km of roads. One of the most important and challenging works of the framework was the southern By-Pass tunnel. This is the test site used in this work as the validation scenario. The By-Pass, located under the Enrique Tierno Galvan Park, consisted of the excavation of two twin tunnels by two Tunnel Boring Machines (TBMs). These TBMs, which

are included within the biggest and most powerful ones at the time with a diameter of 15.2 m, excavated 4280 m for the southern tunnel and 3650 m for the northern tunnel. The excavation of the northern tunnel covered from November 2005 to July 2006 and from February 2006 to October 2006 for the southern tunnel.

Geologically, the tunnels are located in the Tertiary Madrid Basin and four different stratigraphic units can be observed, three with Tertiary materials (hard clays, casts, and gypsum) and the other one with Quaternary materials (alluvial deposits). On top of them, anthropic materials can be found. A schematic profile of the M-30 tunnel works can be found in Figure 3.1.

FIGURE 3.1: Sketch of the geological profile of the area of interest.

The area of study comprises the twin tunnels and the surrounding area where the effects of the construction works can be of interest, Figure 3.2. It has been divided into 12 different sectors, as it can be seen in Figure 3.2, following the same approach of previous studies focused on the same area (Sillerico et al., 2015). Two sections of the M-30 works are of special interest for this work since they contain the higher density of buildings close to the tunnels, sectors 5 (Legazpi Square) and 10 (Ciudad de Barcelona Street).

FIGURE 3.2: Area affected by the M-30 works. The zone has been divided into 12 sectors. The two sectors of interest are highlighted. The location of the leveling and strip measurements used for validation purposes is shown.

3.3 Material and methods

3.3.1 Control instruments and reference data

The definition of the limits of the PSI applicability to operational control and monitoring of construction works starts with the identification of the on ground techniques that can be complemented by the PSI technique with the corresponding economic benefit. In this regard, as part of the control and monitoring of the construction works, a set of instruments were placed along the tunnel and surrounding buildings (Sillerico et al., 2015). This monitoring plan includes:

- Three leveling benchmarks over the tunnel section every 50 m over the vertical axis and the gables.
- A control section with at least 7 leveling benchmarks points every 150 m.

- A piezometer and inclinometer every 300 m, 5 m deeper than the inverted vault.
- The control of other already existing underground constructions has been granted by the installation of rod extensometers in the section prior to the crossing.
- Leveling strips in the buildings close to the tunnels axis.
- An underground leveling base every 250 m.
- Total pressure cells and vibrating rope extensometers in the voussoirs of the coating every 1000-1500 m.

The PSI technique has the potential of complementing the measurements taken on the surface of the construction work. Therefore, in this work, on ground leveling and strip measurements will be used as the reference and their complementation with the PSI technique will be evaluated.

3.3.2 PSI processing

Two different PSI algorithms have been used for validation purposes. The first one relies on the SPN technique ([Crosetto et al., 2008](#); [Duro et al., 2005](#)). It is a multi-master technique that reduces baselines and increases correlation by selecting multiple master images. This technique has proven to be a reliable method for the deformation estimation in tunneling works ([Duro et al., 2010](#)). The correct adjustment of the coherence and the characteristics of the area of study leads to a significant set of reliable PS [García et al. \(2018\)](#); [Sillerico et al. \(2015\)](#).

The second PSI processing relies on the PSP technique ([Costantini et al., 2008](#)). It is a single-master iterative approach that looks for arcs of connected PS rather

than single PS. With this strategy, it removes the initial preprocessing step to calibrate the data common to other approaches. As a result, PS in natural areas or with non-linear trends can be identified. This technique has been widely used in different deformation studies ([Costantini et al., 2011](#); [Daraio et al., 2014](#)).

Ascending and descending images of the area of interest are available. First of all, it should be noted that the region of interest is mainly flat and, therefore, there is no a priori advantageous acquisition geometry. Two common approaches can be applied to combine ascending and descending results in order to better understand and model complex deformations. The first one assumes that there is no movement in the North-South direction allowing the decomposition of the LOS displacements into Vertical and East-West components ([Bovenga et al., 2013](#); [Rosi et al., 2014](#)). This approach relaxes the assumption of considering only vertical displacements. However, for the time series deformation, a temporal interpolation step has to be added to refer the estimations of ascending and descending processing to the same epochs. Taking into account that vertical motion is clearly defining the total movement in tunneling works, the temporal interpolation error certainly overpasses the benefit of removing the horizontal component of the line of sight deformation.

The second approach implies using the outcomes of the PSI processing of both ascending and descending acquisitions independently ([Raspini et al., 2018](#)), taking advantage of the fact that both geometries lead to different sets of features acting as scatterers ([Gernhardt et al., 2009](#); [Tofani et al., 2013](#)). From the statistical point of view of this analysis, an increased amount of PS scatterers is expected (for different time stamps) but with the same average accuracy and limitations for both acquisitions. Therefore, for the sake of simplicity, and acknowledging that an enhanced PS density could be obtained, only ascending images have been processed

in this work for the two considered PSI techniques.

A set of 26 Envisat images in ascending mode covering the complete construction period of the By-Pass M-30 have been processed. The processed images, taken with the Advanced Synthetic Aperture Radar (ASAR) Image Mode (IM), cover from August 2003 to April 2008. The polarization was Vertical (V) both on send and receive. The exact acquisition dates, the perpendicular baselines and the temporal baselines with respect to the first acquisition have been included in Table 3.1. The area processed with both techniques has been included in Figure 3.3. The point used as the reference in both processes has also been included in Figure 3.3. This point has been assumed as stable, i.e. with no deformation.

FIGURE 3.3: Area of the PSI processing. The location of the reference point and the area of interest of this study, the M-30 works, is indicated.

The images were initially received as Level 1 products, transformed into Single Look (SLC) Products and co-registered. Then, the interferogram pairs were generated.

Date	Perpendicular baseline (m)	Temporal baseline (days)
05/08/2003	31	0
14/10/2003	-290	70
23/12/2003	240	140
02/03/2004	-173	210
06/04/2004	-182	245
11/05/2004	-211	280
20/07/2004	-55	350
24/08/2004	-570	385
02/11/2004	345	455
11/01/2005	320	525
26/04/2005	811	630
31/05/2005	-219	665
09/08/2005	-779	735
13/09/2005	790	770
22/11/2005	-281	840
27/12/2005	-805	875
07/03/2006	-769	945
11/04/2006	472	980
20/06/2006	465	1050
25/07/2006	806	1085
03/10/2006	320	1155
20/02/2007	116	1295
05/06/2007	-295	1400
27/11/2007	-592	1575
11/03/2008	-253	1680
15/04/2008	55	1715

TABLE 3.1: Temporal and perpendicular baselines of the radar images used in the PSI processing.

For the PSP, the interferogram pairs were generated with respect to the master which was the image acquired on 13/09/2005. These interferograms were converted into differential interferograms removing the range dependent and the topographic effects. These effects were accounted for using the digital elevation model (DEM) of the Shuttle Radar Topography Mission (SRTM) with a resolution of 90 m ([Jarvis et al., 2008](#)). After the identification of the PS by each algorithm and the removal of the local effects, the phase unwrapping was carried out using the minimum cost flow algorithm. Finally, the deformation maps were geocoded including a manual

correction. The line of sight (LOS) velocity maps of the area of interest of both processes have been included in Figures 3.4 and 3.5.

FIGURE 3.4: LOS velocity map obtained from the SPN processing. The area of study is highlighted in blue.

Taking into account that, for the considered scenario, the vertical displacements are higher than the horizontal ones, the LOS deformations obtained from the PSI processing have been directly converted to vertical deformations applying the incident angle. Note that the same approach is usually followed in similar works ([García et al., 2018](#); [Sarychikhina et al., 2018](#)). An outlier filter has been applied to the PS processing consisting in the removal of the points that have captured an uplifting behavior that matches auxiliary constructions and material removal in the areas intended for this purpose.

The deformation estimation from the leveling benchmarks, strips, and the PS points matches neither spatially nor temporally. Therefore, a pre-processing step that

FIGURE 3.5: LOS velocity map obtained from the PSP processing. The area of study is highlighted in blue.

interpolates the results is required in order to compare the results. Since the number of PS is bigger than the number of leveling strings, the deformation of the PS will be interpolated in the control point locations. Recent studies have shown that the geocoding error of the PS processes can be up to 10 m (Raucoules et al., 2009). Therefore, although the geocoding step has included a manual correction, an area of 10 m around each leveling and strip has been considered as a buffer for the spatial interpolation. The contribution of each PS inside the buffer has been weighted by the coherence of the PS. In a similar way, previous works use a buffer of up to 15 m (Hanssen et al., 2008). Note that only the PS points corresponding to the same building have been considered. The points have been identified by selecting the PS whose estimated height from the PSI processing is higher than the ground height of the area obtained from the DEM. In addition, for large buildings with clearly distinct deformation behaviors on each side, the buildings have been split

into different parts. A final visual inspection of the selected points has been carried out in order to remove outliers.

Regarding the temporal interpolation, since the frequency of the measurements taken at the control points is higher than the revisit time, PSI deformations have been interpolated at the timestamps of the control measurements. This is in line with the approach of previous works ([Hanssen et al., 2008](#); [Raucoules et al., 2009](#)). Note that a cubic spline interpolation has been applied and, no extrapolation has been computed. This interpolation method has been selected since it has been confirmed that it is the approach which better models the trends for the period of interest. The leveling benchmarks, strips, and PS deformations are referred to different timestamps, and, therefore, a bias between the datasets has to be handled. Since the magnitude of interest is, in all the cases, the difference between the PSI deformation and the control point (strip or leveling), for each control point the PSI deformations were referred to the first timestamp of the control point deformation series.

3.3.3 Validation process

The validation process is divided into three scenarios, which correspond to the general assessment of the PSI performance, the identification of the limits of the technique in the monitoring of tunneling works and the assessment of the capabilities of the technique to reliably represent the deformation evolution of a given structure. Note that a special interest is put in the deformation estimation and not only in the deformation rate since the on-ground instruments provide deformation measurements. Hereafter, the description of the validation scenarios is detailed:

1. The first scenario implies the computation of the PSI solution availability and the definition of a global error index which provides a global estimation of the accuracy of the estimated deformations. This provides a general figure of the PSI processing accuracy.
2. As it has been already reported ([Crosetto et al., 2010](#)), the PSI technique is limited by the magnitude of the displacement between different acquisitions. As a rule of thumb, deformations greater than 4-5 cm/yr represent a difficulty for Envisat C-band sensor. This is actually a critical point in control monitoring since a great displacement could be missed or missmodeled by the PSI technique. In this regard, an exhaustive analysis of the impact of the actual displacement between acquisitions has been conducted.
3. Finally, a specific assessment of two areas with a special interest due to the proximity of the tunneling works has been conducted. The deformation time series were analyzed.

3.4 Results of the PSI validation in Madrid tunneling works

3.4.1 Global results of the PSI validation

A total of 1545 control points, 1145 strips located on building sides and 300 on ground leveling points were placed for the monitoring of the M-30 works (Figure [3.2](#)). For the SPN process, 1005 points have, at least, one PS from which the deformation can be interpolated. Therefore, a global availability of 65% has been obtained. Note that, on a general basis, the non-covered areas correspond to green areas. This limitation, mainly driven by the difficulties in finding coherent points

in all the time series, has already been reported in previous works ([García et al., 2018](#)). Regarding the PSP processing, the availability is reduced to 34 % leaving some of the urban areas uncovered. The global index to assess the deformation performance is based on the Root Mean Square Error (RMS) of the deformation time series, which has been computed as:

$$RMS(k) = \sqrt{\frac{\sum_{t=1}^{t=N(k)} (x_{PS}(k, t) - x_{Ref}(k, t))^2}{N(k)}} \quad (3.1)$$

where t represents the epoch, N is the total number of on-ground measurements per control point, k is one of the control points, x_{PS} is the deformation interpolated from the PSI processing in the location of k point and at t time and x_{Ref} is deformation measured at time t at the control point k . This provides a value per on ground measurement. The global index consists of averaging the results of each control point. For the SPN processing, the average of the RMS of the different points is 2.6 mm with a standard deviation of 1.4 mm, meanwhile, for the PSP processing, the average is 3.5 mm with a standard deviation of 2.0 mm.

3.4.2 Limits of the PSI technique in tunneling works

Theoretically, the PSI estimation capabilities are limited by the ambiguity linked to the phased measurements. Taking into account the wavelength of the C-band sensors, this limitation can be expressed in terms of the maximum deformation rate between acquisitions above which difficulties in the estimation are found. In this case, for C-band sensors, the limit deformation rate is 40-45 mm/yr ([Crosetto et al., 2010](#)).

Although the theoretical limit deformation rate is 40-45 mm/yr, it is of great interest assessing the trend of the PSI estimation error from a stable point (i.e. zero

deformation) to a point with a deformation close to the theoretical limit. The great amount of control points available in this work has been used in order to infer this trend. In order to compute the reference deformation rate between SAR acquisitions, the deformation obtained from the leveling and strip measurements has been interpolated at the SAR acquisition times, using a linear interpolation. For each control point for which at least 1 PS has been found, the maximum deformation rate between acquisitions computed from the on ground measurements and the RMS errors of the PSI estimation for the control point, computed as per the Equation 1 are stored. These pairs of RMS errors of the PSI estimation and maximum deformation rate between acquisitions computed from the on-ground measurements have been classified in order to compute a histogram. For each interval, the average RMS error of all the available pairs is shown. See Figure 3.6. Note that there are only 10 PS points for the SPN technique and 6 for the PSP technique with a deformation rate higher than 40 mm/yr, meanwhile, 145 strips and leveling benchmarks measured a deformation rate of more than 40 mm/yr.

3.4.3 In-depth case studies

The applicability of the PSI technique to the monitoring of underground works is not only determined by the global accuracy of the interpolated results, but also by the capabilities of the technique of modeling specific temporal evolutions which are of interest for the active monitoring. In this regard, a detailed analysis has been conducted in two areas, which were considered of great interest by the monitoring responsible. The first one, the sector 5 of the M-30 works (Figure 3.2), is a residential area which is crossed by the tunnels axis and, the second one, in the sector 10 of the M-30 works, is close to a secondary collector pipe of the northern tunnel. Both

FIGURE 3.6: RMS of the PSI displacement error as a function of the maximum displacement rate between acquisitions measured from the on-ground instruments at the control points. The average of the control points per interval is plotted in the histogram.

of them were concisely monitored over the complete construction period in order to ensure that no permanent damage was infringed on the buildings.

3.4.3.1 M-30 sector 5

In sector 5 (Figure 3.7), numerous leveling points were placed and many building sides were provided with leveling strips in order to control the deformation over the construction works. According to previous studies of the M-30 works, (García et al., 2018; Sillerico et al., 2015), the deformation profile transversal to the tunnel axis is longitudinally homogenous. Therefore, taking a longitudinal section parallel to the tunnel axis, a similar behavior can be expected. In this line, a buffer of 5 m to each side of the northern tunnel axis inside sector 5 has been considered for

the deformation analysis. For the SPN processing, 8 points were obtained in the buffer but no points were found for the PSP processing, as a result of the reduced availability of PS in this processing. The contributions of the PS in the buffer were weighted by their coherence and the leveling and strip measurements were averaged. In order to remove the bias between the deformation measured by the strips and leveling benchmarks and the PS processing due to their different reference date, the estimated deformation from the PS processing at the first time the on ground measurements were taken was subtracted from the PS time series. The results can be shown in Figure 3.8.

FIGURE 3.7: Area of sector 5 corresponding to Legazpi Square. The location of the Persistent scatterers and the on-ground data used as reference is shown.

FIGURE 3.8: Time series deformation of the 5 m buffer around the M-30's north tunnel axis. (The buffer can be seen in Figure 3.7).

3.4.3.2 M-30 sector 10

The M-30 works included the construction of an auxiliary pipe passing under the Ciudad de Barcelona Street. This motivated the monitoring of one of the buildings which was expected to be affected by the construction. In Figure 3.9 the location of the building, the auxiliary pipe, and the M-30 twin tunnels is shown. This image also shows the PS found in the building from the two PS techniques used in this work. The contribution of the PS has been weighted by the coherence of the PS and the average of the control monitoring points has been computed. Similarly, as in the previous analysis, the PS processing and the on-ground deformations have been referred to the time the first on ground measurement was taken. The comparison of the measured and estimated deformations can be seen in Figure 3.10.

FIGURE 3.9: Area of Sector 10 corresponding to Ciudad de Barcelona Street. The location of the on-ground data used as reference and the PS is shown. The area is mainly affected by the secondary pipe included in the Figure. The building of interest is highlighted in blue.

3.5 Discussion

The results show that there is a reasonable agreement between the PS results and the on-ground measurements. The obtained average RMS errors are higher than the obtained in previous works which addressed scenarios with low deformations. This is in line with the expected results since the M-30 works represent a highly challenging scenario for the PSI technique. The lack of PS at some points represents the major limitation, especially in the PSP processing. Note that this problem could be eased by using X-band. Moreover, future construction works can also benefit from the Sentinel-1 sensor for which higher densities have been reported (Bakon et al., 2016a; Liu et al., 2018a; Solari et al., 2018).

FIGURE 3.10: Time series deformation of the building of interest highlighted in Figure 3.9.

The analysis of the limits of the technique shows that the higher the deformation rates between acquisitions, the higher the error that is obtained by the PSI technique. The fact that only 7% of the points with a deformation rate higher than 45 mm/yr have at least one PS in the considered buffer is in line with the theoretical limits already reported by Crosetto et al. (2010).

The PSI results of the M-30's sector 10, Figure 3.10, show a great agreement with the on-ground measurements, especially the SPN processing. Nevertheless note that, although at the end of the monitoring period the estimated deformation is close to the reference, the deformation rate is not correctly modeled. This has been explained by the combination of two factors. First of all, a linear deformation between acquisitions has been assumed in the SPN processing and, in this case, the behavior is highly nonlinear in a short period of time. Moreover, the time period between acquisitions is up to 100 days for the time the TBM passed the area of interest (Table 3.1). Indeed this revisit time period is also the reason why the PSP, which is capable of modeling non-linear trends, presents overshoots. The problem

the revisit time of Envisat satellite represents is confirmed by the results in Sector 5 (Figure 3.8). In this case, the overshoot period is not captured by the SPN processing given that it took place between two acquisitions. Note that, Sentinel-1 products with a revisit time of up to 6 days or the X-band sensors could ease this problem.

The differences between the results of PSP and SPN algorithms, mainly the different PS densities, can be explained by the nature of the algorithms and their specific settings. PSP is able to obtain coherent points in natural areas and it identifies non-linear behaviors. However, in this validation scenario, mainly urban, SPN overcomes PSP in terms of PS density.

3.6 Conclusions

The validation effort of this work represents the first step for the integration of geotechnical and SAR data for the superficial monitoring in the control of underground works. The outputs of two PSI processing and a great number on ground measurements have been compared in the urban area of Madrid. The two processing techniques used in this work, SPN and PSP, have been widely used in recent works interested in studying underground works. The historical behavior of the area of interest has been exploited in the processing. This represents a great advantage for practical applications with respect to the main validation efforts conducted by the European Space Agency, PSIC4 ([Raucoules et al., 2009](#)) and Terrafirma ([Hanssen et al., 2008](#)) where the different teams had no previous data about the area of interest which limited the achievable accuracy.

A global availability, understood as the control points for which at least one PS was identified inside a buffer of 10 m around the point's location, of 65% for the

SPN processing and 34% for the PSP processing has been obtained. In the SPN processing sectors with lack of PS have been identified as green areas, and therefore, this lack of data can be expected. The same cannot be applied to the PSP processing whose PS distribution is reduced. Note that the global availability could be increased by considering the descending acquisitions. This implies that, from the point of view of the coverage, the PSI technique, when the correct implementation to each application is selected, can potentially replace, or at least complement, on ground techniques taking superficial measurements in urban areas. An average RMS error of 2.6 mm with a standard deviation of 1.4 mm for the SPN processing endorses the usage of the PSI technique for control monitoring. For the PSP algorithm, the average RMS error was 3.5 mm with a standard deviation of 2.0 mm. It has been shown that there is a great impact on the selection of the appropriate algorithm for each application.

Two main limitations have been identified. First of all, deformation rates of more than 5 cm/yr are not detected by the Envisat sensor. Moreover, the revisit time makes it impossible to detect deformations in near-real time and even some deformation events could be missed. In addition, it has been shown that the selection of the most appropriate PSI algorithm for each application has a great impact on the estimated deformations.

It can be concluded that the PSI technique presents a clear potential to be integrated with other control monitoring technique in tunneling works. The capabilities of the technique to assess deformations have been proven. In addition, it is important to take into account that the number of controlled buildings when using the PSI technique dramatically increases when compared to the on ground techniques. Moreover, the lack of PS in green areas can be foreseen with a study of the area of interest. The main limitations identified have been linked to the revisit time of

Envisat sensor. This problem could be eased by using Sentinel-1 sensor or other X-band sensors with higher revisit times. Therefore, although it is expected that the limitations are overcome with the Sentinel-1 sensor, the complete integration of geotechnical measurements and the PSI techniques based on Envisat images cannot be considered as fully reliable.

A future research line is opened by this work which implies reproducing these results in other construction civil engineering applications using Sentinel-1 sensor. The exploitation of Sentinel-1 could shed light on the application of the PSI technique as a primary control monitoring technique in civil engineering.

CHAPTER 4

STRUCTURAL HEALTH MONITORING THROUGH SAR-DERIVED CLASSIFICATION INDEXES

The content of this chapter is currently under review as:

Adrián Jesús García, Rubén Martínez, Beatriz González-Rodrigo, Miguel Marchamalo, Building Health Monitoring in the old town of Madrid: Applicability of SAR Imagery to the monitoring of underground works through classification indexes, Journal of Surveying Engineering, 2019.

4.1 Abstract

The old city centres of all major cities increasingly demand the underground of the infrastructures in order to cope with the transportation needs. These areas represent a great challenge from a constructive point of view since the foundations of the buildings consist of an aggregation of previous constructions over the same place. This endorses thorough monitoring activities during any underground construction. The capabilities of the persistent scatterer interferometry (PSI) can be exploited in order to cope with this monitoring needs. However, the old city centres represent the most challenging urban scenario since the rooftops are usually filled with air conditioning systems and due to the fact that the streets are usually crowded. This work assesses the applicability of the PSI technique under this challenging scenario. It proposes a set of classification indexes in order to make the most of the capabilities of the PSI algorithms. These indexes allow an objective assessment of the results, as well as remove the high dependency of the results on the sensor and algorithm used in the processing. The applicability of the technique and the proposed indexes is validated in the old city centre of Madrid comparing the results against on ground measurements. The most demanding urban environment to be analysed by the PSI remarks the potential and limits of the technique.

4.2 Introduction

In the last two decades, the increased population of all major cities has led to the collapse of the transportation infrastructure. All the city councils have tried to alleviate this problem by moving the car and rail traffic underground as well as developing an underground metro system. However, the old city centres represent a great challenge for underground activities. They have usually suffered continuous

modifications of pre-existing structures and the construction of new buildings on top of the ruins of older buildings. This has led to an unknown and geologically unstable anthropic layer that requires an exhaustive monitoring and an active treatment prior to any underground activity.

Differential Interferometric Synthetic Radar Aperture (DInSAR), and more specifically the persistent scatterer interferometry (PSI), has proven to be a reliable remote sensing technique. The processing of multiple radar images allows the identification of subcentimetric deformation time series whose applicability in numerous fields has already been proved. Some examples include: crop monitoring ([Erten et al., 2016](#)), earthquake and volcano impact assessment ([Barba-Sevilla et al., 2018](#); [Prasetyo et al., 2011](#)), landslides investigation ([Strozzi et al., 2018](#)), long term deformation analyses ([García et al., 2018](#)), the monitoring of urban areas ([Susaki et al., 2018](#); [Zhu et al., 2018](#)) or even semi-autonomous monitoring tools ([Raspini et al., 2018](#)). A concise review of the PSI techniques and applications was carried out by [Crosetto et al. \(2016\)](#).

The monitoring of ground subsidence of urban areas is one of the main applications of the DInSAR technology. It provides the advantage of covering wide areas at a low cost. The capabilities of the PSI technique are limited by the availability of coherent points over the analysed period, the deformation model assumed and the magnitude of the displacement ([Crosetto et al., 2010](#); [García et al., 2019](#)). In this regard, old town areas represent the most challenging urban scenario. First of all, due to the fact that building facades cannot be modified in order not to alter the architectural style of the city centre buildings, air conditioner systems are usually installed in the rooftops. This introduces thermal fluctuations in the assets that work as scatterers introducing outliers. In addition, given that these areas are usually crowded it is usually difficult to obtain persistent scatterers in the streets.

Up to now, this technique has been successfully applied to the monitoring of a limited number of underground constructions (Barla et al., 2016; Fernandez, 2018; García et al., 2019; Qin et al., 2017; Serrano-Juan et al., 2017; Wang et al., 2017). These underground works are traditionally monitored using on-ground methods, such as levelling, whose effectivity is limited by their spatial density (Wang et al., 2017) and which can strongly benefit from the integration with SAR techniques (García et al., 2019). Furthermore, some recent works have addressed the urban subsidence problem in historical city centres, mainly focused on the enormous heritage of Rome and Florence (Cigna et al., 2014; Pratesi et al., 2015, 2016; Tapete and Cigna, 2017). However, no specific underground activity affecting the area of study was investigated. In this line, this work aims at assessing the capabilities of the PSI technique to monitor the building deformation during underground construction works in the most challenging urban scenario, the old city centres.

The Madrid old town area is a clear example of the old town European cities where numerous underground activities have been recently conducted. The old town, as considered nowadays, was already urbanised by 1600. Since then, the city has been reshaped on numerous occasions. This has led to an unknown foundation which can be potentially unstable. In recent years, numerous activities have been conducted in order to ease the mobility problems in the city centre. These activities include linear actions for the underground of roads, railroads and subway development and punctual actions for the extension of already constructed underground infrastructure. Two samples of these underground works are analysed in this study. The first one, a linear tunnelling work for the underground of the railway near Atocha station and the second one a punctual underground activity aiming at the expansion of a metro station waiting area in one of the most crowded areas of Madrid, Puerta del Sol. In order to remove the dependency on the sensor and the PSI algorithm applied a set of classification indexes have been used for the monitoring assessment

of the underground works. These indexes have been adapted from the ones defined by [Pratesi et al. \(2015\)](#) for the monitoring of heritage areas.

4.2.1 Area of study: Atocha

Atocha is the hub railway station of the metropolitan area of Madrid. The continuous increase of the transportation requirements over the last decade of the 20th century motivated the design of two additional tunnels. The first one, on C1 line, projected on 2004 to ease the traffic between Atocha and Chamartín and the second one, projected for 2018, covering the high-speed tunnel.

The tunnelling works for the expansion of the C1 line, which are analysed in this work, covered from January 2004 to January 2006. The tunnelling works started from Embarcadero de Atocha Square moving to Carlos V square through Atocha Street (Figure 4.1). The works projected a treatment of the area affected that generated an uplift to compensate the later displacement, removing any impact on the constructions of the area. A tunnel boring machine (TBM) with a diameter of 9.38 m was used for the construction. It had the capability of advancing at 37.5 m/day although the sensitivity of the area led to an average velocity of 5 m/day.

Geologically, the area represents a great challenge, since it is a heterogeneous area with different levels of unclear anthropic materials over a waste of pit sand and Tosco, until a depth of 12.3 m and clays without gypsum and carbonated levels and sands until a depth of 19.5 m. The layer of clays and sands has a breaking load between 17.27 and 25.41 kg/cm^2 .

When the TBM was at section 0 + 382 m it suffered a malfunction and the tunnelling works had to be stopped. At this point, whose location is detailed in Figure 4.1,

FIGURE 4.1: Atocha construction work area. The location of the TBM when there was a malfunction is shown as Section 0 + 382 m. The buildings included in the monitoring activities have been highlighted.

the TBM was located over the pavement and not having treated the area. This led to deformations bigger than expected.

4.2.2 Area of study: Puerta del Sol

Metro line 3 is one of the oldest metro lines in Madrid. In order to contend with the increased amount of passengers, a major extension work was projected in the whole line. In Puerta del Sol, which is a crossing point of Metro Lines 1, 2 and 3, it implied the enlargement of the waiting areas and the construction of new accesses. It included the construction of a tunnel under Preciados street (Figure 4.2) and the reinforcement of the surrounding building foundations. Figure 4.3 sketches the

construction works that were carried out. The activities started on January 2005 and covered until June 2005.

FIGURE 4.2: Puerta del Sol construction area. The trace of the underground activities is highlighted in green. The black line shows the location of section A-A'.

Geologically, the area is composed by anthropic materials with low load capacity and a heterogeneous lithology until 2 meters and clays until a depth of 8 meters.

4.3 Material and methods

The persistent scatterer interferometry (PSI) technique has been used in order to obtain the deformation time series over the areas of interest. Note that both areas are within the same SAR image and, therefore, the PSI process is common to both of them. The PSI results have been validated against the actual on-ground measurements used for monitoring purposes in the construction period. Finally, a

FIGURE 4.3: Sketch of Puerta del Sol works. It represents the construction works at section A-A' of Figure 4.2. a) Status prior to the construction works. b) Status after the construction work with the waiting area and enlarged platform.

set of classification indexes is proposed that allow an objective assessment of the building health.

4.3.1 PSI processing

An image dataset of 26 images in ascending mode of Envisat sensor that cover the complete underground activities of both Atocha and Puerta del Sol works have been processed using the Stable Point Network (SPN) technique ([Crosetto et al., 2008](#); [Duro et al., 2010](#)). Note that the area of interest that covers Atocha and Puerta del Sol is mainly flat with no a priori favourable acquisition geometry.

The timestamps of the acquisition dates of the dataset used along with the perpendicular baseline after the removal of the average and the temporal baseline referred to the first image have been included in Table 4.1. All the images, which were received as Level 1 products, have vertical polarization.

The first step implied the transformation of the Level 1 products into Single Look (SLC) Products followed by the coregistration step. From the available set of images the interferogram pairs were generated and then converted into differential Interferograms. The topographic effects were removed using the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM), which has a resolution of 90 m. The minimum cost flow algorithm was selected for the phase unwrapping step ([Costantini, 1998](#)). The line of sight (LOS) geocoded deformation maps were corrected with a manual step. Finally, and taking into account that the deformations due to tunnelling works are mainly vertical and the horizontal movements are negligible, the LOS deformations were converted to vertical displacement with the cosine of the angle of incidence.

Date	Perpendicular baseline (m)	Temporal baseline (days)
05/08/2003	31	0
14/10/2003	-290	70
23/12/2003	240	140
02/03/2004	-173	210
06/04/2004	-182	245
11/05/2004	-211	280
20/07/2004	-55	350
24/08/2004	-570	385
02/11/2004	345	455
11/01/2005	320	525
26/04/2005	811	630
31/05/2005	-219	665
09/08/2005	-779	735
13/09/2005	790	770
22/11/2005	-281	840
27/12/2005	-805	875
07/03/2006	-769	945
11/04/2006	472	980
20/06/2006	465	1050
25/07/2006	806	1085
03/10/2006	320	1155
20/02/2007	116	1295
05/06/2007	-295	1400
27/11/2007	-592	1575
11/03/2008	-253	1680
15/04/2008	55	1715

TABLE 4.1: Temporal and perpendicular baselines of the radar images used in the PSI processing.

4.3.2 On ground measurements

4.3.2.1 Case study: Atocha

The monitoring and control plan for the area of study implied the installation of 80 strips, which were placed in the facades of the buildings within 30 meters from the tunnel axis. In the same line, 23 levelling points were placed in 6 different sections transversal to the tunnel axis. The measurements are referred to the first timestamp and were taken at two different campaigns, from June 2004 to October

2004 and from February 2005 to August 2005, with irregular samplings and data gaps. Additionally, other underground monitoring instruments were installed which are not considered in this work.

From the planned 80 strips, 3 could not be placed due to the denial of the owner. In addition, 6 levelling points were destroyed in the working periods, and therefore, no measurements could be retrieved.

4.3.2.2 Case study: Puerta del Sol

The ground monitoring activities put in place during the construction works implied the installation of 70 strips located in the four buildings affected by the construction work. In addition, underground monitoring instruments were used which are not considered in this work. No major incident was found in the installation of the on-ground instruments.

Measurements from March 2005 to April 2006 were recorded on a daily basis, although some data gaps can be found. The deformation time series is referred to the first time stamp.

4.3.3 Ground-truth validation process

The on-ground measurements and the PSI outputs provide deformation estimations at different timestamps and locations. In order to have a common temporal reference, the deformation time series of the PSI processing have been referred to the epoch the on ground measurements are referred to. A linear interpolation between the PSI deformation estimations has been carried out. This is in line with the approach followed by similar works ([García et al., 2019](#); [Hanssen et al., 2008](#); [Raucoules et al., 2009](#)).

The spatial assessment has been carried out in an asset bases, i.e. following the procedure defined in the actual monitoring period with on ground measurements. In this line, the on ground and PSI deformations are compared per building and levelling section. Note that, although it is not possible to accurately determine the feature that is acting as backscatter (Tofani et al., 2013), it is possible to identify if they belong to a building or to the ground by comparing the estimated heights. The PS estimated deformations of the points which have a similar behaviour within the same building have been weighted by their coherence in order to obtain a single time deformation series that eases the comparison. Regarding the strip and levelling deformations, one time series per representative deformation has been used for the assessment.

4.3.4 Building health assessment

In order to remove the common subjectivity of the PS data interpretation a set of PS classifications indexes derived from the defined by Pratesi et al. (2015) are used here. The indexes include a Completeness of Information Index (I_{ci}), a Conservation Criticality Index (I_{cc}) and a Velocity Dispersion Index (I_{vd}). Defined in the context of the monitoring and control of heritage sites, the application to the monitoring of tunneling works is here investigated.

I_{ci} provides an objective way of assessing the PS coverage over a given building. It categorizes the values from A (completely covered) to E (area not covered by PS) according to the PS density of a building and its surroundings. The index is based on a limiting density, D_m , which is PS dataset dependent and that corresponds to the PS average of the area of study, in this case, $2.5 \cdot 10^{-3} PS/m^2$. The surrounding area is defined by the resolution cell of the PS sensor, in this case, 30 meters. Note that for the area of study the proximity of the buildings reduces the surrounding

I_{ci}	PS coverage score
A	1
B	0.75
C	0.50
D	0.25
E	0

TABLE 4.2: Completeness of Information Index as a function of the PS deformation velocity.

area in some cases. Therefore, in order to compute the value of I_{ci} , the PS density of the building (D_o) and the surroundings (D_a) is computed and a partial score is assigned to the building and surrounding according to their PS density. A score of 0 is given if there are no PS, 0.25 if the density is less than the limiting density and 0.5 if it is bigger. Finally, I_{ci} is the combination of the partial score of the building and the surroundings. The maximum and minimum values that can be obtained are 1 and 0 that correspond to A and E. Table 4.2 contains the classification for all the possible values of I_{ci} . It can be considered that scores of B and A imply that there is a good PS coverage and, therefore, the results any analysis can be considered reliable.

I_{cc} provides a measurement of the status of a building ($I_{cc,o}$) and its surroundings ($I_{cc,a}$). It provides an index from A to E as a function of the maximum detected velocity, being A $|V_{max}| \leq 2.0mm/yr$ and E $|V_{max}| > 15mm/yr$. The values of the indexes have been adapted from the original values proposed by Pratesi et al. (2015) which were developed for historical deformation assessment to the monitoring of underground construction works. It can be considered that scores over C imply a risk to the building's health. Table 4.3 contains the classification thresholds as a function of the PS deformation.

An additional consideration is made in this work. In order to assess the impact of the construction work, if the evaluation of the deformation time series prior and after

I_{cc}	PS velocity range
A	$ V_{max} < 2.0 mm/yr$
B	$2.0 \leq V_{max} < 5.0 mm/yr$
C	$5.0 \leq V_{max} < 8.0 mm/yr$
D	$8.0 \leq V_{max} < 15.0 mm/yr$
E	$ V_{max} > 15.0 mm/yr$

TABLE 4.3: Conservation Criticality index as a function of the PS deformation velocity.

the construction work introduces a change in the asset health a superscript “m” is added to the classification. In this line, the impact of the construction work on the building health is easily identified. Any modification of a classification index after a construction work should be further investigated since the building’s health can be at risk. The computation of I_{cc} relies on the availability of two velocities. The first one, prior to the construction works and the second one during the underground activities. These velocities are directly inferred from the PS deformation time series by computing a linear regression between the deformation estimations prior to the construction and the ones estimated during the underground activities.

Finally, I_{vd} quantifies the dispersion of the PS deformations. The values vary from 0.5 when the distribution is uniform and 1 if there is a great dispersion. It is computed as:

$$I_{vd} = \max\left(\frac{V_{max} - V_{mean}}{V_{max} - V_{min}}, \frac{V_{mean} - V_{min}}{V_{max} - V_{min}}\right) \quad (4.1)$$

where V_{max} , V_{min} , and V_{mean} are the maximum, minimum and average value of the set of points within the building and surroundings.

In addition to the objective analysis that these indexes provide, the normalization with a dataset dependent value allows the extrapolation of the results to any sensor technique or acquisition geometry [Pratesi et al. \(2015, 2016\)](#).

Building	I_{ci}	$I_{cc,o}$	$I_{cc,a}$	I_{vd}
B-1	C	-	D^m	0.74
B-2	B	C^m	C^m	0.77
B-3	B	D^m	D^m	0.61
B-4	A	D^m	D^m	0.67
B-5	C	D	A	0.70
B-6	A	C	C	0.52
B-7	A	D^m	A	0.67
B-8	C	C	A	0.70
B-9	B	B	B	0.54
B-10	C	B	A	N/A
B-11	A	C^m	B	0.57
Accumulated	B	C^m	C^m	0.52

TABLE 4.4: Classification indexes of the buildings affected by the underground activities carried out in Atocha. Refer to Figure 4.1 for the location of each building. The accumulated value is an average of all the analysed buildings.

4.4 Results

4.4.1 Case study: Atocha

The average PS density of the two old town urban areas that are analysed is $2.5 \cdot 10^{-3} PS/m^2$. The average density of the complete urban area of Madrid, as defined by the Corine Land uses, is $4.1 \cdot 10^{-3} PS/m^2$. This is in line with the expected results given that the area of study represents the most challenging urban scenario.

The classification indexes, I_{ci} , $I_{cc,o}$, $I_{cc,a}$ and I_{vd} , have been computed for the buildings within the area of Atocha. The results have been included in Table 4.4. Refer to Figure 4.1 for the building numeration. In addition, an accumulated value, which corresponds to the average of all the buildings has been included.

Building	I_{ci}	$I_{cc,o}$	$I_{cc,a}$	I_{vd}
Sol-10	C	-	C^m	-
Sol-11	A	B	C	0.52
Sol-12	A	C^m	C	0.53
Sol-13	C	-	C	0.58
Accumulated	B	C^m	C	0.55

TABLE 4.5: Classification indexes of the buildings affected by the underground activities carried out in Puerta del Sol. (Refer to Figure 4.2 for the location of each building. The accumulated value is an average of all the analysed buildings).

4.4.1.1 Ground-truth validation

Figures 4.4 a to d contain the comparison of the deformation time series of the levelling sections, whose location is detailed in Figure 1. Note that for section 3, no PS related points were found to assess the performance and no levelling data was obtained from section 6 since the levelling points were destroyed. Figures 4.5 a to f contain the comparison of the odd buildings of Atocha Street (Buildings B-1 to B-6) and Figures 4.6 a to d show the assessment for the even buildings (B-7 to B-9). Note that B-10 and B-11 have not been included since no strips were placed on them during the construction period.

4.4.2 Case study: Puerta del Sol

Similarly, as in the Atocha case study, the classification index of the Puerta del Sol area have been included in Table 4.5. Note that no PS belonging to Sol-10 and Sol-13 were found for the assessment.

FIGURE 4.4: Comparison of the deformation time series of the levelling points and the PSI deformations. PS deformations are joined by a dashed line. When different behaviours are identified different line colors are used.

4.4.2.1 Ground-truth validation

Figure 4.7 contains the comparison of the deformation time series of the PSI deformations and the on-ground strips. Note that no PS were found on Sol-10 and Sol-13. This is the reason why they were not included in the comparison.

FIGURE 4.5: Comparison of the deformation time series of the strips and the PSI deformations of the odd buildings of Atocha Street. PS deformations are joined by a dashed line. When different behaviours are identified different line colors are used.

FIGURE 4.6: Comparison of the deformation time series of the strips and the PSI deformations of the even buildings of Atocha Street. PS deformations are joined by a dashed line.

4.5 Discussion

The data validation shows that there is a great agreement between the on ground measurements and PSI estimations in both areas of interest. However, Figures 4.4, 4.5 and 4.6 show that quick deformation behaviour with a characteristic time higher than the revisiting time cannot be captured by the PSI technique. In this case, the

FIGURE 4.7: Comparison of the deformation time series of the strips and the PSI deformations of SOL 11 (a) and SOL 12 (b) buildings.

Envisat sensor, with a revisiting time of 35 days, cannot detect the initial uplift induced by the pre-treatment activities. Nevertheless, this limitation is reduced by the new C-band sensor Sentinel-1 A/B with a revisit time of up to 6 days.

Despite the limitation introduced by the conditions of the old city centre environment, a considerable number of PS has been obtained for the assessment of the building health. An overall $B I_{ci}$ has been obtained for both areas of study. Therefore, the results can be considered reliable and scalable to any other SAR sensor or processing method, due to the fact that they have been normalized. However, some assets were not completely evaluated, B-1, Sol-10, and Sol-13 since only data in the surroundings were found for these assets. The lack of data for these three buildings remarks two of the main limitations of the technique. B-1 is the closest construction to the section where the TBM had a malfunction which induced high deformation rate. This deformation rate is above the technical limit of Envisat sensor, which prevents from obtaining coherent points. As reported in previous works, this limit for the Envisat sensor is in 4-5 cm/yr (Crosetto et al., 2010; García et al., 2019).

Puerta del Sol area also shows another limitation of the technique which is the data availability over certain areas, as a result of the rooftops characteristics. Puerta del Sol ones are full of air conditioning systems which complicates the identification of coherent points.

None of the buildings of the Puerta del Sol area has a classification index over C, as a result of the reinforcement activities put in place during the construction period. The computation of the classification indexes of the Atocha case study shows 4 buildings with a D critical index. Three of them have worsened the classification as a result of construction works. This is explained by the problem derived from the TBM malfunction. This analysis shows one of the greatest contributions of the PSI technique to the monitoring of underground works. The on-ground measurements are usually placed a short time prior to the construction work. Therefore, unless a previous study is made it is not always possible to infer if the deformation behaviour has been induced from the underground work. The PSI deformation easily overcomes this limitation by selecting the appropriate radar images.

An additional advantage is also remarked by this assessment. During the construction period, buildings B-10 and B-11 were not monitored due to their distance to the tunnel axis and the projected pre-treatment strategy. However, the problem with the TBM prevented the treatment to be applied leading to a higher deformation than expected. As a result, $I_{cc,o}$ for B-11 scaled from B to C. Given that no on-site instrumentation is, in principle, required for the PSI technique, the monitoring area can be increased at any time.

Finally, the inspection of the dispersion index results provides an additional indicator of the velocity distribution. Values close to 1 imply irregular distributions that can lead to cracks. Buildings B-1 and B-2 show the higher dispersion indexes due

to the fact that these are the only buildings that are directly above the tunnel axis. Puerta del Sol building reinforcements have led to a uniform deformation.

4.6 Conclusions

The applicability of the PSI technique to the monitoring of underground construction works in the most challenging urban scenario has been confirmed. The advantages of the PSI technique with respect to the on-ground measurements have been pointed out such as the wide spatial and temporal coverage and the fact that no on ground instrumentation is required. In the same line, the limitations such as the maximum deformation rate that can be measured and the difficulty of obtaining PS in incoherent areas have been pointed out. Note that a reduction of the limitations can be expected with the application of the new sensors such as Sentinel-1 A/B with a reduced revisit time.

The proposed classification indexes adapted from the proposed by [Pratesi et al. \(2015\)](#) have proven to be a reliable and objective tool to assess the building health and the impact of a specific construction work. They provide an index of the PS coverage (I_{ci}), which determines the reliability of the remaining indexes, and the building health thorough the criticality (I_{cc}) and dispersion (I_{vd}) indexes. In addition, the normalization of the results reduces the dependency on the processed sensor and the algorithm used. In order to make the most of them, they have to be computed prior to and during the construction work, providing a direct assessment of the construction impact.

The classification indexes show that there is a good PS coverage to assess the building health in the areas of study. In the Puerta del Sol area, none of the buildings was classified over C although no PS data was found in two of the buildings. In the

Atocha area, as a result of the underground work, 4 buildings scaled to an I_{cc} of D, indicating that independent and specific analyses should be conducted for these cases.

In line with previous works ([García et al., 2019](#)), the integration of PSI and on ground traditional techniques has proven to be the most reliable source of monitoring data, especially for sensitive environments such as the historical city centres. Most of the identified limitations of the PSI technique are expected to be eased by the processing of sensors with a reduced revisit time such a Sentinel-1 A/B or COSMO-SkyMed. Therefore, the promising results obtained in this work can be extrapolated to any low revisit time sensor.

CHAPTER 5

GENERAL DISCUSSION

The rapidly changing metropolitan area of Madrid represents the perfect scenario to assess the performance of any radar application. The combination of the evolving urban and rural areas where numerous on ground and underground works were carried out in the last decades provide a wide variety of areas for the validation of the technique.

The results in chapters [2](#), [3](#) and [4](#) prove the reliability and the wide area capabilities of the PSI results under optimal conditions (high coherence) and bring to light the limitations of the technique. Two different sources of validation data have been exploited: GNSS data and traditional monitoring techniques. The vertical accuracy of the GNSS-based positioning systems is in the order of 2-3 cm under optimal conditions (open sky, appropriate satellite coverage, and no multipath) and applying external corrections, i.e., precise orbit and clock products or local corrections systems such as RTK-DGNSS (Real Time Kinematic-Differential GNSS), ([Teunissen and Montenbruck, 2017](#)). Therefore, GNSS cannot be directly used as a reference to assess the accuracy of the PSI deformation time series but it can be used to compare the deformation tendencies, i.e., the deformation velocity, [Figure 2.5](#). In this regard,

this figure shows that there is a great agreement between the GNSS deformation velocities of all the publicly available GNSS stations in the Madrid metropolitan area and the values estimated by the PSI technique. Note that the most common scenario is that the GNSS and PSI estimations are referred to different timestamps but this has no impact in the comparison of the deformation velocities. Moreover, one of the limitations of the PSI technique is that it is difficult to identify the asset that is acting as the main scatterer for a given PS ([Hanssen et al., 2008](#)), therefore, it is not possible to obtain a PS in the antenna phase center of the GNSS receiver that allows a direct comparison. In this line, a common approach, which is also followed in chapters 2 and 3 implies the spatial interpolation of a circular buffer of points around an asset of interest. This work introduces a weighting scheme to give a higher weight to the values estimated by the PS with higher coherences which have a better a priori accuracy.

The other source of reference data used in this work for validation purposes is the traditional monitoring techniques. The measurements of levelling and strips can be used to assess the deformation time series since the accuracy of these instruments is at the millimeter level ([Ke-liang et al., 2010](#)). The first step for the comparison is the alignment to a common reference. The timestamps at which the measurements are taken do not necessarily match and, therefore, they have to be interpolated. A common approach, which is followed in chapter 3, is to interpolate the PSI measurements at the higher rate of the traditional techniques. This allows assessing the performance without reducing the number of timestamps at which a solution is given. Different interpolation algorithms have been tested, being a cubic spline the implementation that leads to a negligible interpolation error in the scenarios assessed. A linear interpolation method can be applied if the traditional measurements are resampled into the PSI deformations due to their high frequency.

The average error of the PSI deformation time series using Envisat sensor and computed as per equation 3.1 is 2.6 ± 1.4 mm for the SPN algorithm and 3.5 ± 2.0 mm for the PSP algorithm in the M-30 underground works (Chapter 3). In the area of Sol and Atocha, the error of the SPN algorithm is 2.7 ± 1.0 mm. A general accuracy figure, computed as per equation 3.1 for Envisat sensor, for the three scenarios analysed is 2.9 ± 1.5 mm. Moreover, it can be seen that the accuracy is the same for a nominal urban scenario or a city center. Similar works have provided a standard deviation comparing against levelling of 2.4 mm and 4.5 mm for Envisat and ERS, respectively, if no outliers are removed (Marinkovic et al., 2008). In the same line, Liu et al. (2014) reported a standard deviation of 3 mm for TerraSAR-X sensor. Therefore, the results obtained in this work are in line with previous works carried out in different scenarios. In terms of availability, the PS density of the SPN algorithm in the M-30 area is of $4.1 \text{ PS}/\text{m}^2$ meanwhile in the areas of the city center analysed in this work the average density is $2.5 \text{ PS}/\text{m}^2$. Therefore, the city center scenario mainly impacts the PS availability which is reduced around 39% due to the challenging conditions of the city center.

The comparative analysis of the different datasets processed in this work also allows the assessment of the performance of the different frequency bands and satellite missions as well as the algorithms used in the processing. First of all, as it was expected, X-band PS density is between 10-20 times bigger than in C-band sensors, as a result of the reduced revisiting time and higher resolution. This is in line with previous works (Bovenga et al., 2012; Prati et al., 2010; Sansosti et al., 2014). Regarding C-band sensors, it was expected to have an increased availability, A , with the evolution of the C-band sensors, i.e., $A_{\text{Sentinel}} > A_{\text{Envisat}} > A_{\text{ERS}}$. However, in this case, and for the algorithms processed, PSP SPN and PSInSAR (Table 2.1), Envisat provided higher availability rates than Sentinel-1 A/B. This confirms that, although the increased revisiting time and resolution of Sentinel-1 A/B is a key

factor in the PS results, the interferometric technique is a complex process which depends on a high number of interdependent variables. In this case, more restrictive coherence thresholds and a different algorithm were used for the PSI processing. Regarding the comparison of the different algorithms used conclusive results can only be obtained from SPN and PSP algorithms given that the exact same dataset has been processed and with the same coherence threshold. In the scenarios of this work, the SPN algorithm provides higher PS density than PSP.

The work of Chapters 3 and 4 not only allows assessing the accuracy of the PSI deformation estimation but also allows the identification of the limits of the technique:

- Spatial coverage. The PSI technique provides deformation estimations for the coherent points over wide areas but these points, in principle, cannot be previously selected. Note that X-band missions ease this limitation due to the higher PS density that can be obtained with this frequency band, as it can be derived from the results in chapter 2. Nevertheless, if this increased PS density is not enough, artificial corner reflectors that ensure a coherent point in the processing can be set on an asset (Ferretti et al., 2007b).
- Frequency of the estimation update. The PSI can only provide a deformation estimation at the rate at which the acquisitions are taken. Former C-band sensors had a revisit time of 35 days. This leads to a missmodeling of rapid-changing events, as it can be clearly seen in Figure 3.8. This problem is reduced with Sentinel-1 A/B, with a revisit time of 6 days and commercial X-band sensors with a revisit time of up to 3 days.
- Limit deformation rate that can be detected. Theoretically, the limit deformation that can be detected by a SAR sensor is given by $\lambda/2$, as it was introduced

in chapter 1. The wavelength of the Envisat sensor, 5.6 cm, and the revisiting time of 35 days set the theoretical limit in 29.2 *cm/yr*. However, the actual limit has been reported in different works as 4 – 5 *cm/yr* due to the different decorrelation effects (Crosetto et al., 2010). The results of this work are in line with the previous studies since the maximum deformation rate that has been detected is 4.5 *cm/yr*. In addition and, to the author’s knowledge, this work is the first attempt to assess the degradation of the performance from the optimal conditions (stable points) (Ferretti et al., 2007b; Quin and Loreaux, 2013) to the maximum deformation, Figure 3.6. It can be seen that the error increases from 2 mm up to 4 mm when the deformation rate is increased. Therefore, it can be stated that deformation accuracy figures should always be evaluated in terms of the estimated deformation rate.

- Dependency on the sensor, algorithm, and a priori information. The outcomes of Chapters 2 and 3 show that there is a great dependency on the sensor, algorithm and the reference point used in the processing of the SAR images.
- Difficult interpretation of the results. The difficulty of identifying the point that acts as scatterer as well as the dependency on the reference point and the local effects make difficult the fast an objective interpretation of the PSI results.

In order to remove the subjectivity associated with the PS interpretation results and the dependency with the sensors and algorithm Pratesi et al. (2015) proposed a set of classifications index to rate the building health of heritage areas. However, they did not consider any building affected by construction works. In this work (Chapter 4) these classification indexes are extended to measure the criticality of the deformation, the coverage, and the dispersion velocity. The proposed classification procedure allows the straightforward assessment of the impact of a given

construction work at any point of the construction period. These classification indexes can be applied along with post-processing data mining approaches such as the proposed by [Bakon et al. \(2017\)](#) to provide a more reliable and relevant results interpretation.

Three different methodologies for the monitoring of building deformations have been investigated in this work. First of all, the GNSS measurements, which have the advantage of providing deformation estimates at a high rate (1 Hz) at the cost of the receiver infrastructure and with an accuracy of 2-3 cm in vertical height. The levelling techniques, whose main advantages are the high level of confidence in their capabilities after decades of usage and the millimeter accuracy they can provide. However, they require the installation of the instrumentation which, at some locations, might be inconvenient or not possible. Finally, the PSI technique allows the monitoring of wide areas with the cost of only the processing time and the images cost if a commercial X-band is used. The main limitations introduced before can be reduced by using high revisit satellite sensors and with classification indexes such as the proposed. Nevertheless, from the results of chapter [3](#) and [4](#) it can be inferred that the optimal monitoring is achieved by integrating the results of the different sensors and technologies. First of all, the data from GNSS receivers can be applied in the PSI processing to refine the results in the final geocoding step. In this line, numerous SW packages already contemplate this feature. The PSI and the traditional techniques can be used together to make the most of both of them. Traditional instruments can be placed in the most sensitive infrastructures that require high-frequency control meanwhile, the remaining ones are monitored by PSI. The junction of data can be used to cross-validate the results. Figure [5.1](#) illustrates the characteristics of the three methodologies.

Although up to date data from already ended missions such as ERS-1/2 and Envisat

FIGURE 5.1: Comparative illustration of the characteristics of the different monitoring methods analysed in this work.

cannot be obtained they can be exploited to derive historical deformation assessments. The historical data can be used to extrapolate future trends. This possibility is addressed in chapter 1. Two difficulties have to be overcome to achieve the integration of data from different sensors. First of all, all of them have to be referred to a common reference. This can be easily solved by selecting a reference and temporally interpolating or extrapolating the behaviour of the other datasets to the common reference. The second problem is derived from the fact that it is difficult to identify the same asset as scatterer in different datasets. The solution to this problem requires the spatial interpolation of the available PS data. The historical deformation of a given point of interest can be derived by adding the contributions of the PS inside a circular buffer. This work proposes an innovative weighting approach that

gives bigger weights to PS with higher coherence values. Numerous applications can be derived from this capability such as the computation of historical deformation maps. These maps (Chapter [2](#)) are of great interest, providing a first estimation of the historical ground deformation behaviour prior to starting any construction work.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

The satellite-based SAR systems provide the tools to achieve continuous monitoring of any area of the world only at the cost of the data, if any, and the processing time. Therefore, the potential of this technique is enormous. The variety of applications that can benefit from it is so large that specific algorithms have to be implemented or tuned for each one of them. Moreover, the limitations of the technique, whose standardization is as important as the identification of the benefits in the process of achieving operational solutions based on SAR technology, have to be investigated for each application. In this thesis, a concise work on the applicability of the SAR data and, more specifically, through the time series technique, has been conducted. Hereafter, the main conclusions are depicted:

1. **The impact of the algorithm and sensor used in the processing has been reported.** Under the conditions of the validation scenarios of this work, SPN provides better accuracies and densities than PSP in urban areas. This comparison effort partially fulfills **objective 1** and contributes to the different

- algorithm comparison efforts carried out in previous works (Crosetto et al., 2016; Osmanoglu et al., 2016; Sousa et al., 2011).
2. **The influence of the frequency band on the PS density has been acknowledged.** X-band provides a higher density than C-band although the advantage of C-band is that the images are free-of-charge. This is in line with the conclusions of previous works in different applications (Crosetto et al., 2010; Nutricato et al., 2010) and completes the **objective 1**.
 3. **The continuity of the ERS and Envisat SAR data archives has been confirmed in the long term** with the processing of Sentinel-1 A/B and CSK data, fulfilling **objective 2**. Although not applied in this work, data from other SAR missions are also available such as TerraSAR-X/TanDEM-X or the future launch of the RADARSAT constellation, which is expected for June 2019.
 4. **It has been shown that long data archives that cover more than 25 years can be exploited to generate historical deformation maps,** as the presented in Figure 2.12, which can be of great interest to assess the historical deformation behaviour of any area. Datasets from different sensors and processing algorithms can be combined to derive a historical time series as soon as the PS density obtained is high enough, i.e., higher than $2 \text{ PS} \cdot \text{ha}^{-1}$. This fulfills **objective 3**.
 5. **The applicability of the PSI technique to the monitoring of ground civil infrastructure has been proved** in three different scenarios: The M-30 construction works, the enlargement of Sol metro station waiting areas and the tunneling work of the Atocha-Chamartín railway. Therefore, **objective 4** has been achieved.

6. **The performance of the time series deformation estimation have been validated** against the output of a PPP process at different GNSS stations and against the measurements of geotechnical instruments such as leveling and strips that correspond to the actual monitoring instrumentation of the construction works. The comparison against GNSS shows that the deformation of both methods is in line. A quantitative assessment cannot be carried out due to the higher noise of the vertical PPP estimation. The comparison against the traditional instruments shows that an accuracy of 2.9 ± 1.5 mm can be achieved in the deformation estimation. Moreover, the large area that can be monitored with satellite-based SAR applications has been confirmed. Therefore, the potential of the PSI technique has been proved, as per **objective 5**.

7. **The limitations of the PSI technique in the monitoring of ground civil engineering have been identified.** The nature of these limitations can be classified into 4 groups: decorrelation, spatial data availability, the frequency at which estimations can be updated and the subjectivity in the interpretation of the results:

7a. **Decorrelation:** The PSI technique is highly sensitive to decorrelation problems that prevent from identifying coherent points. Vegetation growth and crowded areas are some examples of decorrelation sources. Other sources are geometric problems such as high elevations or shadowing effects, thermal effects or orbital inaccuracies. In general, these problems can be easily predicted and eased with the combination of the PSI technique with other monitoring sources.

7b. **Spatial data availability:** The PSI technique provides a time series deformation only in the coherent points. Although dense PS datasets

are usually obtained, especially with X-band sensors, it is possible that a specific point that wants to be monitored is not identified as PS. This limitation is even more critical in the historical city centers, as it has been derived in Chapter 4. In order to ease this problem, previous works propose the installation of artificial corner reflectors that ensure the coherence of a certain point (Ferretti et al., 2007b).

- 7c. **Limited measurement frequency:** The frequency at which the deformation estimation is updated is limited by the satellite revisit time. Former revisit times of 35 days of ERS and Envisat sensors have been reduced to a few days with the new satellite sensors such as the new C-band satellites, Sentinel-1 A/B, or the X-band sensors. Nevertheless, assets that require an hourly or daily estimation cannot be monitored with current satellite-based sensors.
- 7d. **Subjectivity of result interpretation:** In this work, it has been identified that the subjectivity associated with the results interpretation and the algorithm and the sensor used in the processing is a great limitation, as it had been already reported in similar works (Pratesi et al., 2015, 2016). In order to ease this problem a set of objective classification indexes has been proposed in this work.

Note that the identification of these limitations endorses the correct application of the PSI technique and fulfills **objective 5**.

8. **It has been proved that the PSI technique can be integrated with GNSS based systems or geotechnical sensors to achieve an optimal monitoring,** as per **objective 6**. Indeed, the integration can ease the aforementioned limitations of the PSI technique. Therefore, in a combined monitoring system based on PSI and geotechnical measurements, instruments

would be installed only in areas where a measurement is required with a frequency higher than the revisit time of the SAR sensor used, in areas where the deformation is expected to be higher than the actual limit deformation rate of the sensor used (e.g. in the axis of a tunneling work) and in areas where the decorrelation problems difficult the PSI estimation, such as the streets of crowded historical city centers.

9. **The limitations of the PSI technique when applied to the historical city centers have been investigated.** While the accuracy of the estimated deformation is in line with the other urban areas, a reduced PS availability has been obtained due to the decorrelation problem associated with the historical city centers (**objective 7**). Therefore, although the results show that the technique is not reliable as a primary monitoring system, it can contribute to the monitoring of non-critical areas in construction works.
10. **A set of classification indexes has been defined** that allows an objective interpretation of the PSI results and remove the dependency on the sensor and algorithm used in the processing, meeting **objective 8**.

Being the specific objectives of this work fulfilled, there are still numerous open points that have to be addressed in order to make the most of SAR data in the monitoring of ground civil structures, as it is detailed in the following section.

6.1 Future work

As a result of the activities conducted in this thesis the following future works have been identified:

- The continuity of the PSI application with the new C-band sensors has been ensured. However, a concise validation of the accuracy of the estimated deformations and the limitations, like the one performed in this work, should be carried out in a real scenario with actual on-ground data.
- As it has been identified in this work, one of the main limitations of SAR data is the decorrelation introduced by sudden deformation rates over the limit of the technique. Although a quantitative estimation of the deformation in this scenario cannot be provided, the changes of the coherence could be linked to high deformation rates if the dataset of images is processed in a sequential algorithm that estimates the coherence with each new SAR acquisition. In this line, a sudden coherence change can be used as an alert to further investigate a specific building or area.
- Real time monitoring systems cannot be achieved with satellite-based SAR systems, however, near real-time systems that automatically update the estimation information when a new acquisition is available can be achieved. In this line, an initial step has been proposed by ([Raspini et al., 2018](#)), although the process has yet to be refined and specified for each application.
- Standardization. This work has shown the relevance of identifying and clarifying the performance of the technique under different scenarios. In this line, the performance and limitations of the PSI technique for the monitoring of underground works have been clearly identified in this work. A concise and deep analysis of the performance of the technique under the different scenarios (firstly identifying the representative number of scenarios) should be carried out. The outcomes of this work and the PSIC4 project ([Raucoules et al., 2009](#)) should be considered as the foundation of this future standardization process.

- Exploit the future integration of GNSS and DInSAR in the European Plate Observing System (EPOS) initiative which will provide corner reflectors in the GNSS stations that are included in the EUREF GNSS Permanent Network (EPN). The PSI can highly benefit from this initiative by using these points as reference or ground control points for the processing.

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APPENDIX A

NEW TECHNIQUES APPLIED

TO MOVEMENTS

MONITORING IN CIVIL

ENGINEERING

Nuevas técnicas aplicadas a la auscultación de movimientos en Ingeniería Civil

New techniques applied to movements monitoring in Civil Engineering

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REVISTA **MAPPING**
Vol. 27, 188, 36-39
marzo-abril 2018
ISSN: 1131-9100

Resumen

Los avances que se han producido en los últimos años, en el campo de la instrumentación electrónica, han permitido su aplicación en numerosos campos de la ingeniería civil. En concreto, una aplicación que puede beneficiarse de los mencionados avances es la auscultación de movimientos, tanto del terreno como de las estructuras. En este artículo se exponen dos de las últimas técnicas que se están aplicando a la medición de movimientos en estructuras: El GPS diferencial con algoritmos de filtrado (DGPS filtrado) y el Láser-escáner Terrestre (Terrestrial Laser Scanner, TLS).

Dos son las características que diferencian ambas técnicas. Mientras el DGPS permite la medición en continuo, el TLS realiza sus mediciones por campañas, de igual forma que se realizaría aplicando la nivelación o la colimación angular. La segunda característica que los diferencia es la precisión obtenida. En el caso del DGPS se consigue apreciar movimientos del orden del milímetro, mientras que la precisión del TLS está cercana a los 3 milímetros, si bien se espera que evoluciones futuras mejoren la actual precisión hasta alcanzar el milímetro.

Al margen de sus precisiones, es de destacar que ambas técnicas pueden ser aplicadas con éxito a la auscultación de movimientos de estructuras y elementos relacionados con las mismas, como por ejemplo taludes, obras auxiliares, etc.

Abstract

The advances that have occurred in recent years, in the field of electronic instrumentation, have allowed their application in many fields of civil engineering. In particular, the auscultation of movements of both the terrain and the structures can benefit from the aforementioned advances. In this article two of the latest techniques that are being applied to the measurement of movements in structures are exposed: Differential GPS with filtering algorithms (filtered DGPS) and the Terrestrial Laser-scanner (TLS).

There are two characteristics that differentiate both techniques. While the DGPS allows continuous measurement, the TLS performs its measurements by campaigns, just as it would be done by applying leveling or angular collimation. The second characteristic that differentiates them is the precision obtained. In the case of the DGPS it is possible to appreciate movements of the order of the millimeter, while the TLS achieves an accuracy of 3 millimeters. Nevertheless it is expected that future enhancements will enhance this performance up to one millimeter in the near future.

Regardless of their precisions, it is noteworthy that both techniques can be applied successfully to the auscultation of movements of structures and elements related to them, such as slopes, auxiliary structures, etc.

Keywords: DGPS filtrado, Láser-escáner Terrestre, TLS, auscultación, control de movimientos en estructuras.

Palabras clave: Filtered DGPS, Terrestrial Laser Scanner, TLS, monitoring, structures movements control.

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Recepción 16/01/2018

Aprobación 26/02/2018

APPENDIX B

**EVOLUTION OF URBAN
MONITORING WITH RADAR
INTERFEROMETRY IN
MADRID CITY:
PERFORMANCE OF
ERS-1/ERS-2, ENVISAT,
COSMO-SKYMED, AND
SENTINEL-1 PRODUCTS**

Evolution of urban monitoring with radar interferometry in Madrid City: performance of ERS-1/ERS-2, ENVISAT, COSMO-SkyMed, and Sentinel-1 products

Adrián Jesús García, Matus Bakon, Rubén Martínez & Miguel Marchamalo

To cite this article: Adrián Jesús García, Matus Bakon, Rubén Martínez & Miguel Marchamalo (2018) Evolution of urban monitoring with radar interferometry in Madrid City: performance of ERS-1/ERS-2, ENVISAT, COSMO-SkyMed, and Sentinel-1 products, International Journal of Remote Sensing, 39:9, 2969-2990, DOI: [10.1080/01431161.2018.1437299](https://doi.org/10.1080/01431161.2018.1437299)

To link to this article: <https://doi.org/10.1080/01431161.2018.1437299>

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APPENDIX C

**HISTORICAL MONITORING
OF URBAN SUBSIDENCE
BASED ON LONG-TERM SAR
DATA ARCHIVES**

Historical monitoring of urban subsidence based on long-term SAR data archives

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Abstract

Civil engineering works represent a key end user of the Synthetic Aperture Radar (SAR) archives. The great amount of SAR data collected over the last 30 years allows the generation of historical deformation maps for target areas of interest. A concept proof of the potential of historical deformation maps is presented using the Madrid urban area as a testing environment. For this purpose, 4 different C-band SAR datasets from ERS, Envisat and Sentinel-1 and 1 X-band dataset, COSMO Sky-Med, are used in this work covering 25 years. The data of the considered SAR datasets have been processed with different Persistent Scatterer Interferometry (PSI) algorithms. The outputs have been combined over a grid buffering the contributions of the different PSI in the area obtaining a historical deformation map which has been validated with GNSS measurements.

Keywords: SAR; PSI; MT-InSAR; Historical deformation.

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APPENDIX D

INTEGRATING

GEOTECHNICAL AND SAR

DATA FOR THE MONITORING

OF UNDERGROUND WORKS

IN THE MADRID URBAN

AREA: APPLICATION OF THE

PERSISTENT SCATTERER

INTERFEROMETRY

TECHNIQUE

Integrating geotechnical and SAR data for the monitoring of underground works in the Madrid urban area: Application of the Persistent Scatterer Interferometry technique

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ARTICLE INFO

Keywords:

PSI
SAR
PSI validation
Deformation monitoring
DInSAR
Sensor fusion

ABSTRACT

The Differential Interferometric Synthetic Aperture Radar (DInSAR) is a powerful deformation control technique for civil engineering applications. However, the performance definition and limitations of the technique in tunneling works are far from being standardized. This work presents a thorough validation effort of the applicability of the Persistent Scatterer Interferometry (PSI) technique to the Madrid's M-30 tunneling works. A set of 26 Envisat images, covering from August 2003 to April 2008, were processed with two PSI techniques and the results were validated with on-ground measurements from leveling benchmarks and strips. The comparison of the deformations of more than 1500 control points has led to a global deformation difference of 2.6 mm RMS and 3.5 mm RMS with a coverage of the area of interest with persistent scatterers of 65% and 34% for the two PSI algorithms used. The limitations of the PSI technique when using SAR missions with low revisit time were shown. PSI has proven the potential to complement on ground monitoring techniques in tunneling works as soon as the limitations are overcome.

1. Introduction

The Persistent Scatterer Interferometry (PSI), the most developed differential Interferometric Synthetic Aperture Radar (DInSAR) technique, is a powerful remote sensing technique that allows the estimation of Earth surface's deformation with an accuracy of up to 1 mm/yr in optimal conditions (Armas et al., 2017; Wang et al., 2018; Castellazzi et al., 2017; Cigna and Sowter, 2017; Maghsoudi et al., 2018; Yang et al., 2018). From the initial approach of Ferretti et al. (2001), different algorithms have been proposed that exploit the phase information contained on a set of radar images taken over the same area and with the same sensor (Costantini et al., 2008; Duro et al., 2005; Perissin and Wang, 2012). Concise reviews of all the currently available techniques were carried out by Osmanoglu et al. (2016) and Crosetto et al. (2016) using as inputs the different works that have been conducted in the line of the PSI exploitation.

Although the potential and capabilities of the PSI technique have been shown in numerous applications in the last decade (Crosetto et al., 2010), the actual limits of the technique are far from being

standardized. Uncertainties such as the deformation rates that can be observed, the geocoding error, the assumption of a linear deformation and the sensitivity to phase noise have limited the application of the SAR-based monitoring techniques to operational subsidence control systems. In order to put the PSI techniques at the level of the geodetic and geotechnical deformation measurement techniques, a concise and deep validation effort for each specific application has to be conducted. The outcome of this validation process should be a clear definition of the scenario and specific conditions under which PSI can be used as a reliable deformation control technique in tunneling works.

Different validation efforts have been carried out in the recent years aiming at validating the applicability of the PSI techniques to specific applications. Two main important validation works were carried out in the frame of the Terrafirma and the Persistent Scatterer Interferometry Codes Cross-Comparison And Certification (PSIC4) projects. The Terrafirma project, funded by ESA, aims at creating a European ground hazard information service. The validation activities carried out within the project were divided into two main parts: the process validation (Adam et al., 2009), and the product validation (Hanssen et al., 2008).

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<https://doi.org/10.1016/j.jag.2018.08.025>

Received 14 May 2018; Received in revised form 25 August 2018; Accepted 31 August 2018

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APPENDIX E

MONITORING

UNDERGROUND WORKS IN

THE MADRID URBAN AREA:

DINSAR VS CONVENTIONAL

TECHNIQUES

1. Introduction

The PSI applied to measure surface subsidence has several **advantages** including **large area** coverage with a single image (10,000 km²), **lower cost** per m² compared to conventional techniques and the possibility of obtaining **data before, during and after the construction** or phenomenon that is being studied. Although the potential and capabilities of the PSI technique have been shown in numerous applications in the last decade (Crosetto et al., 2010), the actual limits of the technique are far from being standardized, especially when applied to the monitoring of construction works.

In this work, the **potential and limits** of the PSI technique are compared against conventional techniques allowing a cross-validation of PSI technique and the assessment of the potential benefits of the **integration** of both techniques.

- **M-30 tunneling mega project** recovered an area of 1,210,881 m² transformed into a linear park.
- Expansion of **underground lines**
- **Construction**
- **Roads and streets**
- **Aquifer extractions**

2. Material and methods

A validation of the PSI technique, from the point of view of an end-user, is carried out using as the testing environment the **urban area of Madrid** during the **construction works of the M-30 tunnel**, which were conducted from November 2005 to October 2006. The outputs of two PSI processing are compared against the **on-ground geotechnical techniques** used during the construction work.

A set of 26 Envisat images in ascending mode covering the complete construction period of the By-Pass M-30 have been processed. The processed images, taken with the Advanced Synthetic Aperture Radar (ASAR) Image Mode (IM), cover from **August 2003 to April 2008**. The polarization was Vertical (V) both on send and receive. Two different PSI algorithms have been used for validation purposes. The first one relies on the SPN technique (Crosetto et al., 2008; Duro et al., 2005). The second PSI processing relies on the PSP technique (Costantini et al., 2008)

A total of 1545 ground control points, 1145 strips located on building sides and 300 on ground leveling points were placed for the monitoring of the M-30 works and the actual data is used in this work. PSI results have been spatially and temporally **interpolated** to perform the comparison.

Data availability and accuracy as a function of the deformation rate has been investigated.

3. Results

Algorithm	Availability	RMS
SPN	65	2.6 ± 1.4 mm
PSP	34	3.5 ± 2.0 mm

$$RMS(k) = \sqrt{\frac{\sum_{t=1}^{t=N(k)} (x_{PS}(k, t) - x_{Ref}(k, t))^2}{N(k)}}$$

4. Conclusions and further research

- ❖ Two main **limitations** have been identified. First of all, deformation rates of more than 5 cm/yr are not detected by the Envisat sensor, in line with previous works in other applications (Crosetto et al., 2010). Moreover, the revisit time makes it impossible to detect deformations in near-real time and even some deformation events could be missed.
- ❖ The **advantages** of PSI when compared to conventional techniques are the reduced cost, the large area covered and the temporal coverage (even with different sensors (Garcia et al., 2018)). The main **disadvantages** are the lack of information in vegetated areas and the frequency of the measurements which depends on the satellite revisit time. Moreover, the accuracy of the PSI techniques reduces with the magnitude of the deformation rate.
- ❖ The integration of conventional and PSI techniques can lead to the optimal monitoring of construction work. PSI provides a low-cost monitoring of large areas, meanwhile, a reduced number of conventional instruments are placed in areas where a high-frequency measurement is required (Garcia et al., 2019).

FURTHER RESEARCH LINES:

- ❖ **Conduct** an analogous analysis with X-band sensors to check the impact of the increased availability and higher resolution.
- ❖ Assess the **integration** of GNSS, conventional instruments and PSI to achieve the most optimal construction monitoring.
- ❖ **Standardize** the usage of PSI technique.

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