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Escuela de Doctorado

TESIS DOCTORAL



**CINEMÁTICA 3D DE LA PENÍNSULA IBÉRICA
Y MARRUECOS A PARTIR DE SERIES
TEMPORALES DE LAS ESTACIONES CGPS
TOPO-IBERIA (2008–2019): EVALUACIÓN DE
LA CALIDAD Y ESTRATEGIA DE PROCESADO**

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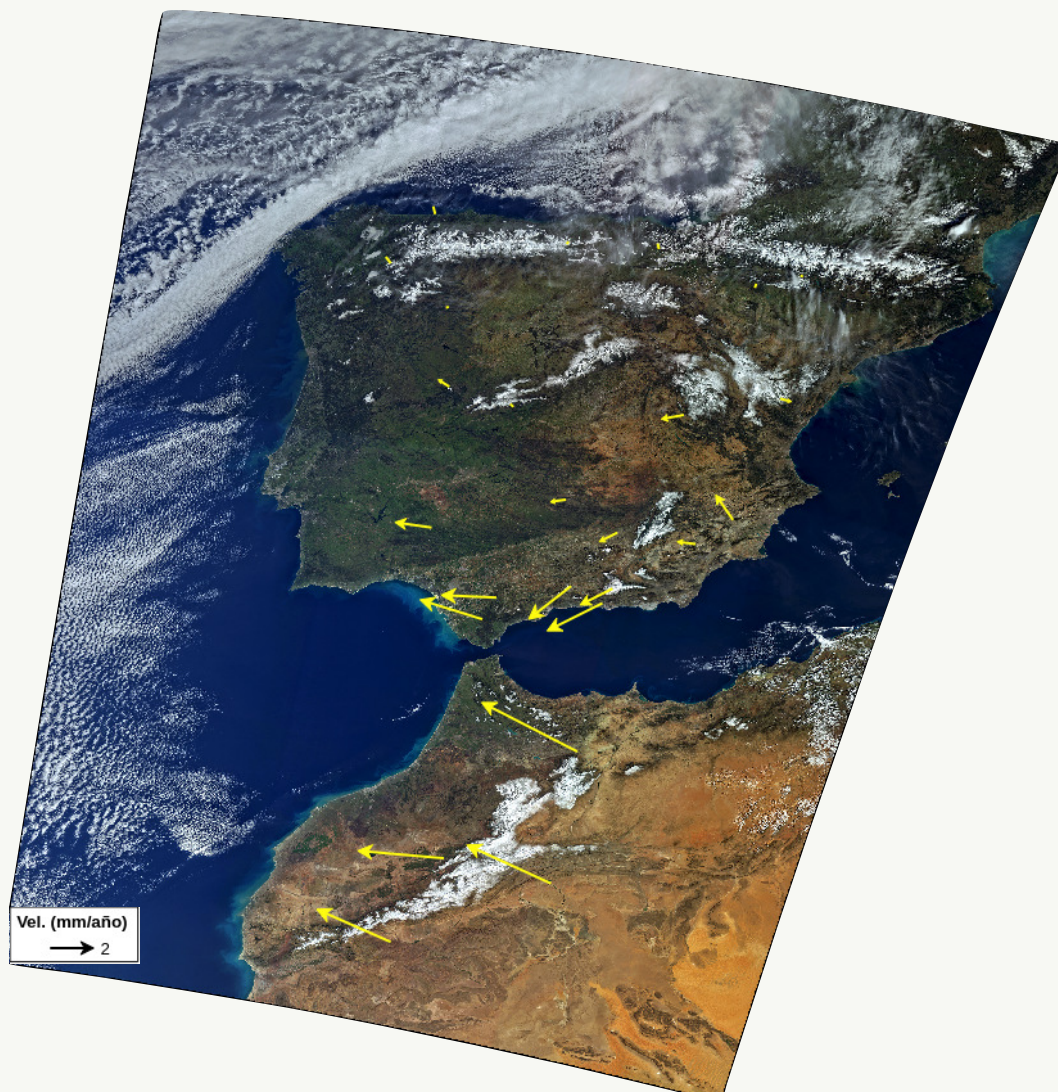


CEACTEMA
CENTRO DE ESTUDIOS AVANZADOS
EN CIENCIAS DE LA TIERRA,
ENERGÍA Y MEDIO AMBIENTE

Cinemática 3D de la península ibérica y Marruecos a partir de series temporales de las estaciones CGPS Topo-Iberia (2008–2019): evaluación de la calidad y estrategia de procesamiento

Tesis doctoral

Juan Antonio García Armenteros



Director

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Imagen de la cubierta: una de las primeras imágenes del satélite Sentinel-3A que muestra la península ibérica y el norte de África tomada el 1 de marzo de 2016 (https://www.esa.int/Space_in_Member_States/Spain/La_Peninsula_Iberica_entre_las_primeras_vistas_de_la_Tierra_desde_Sentinel-3A). La imagen ha sido modificada con QGIS 2.18 (<https://www.qgis.org>) georreferenciándola en el sistema ETRS89 (European Terrestrial Reference System 1989). Los vectores en color amarillo corresponden a las velocidades horizontales GPS (Eurasia fijada) de las estaciones Topo-Iberia calculadas en esta tesis.

Imagen de la contracubierta: fotografía del pilar y antena GNSS de la estación PILA (Sierra de la Pila, Murcia, España) de la red CGPS Topo-Iberia tomada el 13 de junio de 2017.



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Departamento de Geología

Mario Sánchez Gómez, Profesor titular del Departamento de Geología de la Universidad de Jaén.

CERTIFICA:

Que la presente memoria titulada *Cinemática 3D de la península ibérica y Marruecos a partir de series temporales de las estaciones CGPS Topo-Iberia (2008–2019): evaluación de la calidad y estrategia de procesado*, presentada por D. Juan Antonio García Armenteros para optar al grado de Doctor por la Universidad de Jaén en el Programa de Doctorado en Ciencia y Tecnología de la Tierra y del Medio Ambiente, ha sido realizada bajo mi dirección en el Centro de Estudios Avanzados en Ciencias de la Tierra, Energía y Medio Ambiente de la Universidad de Jaén.

Considerando su nivel científico y académico, autorizo su presentación para optar al grado de Doctor por la Universidad de Jaén en el Programa de Doctorado en Ciencia y Tecnología de la Tierra y del Medio Ambiente.

Y para que conste, firmo el presente certificado en Jaén, a 16 de noviembre de 2023

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Resumen

Esta tesis presenta la cinemática 3D actual de la península ibérica y Marruecos a partir de los datos disponibles de la red CGPS Topo-Iberia (2008–2019), utilizando una estrategia de procesamiento que combina diferentes técnicas de posicionamiento GNSS, y evaluando la calidad de todas sus estaciones y datos. Se ha usado el programa GAMIT (técnica de doble diferenciación) y el programa GipsyX (posicionamiento de punto preciso) combinando sus soluciones mediante un filtro kalman (GLOBK). La solución velocidad combinada se presenta como el nuevo campo de velocidad GPS horizontal y el primer campo vertical de la red Topo-Iberia basado en 11 años. Para aplicar esta estrategia es necesaria la conversión de los archivos GipsyX gdcov a SINEX, y se proporciona un programa creado específicamente para ello. Los resultados en el marco de referencia IGB14 (Eurasia fijada) coinciden en general con los obtenidos en anteriores investigaciones, excepto por algunas discrepancias en estaciones concretas en el sector central de la Cordillera Bética donde las nuevas velocidades son generalmente más bajas y presentan una mayor componente hacia el suroeste, y en el sector occidental hacia el noroeste, en lugar de un movimiento puramente hacia el oeste. A partir de las nuevas velocidades se ha determinado en los sectores central y oriental de las Béticas una tasa media de convergencia noroeste-sureste de 4 ± 0.1 mm/año con respecto a Nubia. En la península ibérica se observa una baja subsidencia generalizada (valor medio de 0.5 ± 0.1 mm/año), excepto en algunas estaciones aisladas que presentan levantamiento.

Se ha evaluado la calidad de los datos de las 26 estaciones Topo-Iberia en base a indicadores de calidad contemplados en las directrices del IGS para estaciones GNSS y, tomando como referencia los valores recomendados, tres estaciones han destacado como las de peor calidad y, por el contrario, cuatro cumplen los requisitos para ser una estación del IGS. Los resultados revelan una relación inversamente proporcional entre la calidad de los datos y los residuales de fase post-ajuste derivados de su procesamiento. Se ha encontrado que las estaciones que muestran cambios en el horizonte de oclusión también presentan un aumento en los saltos de ciclo y efecto multitrayectoria, y están en el grupo de las estaciones de peor calidad y más alta dispersión RMS post-ajuste de los residuales de fase. Además, se debería tener en cuenta la evolución de la vegetación alrededor de la antena, ya que podría provocar una pérdida progresiva de la calidad, no cumpliendo así los estándares del IGS. También se ha propuesto un método para caracterizar la calidad de los datos GNSS basado principalmente en el porcentaje de cumplimiento conjunto de los indicadores de la calidad, y no individualmente.

Se ha determinado la relación entre el entorno de la antena y los residuales de fase dependientes del ángulo de elevación (elmean) derivados de GAMIT, y a partir de la forma del patrón resultante de la traza de estos residuales se han establecido cinco tipos. Además, se ha creado un diagrama de tipos de patrones que podría ser útil para seleccionar el entorno óptimo para una antena GNSS. Se ha propuesto una nueva métrica para cuantificar las diferencias entre patrones, el índice de diferencia de patrones de residuales de fase (PRPDI), que ha resultado ser una buena herramienta para identificar cambios en el entorno de la antena, así como las estaciones de mejor y peor calidad. Los valores más altos de PRPDI corresponden a las estaciones de peor calidad y que han mostrado cambios en el horizonte de oclusión. Los resultados también revelan que los residuales de fase elmean más pequeños se producen en entornos de antena con terreno irregular y cubierta vegetal, y los residuales más altos se producen en tejados planos de edificios. También se ha determinado que los monumentos de la red Topo-Iberia presentan un nivel de ruido de camino aleatorio (RW) adecuado para un monumento geodésico. Las estaciones con pilar estándar y con monumento reforzado de perforación corta sobre lecho rocoso (SDBM) presentan menos ruido que aquellas con pilar pequeño y con monumento sobre edificio. Los resultados respecto a los tipos de monumentos menos ruidosos coinciden con los de publicaciones previas. No se ha observado relación entre el ruido y la ubicación geográfica de las estaciones, pero sí entre el ruido estacional y el entorno de la antena. La evaluación de la calidad ha mostrado que las estaciones Topo-Iberia son apropiadas para fines geodésicos, pero sería necesaria su monitorización permanente para evitar la pérdida de datos y de calidad.

Palabras clave Campo de velocidad 3D · Efectos de la calidad de los datos GPS · Entorno de antenna · Estándar de calidad IGS · Estrategia de procesamiento GPS · Evaluación de la calidad · GAMIT/GLOBK · GipsyX · Patrón de residuales de fase elmean · PRPDI · Red CGPS Topo-Iberia · Región Ibérica-Marroquí · Ruido de monumento geodésico

Abstract

This thesis presents the 3D kinematics of the Iberian Peninsula and Morocco based on the available data from Topo-Iberia CGPS network (2008–2019), using a processing strategy that combines different GNSS positioning techniques, and evaluating the quality of all the stations and data. The GAMIT software (double-differencing technique) and the GipsyX software (precise point positioning) have been used, combining their solutions through a kalman filter (GLOBK). The combined velocity solution is presented as a new horizontal GPS velocity field and the first vertical velocity field from the Topo-Iberia network based on 11 years. A program created to convert GipsyX gdcov files to SINEX files is also provided, which is necessary to apply this strategy. The results in the IGB14 reference frame (fixed Eurasia) are in good agreement with those from previous research, except for some discrepancies at specific stations in the central sector of the Betic Cordillera where the new velocities are generally lower and present a higher southwestward component, and in the western sector a northwestwards component, rather than a purely westward motion. From the new velocities, a mean northwest-southeast convergence rate of 4 ± 0.1 mm/yr with respect to Nubia has been determined in the central and eastern sectors of the Betics. A general low subsidence (mean value of 0.5 ± 0.1 mm/yr) is observed in the Iberian Peninsula except for some isolated stations presenting uplift.

The data quality from all 26 Topo-Iberia stations has been evaluated based on the quality indicators contemplated in the IGS guidelines for GNSS stations and, considering the recommended values as a reference, three stations have stood out as the worst quality and, on the contrary, four stations meet the quality requirements to become an IGS station. The results reveal an inversely proportional relationship between the data quality and the postfit phase residuals derived from the processing. It has been found that the stations showing changes in the occlusion horizon also present an increase in the cycle slips and multipath effect, and are among the stations with the worst quality and the highest postfit RMS of phase residuals. Moreover, the evolution of the vegetation around the antenna should be considered as it could cause a progressive loss of quality, thus not meeting the IGS standards. A method has also been proposed to characterize the GNSS data quality based mainly on the compliance percentage of the quality indicators together, and not individually.

The relationship between the antenna environment and the elevation angle dependent mean (elmean) phase residuals derived from GAMIT has been determined, and based on the shape of the pattern resulting from the trace of these residuals, five types have been established. In

addition, a diagram of pattern types has been created that could be useful to select the optimal GNSS antenna environment. A new metric has been proposed to quantify the differences between patterns, the phase residuals pattern difference index (PRPDI), which has turned out to be a good tool to identify changes in the antenna environment, as well as the best and worst quality stations. The highest PRPDI values correspond to the poorest quality stations that have shown changes in the occlusion horizon. The results also reveal that the smallest elmean phase residuals are produced by antenna environments with uneven ground and vegetation cover, and the highest residuals occur on flat roof of buildings. It has also been determined that the Topo-Iberia monuments present a random-walk (RW) noise level adequate for a geodetic monument. Stations with standard pillar and with shallow-drilled braced monument (SDBM) present less noise than those with little pillar and monument on building. The results regarding the least noisy monument types agree with those of previous publications. No relationship between noise and geographical location of the stations has been observed, but between seasonal noise and the antenna environment. The quality assessment has shown that the Topo-Iberia stations are appropriate for geodetic purposes, but permanent monitoring would be necessary to avoid loss of data and quality.

Keywords 3D velocity field · Antenna environment · Elmean phase residuals pattern · GAMIT/GLOBK · Geodetic monument noise · GipsyX · GPS data quality's effects · GPS processing strategy · Iberia-Morocco region · IGS quality standard · PRPDI · Quality assessment · Topo-Iberia CGPS network

1

Introducción, objetivos y estructura de la memoria

1.1 Introducción

Topo-Iberia fue un proyecto de investigación titulado *Geociencias en Iberia: Estudios integrados «Topo-Iberia»* apoyado por el Gobierno español (Gallart 2006). La medición de la deformación cortical utilizando técnicas basadas en el Sistema Global de Navegación por Satélite (GNSS) fue una de las metodologías utilizadas, específicamente el Sistema de Posicionamiento Global (GPS). En el marco de este proyecto se estableció la red Topo-Iberia compuesta de 26 estaciones GPS en funcionamiento continuo (CGPS), cubriendo la parte española de la península ibérica (22) y Marruecos (4) (Fig. 1.1), complementando las redes existentes y estando plenamente operativa en diciembre de 2008. El Instituto Geológico y Minero de España (IGME) implantó el Sistema de Información Topo-Iberia (SiTopo) donde se almacenan los datos y cuyo acceso está limitado a los miembros del equipo Topo-Iberia a cargo del mantenimiento y control de las estaciones.

Garate et al. (2015) presentaron un campo de velocidad basado en el análisis de los primeros cuatro años de observaciones GPS continuas de la red Topo-Iberia. El análisis de datos fue realizado por tres grupos independientes utilizando tres programas científicos de procesamiento GNSS con dos enfoques diferentes: la técnica de posicionamiento de punto preciso (PPP) usando el software GIPSY/OASIS desarrollado por el Jet Propulsion Laboratory (JPL) (Zumberge et al. 1997); y la técnica de doble diferenciación usando el software Bernesse desarrollado por la Universidad de Bern (Dach et al. 2007) y el software GAMIT/GLOBK desarrollado principalmente por el Instituto Tecnológico de Massachusetts (MIT) (Herring et al. 2010). La solución final de cada grupo se transformó en un marco de referencia común y, finalmente, se calculó un campo de velocidad promedio de las tres soluciones. Con este trabajo se proporcionó un campo de velocidad de deformación cortical para la península ibérica y Marruecos basado en los primeros cuatro

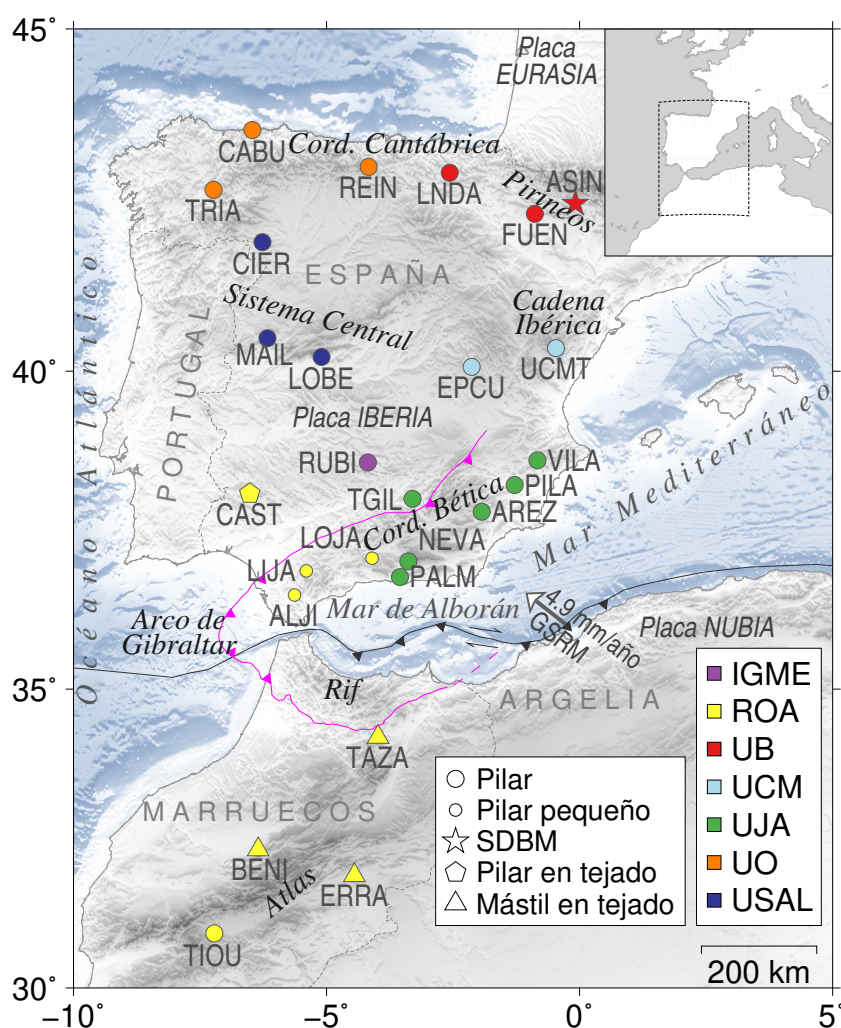


Fig. 1.1 Distribución de las estaciones CGPS Topo-Iberia en función del tipo de monumento geodésico usado y de la institución responsable, y esquema tectónico de la zona de estudio. La zona de deformación Bético-Rifeña (línea magenta) y el hipotético límite de placas Eurasia-Nubia (línea negra) se basan en Mancilla et al. (2015) y comunicación personal Sánchez-Gómez (2022). El vector gris representa la dirección de convergencia y velocidad entre las placas según el modelo GSRM (Global Strain Rate Model) v2.1. La imagen del relieve sombreado de la Tierra con iluminación desde el sur está remuestreada a 1 minuto de arco de la base de datos topográfica SRTM15+V (Tozer et al. 2019)

años de actividad, aunque solo se estimó el campo de velocidad horizontal (2D). De hecho, pocos trabajos, como Serpelloni et al. (2013), Nguyen et al. (2016), Devoti et al. (2017) y Khazaradze et al. (2019), han estimado la deformación vertical en la península ibérica hasta la fecha. El proyecto finalizó pero los diferentes grupos o instituciones a cargo de las estaciones hicieron un gran esfuerzo para mantenerlas activas, aunque algunas estaciones fueron desmanteladas (Tabla 1.1). En el momento de realizar esta investigación había disponibles más de 11 años de datos en algunas estaciones Topo-Iberia.

Por otro lado, la información sobre la calidad de los datos es esencial en las redes GNSS para asegurarse de que las estaciones funcionan correctamente y que los datos son apropiados para estudios geodinámicos. Ejemplo de este tipo de información lo proporcionan servicios internacionales a cargo de redes GNSS como la EUREF Permanent GNSS Network (EPN) (EUREF 2021) y el University NAVstar Consortium (UNAVCO) a través de la red Plate Boundary Observatory (PBO) (UNAVCO 2021), o estudios como el de García-Armenteros (2020) sobre la calidad de 6 estaciones Topo-Iberia. El poder disponer de esta información para toda la red ayudaría a seleccionar qué datos procesar y así evitar pérdidas de tiempo y de precisión, además de

Tabla 1.1 Estaciones CGPS Topo-Iberia. Identificador, localización, fecha de instalación/desmantelación (año–día del año) e institución responsable

ID	Localización	Instal. / Desmant.	Inst. ¹
ALJI	Sierra del Aljibe, Cádiz (ES)	2008–101 / - - - - -	ROA
AREZ	Sierra del Almirez, Murcia (ES)	2008–116 / - - - - -	UJA
ASIN	Asín de Broto, Huesca (ES)	2008–269 / - - - - -	UB
BENI	Beni-Mellal (MA)	2008–204 / 2013–318	ROA
CABU	Faro Cabo Busto, Asturias (ES)	2008–078 / - - - - -	UO
CAST	Castillo de Segura, Badajoz (ES)	2008–069 / - - - - -	ROA
CIER	Villardecervos, Zamora (ES)	2008–191 / - - - - -	USAL
EPCU	Polytechnic School of Cuenca (ES)	2008–185 / - - - - -	UCM
ERRA	Errachidia (MA)	2008–156 / - - - - -	ROA
FUEN	Fuencalderas, Huesca (ES)	2008–205 / - - - - -	UB
LIJA	Sierra de Líjar, Cádiz (ES)	2008–043 / - - - - -	ROA
LNDA	Landa, Alava (ES)	2008–214 / - - - - -	UB
LOBE	Lobera, Avila (ES)	2008–191 / - - - - -	USAL
LOJA	Loja, Granada (ES)	2008–069 / - - - - -	ROA
MAIL	Maillo, Salamanca (ES)	2008–218 / - - - - -	USAL
NEVA	Sierra Nevada, Granada (ES)	2008–291 / - - - - -	UJA
PALM	Sierra los Guájares, Granada (ES)	2008–157 / - - - - -	UJA
PILA	Sierra de la Pila, Murcia (ES)	2008–165 / - - - - -	UJA
REIN	Reinosa, Cantabria (ES)	2008–137 / - - - - -	UO
RUBI	Cabezarrubias, Ciudad Real (ES)	2008–127 / - - - - -	IGME
TAZA	Taza, Fes (MA)	2008–204 / 2014–044	ROA
TGIL	Torreperogil, Jaén (ES)	2008–099 / 2017–277	UJA
TIOU	Tiouine (MA)	2008–156 / - - - - -	ROA
TRIA	Triacastela, Lugo (ES)	2008–106 / - - - - -	UO
UCMT	Mosqueruela, Teruel (ES)	2008–197 / - - - - -	UCM
VILA	Sierra de la Villa, Alicante (ES)	2008–253 / 2009–249	UJA

¹Institución responsable: Instituto Geológico y Minero de España (IGME), Real Observatorio de la Armada (ROA), Universidad de Barcelona (UB), Universidad Complutense de Madrid (UCM), Universidad de Jaén (UJA), Universidad de Oviedo (UO), Universidad de Salamanca (USAL)

ser esencial para comprender el comportamiento de la estación y servir de apoyo en el posterior análisis de series temporales. El IGME, actualmente dependiente del CSIC, realiza la labor de almacenamiento de los datos Topo-Iberia, pero no ofrece este tipo de información.

Entre los elementos a considerar en relación a la calidad de una red GNSS permanente con fines geodésicos, como la red Topo-Iberia, están el equipamiento instalado, la estabilidad del monumento que lo sostiene y la ubicación o entorno de la estación. En relación con éste último, los residuales de fase de la combinación libre de ionosfera (LC) del procesamiento GPS con GAMIT varían en azimuth y elevación sobre el horizonte en función del efecto multitrayectoria del entorno de la antena del receptor. Herring et al. (2016) encontraron que esta dependencia en elevación de los residuales de fase, promediados sobre todos los azimuths, es útil para determinar el modelamiento de fase y del efecto multitrayectoria en cada estación. El efecto multitrayecto-

ria producido por el entorno de la antena es característico del emplazamiento, y generalmente es más o menos constante en el tiempo, lo que permitiría relacionar los residuales de fase LC promediados dependientes del ángulo de elevación (elmean) con el entorno de cada emplazamiento.

La instalación del equipamiento de las estaciones Topo-Iberia siguió los criterios recomendados por el University Navistar Consortium (UNAVCO) (Gárate et al. 2008) y las antenas se instalaron principalmente en pilares de hormigón sobre lecho rocoso para mayor estabilidad, aunque también se usó: pilar pequeño de hormigón sobre lecho rocoso con dos cuerpos y altura de 0.344 m; pilar de hormigón en tejado de edificio; monumento reforzado de perforación corta sobre lecho rocoso (SDBM); y mástil de acero sobre tejado de edificio (Fig. 1.1). La inestabilidad de los monumentos geodésicos debido a los diferentes medios de anclaje se considera una fuente importante de ruido y se piensa que sigue un proceso de camino aleatorio (RW) (Johnson y Agnew 1995), pero hasta la fecha no se ha realizado ninguna investigación sobre el ruido de los monumentos usados en la red Topo-Iberia.

1.2 Marco tectónico

La península ibérica se puede dividir en tres grandes cadenas montañosas, separadas por dos mesetas (Fernández-Lozano et al. 2011): (1) la cordillera Pirenaico-Cantábrica (en el norte); (2) la región central incluyendo las regiones deformadas del interior de la placa como el Sistema Central y la Cadena Ibérica; y (3) el sistema Bético-Rifeño (en el sur) incluyendo el límite de placas convergente noroeste-sureste de Eurasia-Nubia (África) en el Mediterráneo más occidental. En un marco de referencia con Eurasia fijada, la mayor deformación horizontal se localiza en este tercer dominio, lo que convierte a las Béticas en la zona tectónicamente más activa de la península. Las placas convergen en esta región a una velocidad de 4.9 mm/año (vector gris en Fig. 1.1) según el modelo de movimiento de placas GSRM v2.1 (Kreemer et al. 2014), calculado utilizando la Calculadora de movimiento de placas de Geodetic Facility for the Advancement of Geoscience (GAGE) operado por EarthScope Consortium (<https://www.unavco.org/software/geodetic-utilities/plate-motion-calculator/plate-motion-calculator.html>).

Se han realizado numerosos estudios sobre la deformación a lo largo del límite de placas Eurasia-Nubia en esta región, como Koulali et al. (2011) que establecieron movimientos oeste-suroeste con respecto a Eurasia ($\sim 2\text{--}3$ mm/año) en la parte suroeste de la Cordillera Bética. En general se admite que el orógeno Bético-Rifeño, aunque instalado en gran parte sobre el límite de placa, ha tenido una evolución controlada por el hundimiento de una losa litosférica (roll-back) de naturaleza mixta continental-oceánica (Lonergan y White 1997; Duggen et al. 2008). Este proceso, determina una compleja situación de desplazamientos hacia el oeste, compresión y extensión, junto con la mencionada aproximación entre Eurasia y Nubia (p.ej. García-Dueñas et al. 1992; Alfaro et al. 2002; Martínez-Martínez et al. 2006; Balanyá et al. 2007), que está ligada a una igualmente compleja estructura subcortical (Gurtner y Estey 2012; Mancilla et al. 2015).

En la Cordillera Bética oriental, dentro del complejo contexto general de extensión y desplazamientos hacia el oeste, existen tectónicas compresivas activas moderadas (Palano et al. 2013; Galindo-Zaldivar et al. 2015), donde parte de la convergencia entre Nubia y Eurasia se acomoda mediante acortamiento (Borque et al. 2019). En la Cordillera Bética occidental, el desarrollo del Arco de Gibraltar, cinturón tectónico que conecta las Cordilleras Bética y Rif que rodean el Mar de Alborán, continúa en el presente (Gonzalez-Castillo et al. 2015). En este contexto, es clave determinar las interacciones entre la zona Bética y Rifeña, y sus respectivos antepaíses ibérico y nubio, mediante el estudio preciso de la cinemática actual.

1.3 Objetivos

El objetivo fundamental de esta tesis es ofrecer la cinemática 3D actual de la península ibérica y Marruecos a partir de los datos disponibles de la red CGPS Topo-Iberia, utilizando una estrategia de procesamiento que combine las diferentes técnicas de posicionamiento GNSS existentes, y evaluar la calidad de todas sus estaciones y datos.

Para alcanzar este objetivo principal los objetivos específicos planteados son:

1. Evaluar la calidad de las estaciones y datos GPS Topo-Iberia, identificando los datos problemáticos o anómalos que pudieran afectar al resultado final.
2. Establecer una estrategia de procesamiento GPS combinando diferentes técnicas de posicionamiento sin redundancia.
3. Obtener un campo de velocidad GPS confiable a partir de los datos Topo-Iberia disponibles, incluyendo la componente vertical.
4. Establecer la relación entre la calidad de los datos GPS y los residuales de fase LC post-ajuste derivados de su procesamiento.
5. Determinar la posible relación entre el entorno de la antena en cada estación Topo-Iberia y los residuales de fase elmean.
6. Determinar la posible relación entre el ruido estimado y el tipo de monumento geodésico usado en cada estación.
7. Proponer nuevos parámetros o métodos para evaluar la calidad de las estaciones y datos, de modo que ayuden a cumplir los requisitos de calidad recomendados en redes GNSS.

En la evaluación de la calidad se tomará como referencia las recomendaciones y valores establecidos por el Servicio Internacional GNSS (IGS) en sus estaciones, siendo el umbral de calidad principal el correspondiente a los valores mínimos recomendados (REC) para ser una

estación del IGS. De este modo también se pretende evaluar si las estaciones Topo-Iberia tendrían la calidad suficiente para serlo. Los parámetros o indicadores a tener en cuenta son los habituales en los controles de calidad GNSS, como son el número máximo de observaciones registradas (OBS), la integridad (INT), número de saltos de ciclo por cada 1000 observaciones (CSR) y el valor medio cuadrático (RMS) del efecto multitrayectoria en L1 y L2 (MP1 y MP2).

En la estrategia de procesado GPS se mantiene la premisa de que el software no sea redundante atendiendo a la técnica de posicionamiento que utiliza, es decir, un programa por cada técnica de posicionamiento. Para este propósito se ha elegido la estrategia de procesado y combinación establecida por Herring et al. (2016). Entre los programas que utilizan la técnica de doble diferenciación se ha elegido a GAMIT versión 10.71 (Herring et al. 2018), y para la técnica PPP se ha elegido a GipsyX versión 1.7 (Bertiger et al. 2020). Las soluciones de ambos programas se combinan mediante un filtro kalman (GLOBK). Un inconveniente de promediar o combinar la solución final de cada programa es que cualquier anomalía en el procesado individual o en los datos usados se transmite a la solución final combinada. En la metodología seguida, la combinación forma parte de la estrategia de procesamiento, no de los resultados finales. Es decir, cuando se realiza la combinación de una nueva solución diaria libremente constreñida de GAMIT con la de GipsyX, GLOBK calcula el incremento χ^2 que ocurriría si los datos de la nueva solución diaria se añadieran a la solución combinada. Si este incremento excede una tolerancia dada, los datos son excluidos (Herring et al. 2015). De este modo se evita que datos corruptos o estaciones con valores no razonables contaminen el resultado de la solución final combinada.

Además de estimar las velocidades con mayor precisión al disponer de series temporales más largas, 11 años en algunos casos, se ofrecería el primer campo de velocidad 3D de la red Topo-Iberia. Para ello, además de las estaciones pertenecientes al proyecto, se seleccionarán estaciones de referencia de operación continua (CORS) de redes geodésicas internacionales públicas idóneas para la zona de estudio.

Se pretende investigar cómo la calidad de los datos GPS afecta a los resultados de su procesamiento con GAMIT y GipsyX, es decir, la relación entre la calidad de los datos GPS y los residuales de fase LC post-ajuste derivados de su correspondiente estrategia de procesado. También se pretende determinar la relación entre el entorno de la antena y los residuales de fase elmean, así como con la calidad de los datos GPS de las estaciones Topo-Iberia. Esta investigación se realiza por primera vez en estas estaciones evaluando cómo el tipo de terreno en el que se ubica la antena afecta al posicionamiento, su idoneidad para una estación geodésica, si el entorno de la antena es estable o no, y sus consecuencias. Además, se analizará el ruido asociado a señales periódicas, es decir, el ruido estacional. Este análisis se basa en el ruido de fondo de las series temporales de posición GPS obtenidas en el procesamiento.

1.4 Estructura de la memoria

Esta tesis doctoral se presenta como un conjunto de trabajos publicados por el doctorando (*tesis por compendio*), que de acuerdo con el Reglamento de los Estudios de Doctorado de la Universidad de Jaén, deberá estar conformado por un mínimo de dos artículos publicados o aceptados, su calidad estará acreditada de acuerdo a los criterios establecidos por la Comisión Nacional Evaluadora de la Actividad Investigadora (CNEAI), y habrán sido aceptados para su publicación con posterioridad al inicio de los estudios de doctorado. Aunque la parte más importante de esta tesis es la correspondiente a las publicaciones, es necesario incluir una introducción en la que se justifique la unidad temática de la tesis, objetivos a alcanzar (ambos contenidos en este capítulo 1), un resumen global de los resultados, la discusión integrada de estos resultados y las conclusiones finales. En esta memoria cada una de las publicaciones se corresponde con un capítulo, y estas publicaciones tienen asociados varios suplementos electrónicos con gran número de figuras y tablas sobre sus resultados. A fin de facilitar su consulta y mejorar la exposición, parte del material suplementario se ha incluido en esta memoria como un apéndice en su respectivo capítulo. Para facilitar también la consulta de referencias citadas en el texto, cada capítulo finaliza con su apartado de referencias correspondiente. El contenido de los capítulos se describe a continuación:

Capítulo 2 *Topo-Iberia CGPS network: a new 3D crustal velocity field in the Iberian Peninsula and Morocco based on 11 years (2008–2019)*. Este capítulo se corresponde con el trabajo del mismo nombre publicado en *GPS Solutions* (28 junio 2023), revista de revisión por pares con un factor de impacto (Journal Impact Factor o JIF) de 4.9 (2022) y cuartil (SCImago) Q1, que además tiene 3 suplementos electrónicos disponibles en <https://rdcu.be/dfCAR> y <https://doi.org/10.1007/s10291-023-01484-8>.

En este capítulo se abordan los objetivos específicos 2 y 3. Se detalla el procesamiento de todos los datos disponibles de la red CGPS Topo-Iberia y se presenta su campo de velocidad 3D. Se ha seguido la estrategia de procesamiento y combinación establecida por Herring et al. (2016), y considerando la complejidad y la escasa literatura sobre esta estrategia, se proporciona detallada descripción de algunas de sus fases, además de algunos cambios introducidos. También se presenta el programa *gdcov2sinex.sh* creado específicamente para convertir los archivos *gdcov* de GipsyX a archivos SINEX (Solution Independent Exchange) (IERS 2006), imprescindible para aplicar la estrategia mencionada. El objetivo específico 1 se aborda parcialmente presentando una visión global de la calidad de los datos GPS Topo-Iberia con la que seleccionar además los tramos de datos óptimos para procesar.

Capítulo 3 *Quality assessment of the Topo-Iberia CGPS stations and data quality's effects on postfit ionosphere-free phase residuals*. Este capítulo se corresponde con el trabajo del mis-

mo nombre publicado en *Geodesy and Geodynamics* (1 octubre 2023), revista de revisión por pares con un JIF (2022) de 2.4 y cuartil (SCImago) Q2, con un suplemento electrónico disponible en <https://doi.org/10.1016/j.geog.2023.07.006>.

En este capítulo se abordan los objetivos específicos 1 y 4. Se evalúa la calidad de los datos GPS de la red Topo-Iberia y se proporciona información sobre la calidad de todas sus estaciones. Se describen diferentes análisis realizados a los datos basados en parámetros de la calidad tomando como referencia los valores recomendados por el IGS. También se determina la relación entre la calidad de los datos GPS y los residuales de fase LC post-ajuste derivados de su procesamiento obtenidos en el capítulo 2. Esta evaluación de la calidad es importante no sólo por ser la primera vez que se realiza en la red Topo-Iberia, sino también por mostrar si sus estaciones son apropiadas para fines geodésicos y proporcionar información esencial para el procesamiento de sus datos y posterior análisis de series temporales. Finalmente, se propone un método para caracterizar la calidad de los datos GNSS.

Capítulo 4 *Antenna environment's effects on elevation angle dependent ionosphere-free phase residuals, and geodetic monument noise in the Topo-Iberia CGPS network.* Este capítulo se corresponde con el trabajo del mismo nombre en revisión en *Journal of Geodesy* (29 agosto 2023), revista de revisión por pares con un JIF (2022) de 4.4 y cuartil (SCImago) Q1. Esta publicación también tiene un suplemento electrónico.

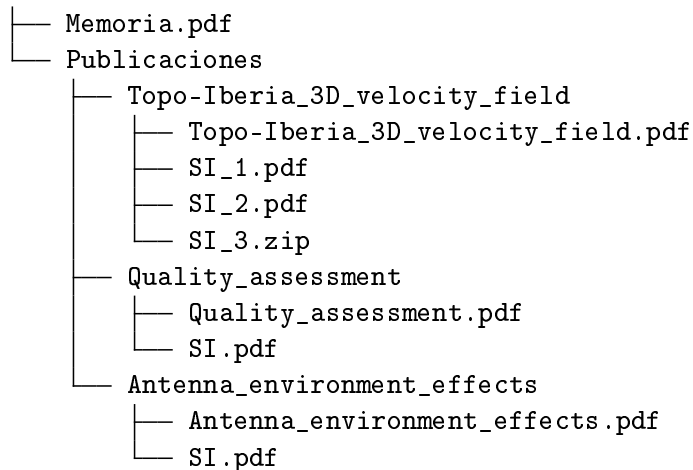
En este capítulo se abordan los objetivos específicos 5 y 6. Se analiza la relación entre el entorno de la antena y los residuales de fase LC dependientes del ángulo de elevación derivados del procesamiento con GAMIT del capítulo 2. El patrón formado por la representación de estos residuales de fase elmean se ha relacionado con características del entorno de la antena definiéndose diferentes tipos de patrón que podría ser útil en la selección del entorno óptimo para una antena GNSS. Los resultados obtenidos en este capítulo también se han relacionado con los resultados de la evaluación de la calidad del capítulo 3, y se ha creado una nueva métrica para identificar cambios en el entorno de la antena y las estaciones de mejor y peor calidad, el índice de diferencia de patrones de residuales de fase (PRPDI). Finalmente se determina el ruido, incluido el asociado a señales periódicas, que presentan los diferentes tipos de monumentos geodésicos de las estaciones Topo-Iberia y su posible relación con el entorno de la antena y la ubicación geográfica.

Capítulo 5 *Resultados generales y discusión.* En este capítulo se recopilan los resultados obtenidos a la vez que se desarrolla su discusión.

Capítulo 6 *Conclusiones.* En este capítulo se enumeran las conclusiones principales que se han alcanzado durante la realización de esta tesis doctoral.

Como se ha indicado anteriormente, las publicaciones tienen asociado material suplementario electrónico que no se ha incorporado en su totalidad a esta versión impresa de la memoria, pero se proporciona en la versión digital con el siguiente contenido:

Tesis



Todo el software utilizado en esta tesis es gratuito y operado en entorno GNU/Linux. A parte de los programas GAMIT/GLOBK y GipsyX usados para el procesamiento GPS realizado en dos ordenadores con sistema operativo Debian GNU/Linux 10 (<https://www.debian.org>), se ha usado el programa GMT 5.4.5 (Wessel et al. 2013) para crear los mapas, Gnuplot 5.2 (<http://www.gnuplot.info>) para crear los gráficos y Inkscape 0.92.4 (<https://inkscape.org>) para editar las figuras. Además, en algunas figuras se ha utilizado el mapa de colores científico roma (Crameri 2021) para evitar la distorsión visual de los datos y la exclusión de lectores con deficiencias en la visión de los colores (Crameri et al. 2020). El programa gdcov2sinex se ha escrito principalmente en GNU Bash (<https://www.gnu.org/software/bash>). Otros datos y recursos adicionales utilizados se indican en el cuerpo principal.

Esta memoria se ha escrito en L^AT_EX (<https://www.latex-project.org>) con el editor Texmaker 5.0.3 (<https://www.xmlmath.net/texmaker>). Para facilitar la navegación en su versión digital se han añadido hiperenlaces en color azul para referencias internas (índices, citas, figuras y tablas) y en azul claro para referencias externas. En cuanto al formato de citación y referencia, para mayor coherencia con las publicaciones se ha seguido el formato de las dos realizadas con la editorial Springer (GPS Solutions y Journal of Geodesy).

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Topo-Iberia CGPS network: a new 3D crustal velocity field in the Iberian Peninsula and Morocco based on 11 years (2008–2019)

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ORIGINAL ARTICLE



Topo-Iberia CGPS network: a new 3D crustal velocity field in the Iberian Peninsula and Morocco based on 11 years (2008–2019)

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Abstract

The Topo-Iberia network covering the Spanish part of the Iberian Peninsula and Morocco was established in 2008. Following the first publication of the horizontal velocity field based on an analysis of the first 4 years (2008–2012) in 2015, a new 3D velocity field based on 11 years (2008–2019) is presented. The double-differencing technique is applied with GAMIT software, and the precise point positioning (PPP) technique is applied with GipsyX software for GPS processing to obtain loosely constrained solutions. Then, a kalman filter is used to merge both solutions using GLOBK software and produce a velocity solution. The combined velocity solution is presented as a new horizontal velocity field and the first vertical velocity field of the Topo-Iberia CGPS network. A global view of the data quality from the Topo-Iberia stations is also presented for the first time, as well as a program specifically created to convert GipsyX gdcov files to SINEX files, gdcov2sinex.sh. The results in the IGB14 reference frame are in good agreement with previous publications, except in the Betic Cordillera, where the new velocities with respect to Eurasia are generally lower and present a higher southwestward component rather than a purely westward motion. The main discrepancy is observed at the ALJI station, where the maximum velocity is reached (3 ± 0.1 mm/yr), showing west-northwestward motion. The smallest and highest residual displacements with respect to Eurasia occur in northern Iberia and Morocco, respectively. The results support the conclusions of other studies that a clockwise block rotation occurs at present in the northern branch of the Gibraltar Arc. The velocities indicate a northwest-southeast convergence rate of 3.5 ± 0.1 mm/yr with respect to Nubia. A general low subsidence (mean value of 0.5 ± 0.1 mm/yr) is observed in the Iberian Peninsula except for some isolated stations presenting uplift.

Keywords 3D velocity field · GAMIT/GLOBK · GipsyX · GPS processing strategy · Iberia Morocco region · Topo-Iberia CGPS network

2.1 Introduction

The Topo-Iberia network was part of a research project entitled *Geosciences in Iberia: Integrated studies of topography and 4-D evolution*. ‘Topo-Iberia’ supported by the Spanish Government (Gallart 2006). Using a Global Navigation Satellite System (GNSS) technique, specifically the Global Positioning System (GPS), was one of the methodologies used to take crustal deformation measurements. As part of the project, a Topo-Iberia network composed of 26 continuously operating GPS stations (CGPS), covering the Spanish part of the Iberian Peninsula (22) and Morocco (4), was established (Fig. 2.1). The Spanish Geological Survey (IGME) implemented the Topo-Iberia Information System (SiTopo) to store the data.

Garate et al. (2015) presented a velocity field based on the analysis of the first 4 years of continuous GPS observations from the Topo-Iberia network. Data analyses were performed by three different groups using different scientific software packages and approaches. The final solution from each group was transformed to a common reference frame, and finally, an average velocity field from the three solutions was calculated.

At the time of this study, there are more than 11 years of data from some Topo-Iberia stations whose analysis can allow us to estimate the velocity field with greater precision. The abovementioned study on the Topo-Iberia network estimated only a horizontal (2D) velocity field, and few studies, such as Serpelloni et al. (2013), Nguyen et al. (2016), Devoti et al. (2017) and Khazaradze et al. (2019), have estimated the vertical deformation in the Iberian Peninsula. Therefore, the main aims of this study are (1) to process all available data from the Topo-Iberia CGPS network; (2) to offer a new 3D velocity field showing present-day deformation in the Iberia plate and along its boundary zone with the Nubia plate in the western Mediterranean region; and (3) to use software with different GNSS processing techniques. Some reasons for applying different software are to check for possible systematic effects due to software or to remove mistakes introduced during processing, which are difficult to detect without a second analysis for comparison. In this way, among software programs using double-differencing and precise point positioning (PPP) techniques, GAMIT version 10.71 (Herring et al. 2018) and the Jet Propulsion Laboratory’s (JPL) GipsyX software version 1.7 (Bertiger et al. 2020) have been chosen, respectively, and GLOBK is used to analyze the time series and fix the reference system. For geodetic applications and static positioning, with 24-hr sessions, the expected precision using GAMIT is at the level of 1–2 mm and 3–5 mm for horizontal coordinates and heights, respectively. On the other hand, the expected precision using GipsyX, PPP with ambiguity resolution, is 2 mm and 6.5 mm, also, respectively.

Although some EUREF permanent network (EPN) stations have been included in the new analysis, this work is not on the densification of the EPN, nor is it intended to be, nor is it related to any processing strategy that EUREF has established for its data. As indicated above, one of the objectives is to re-process Topo-Iberia GPS data with two different software, and for this purpose,

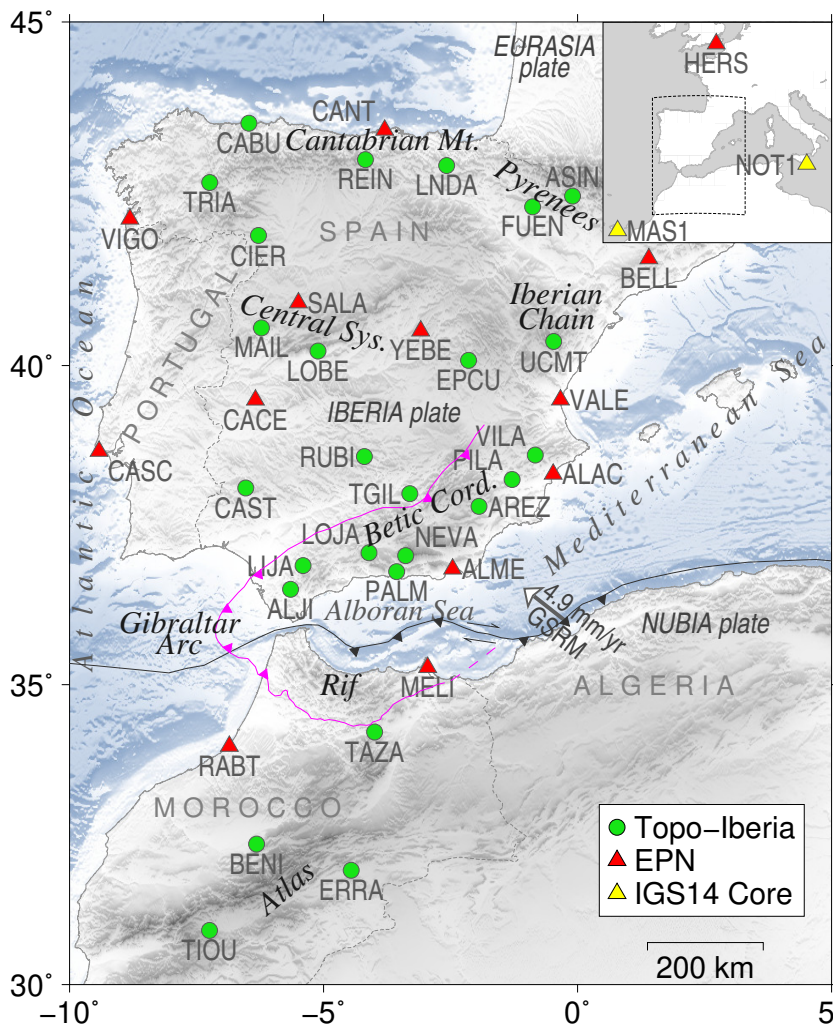


Fig. 2.1 Simplified tectonic map and distribution of the GNSS/GPS stations used in the new analysis. CORS are denoted with a triangle symbol. The Betic-Rif deformation zone (magenta line) and hypothetical Eurasia-Nubia plate boundary (black line) are both based on Mancilla et al. (2015) and personal communication with Sánchez-Gómez M (2022). The gray vector represents the convergence direction and rate between the plates based on the GSRM v2.1 model. The shaded-relief image of the Earth illumination from the south is at 1 arc minute resampled from the SRTM15+V topography database (Tozer et al. 2019) plotted with Generic Mapping Tools (GMT) software version 5.4.5 (Wessel et al. 2013)

the combination and processing strategy established by Herring et al. (2016) is followed and the International Terrestrial Reference Frame (IGb14) is used. Considering the complexity of the process, details and explanations of some strategy steps are provided to help GAMIT/GLOBK and GipsyX users. Due to space limitations, much of the detail is provided in supplementary material.

2.2 Tectonic setting

In terms of tectonic regime, the Iberian Peninsula can be divided into three main domains: (1) the Pyrenean-Cantabrian system (in the north) (Fig. 2.1) is a collisional orogen with double vergence, resulting from the convergence of the Iberia and Europe plates between the late Cretaceous and the early Miocene (Choukroune 1992); (2) the Central region includes deformed regions, mainly of Neogene age, in the plate interior, such as the Central System and the Iberian Chain, together with their associated sedimentary basins; and (3) the Betic-Rif system (in the south) includes the northwest-southeast Eurasia-Nubia convergent plate boundary in the west-

ernmost Mediterranean originating in the Cretaceous (Dewey et al. 1989). In a Eurasian-fixed reference frame, the largest horizontal deformation is located in this third domain. The plates converge in this region at a rate of 4.9 mm/yr (represented in the map figures with a gray vector) according to the GSRM v2.1 plate motion model (Kreemer et al. 2014), calculated using the Plate Motion Calculator of the Geodetic Facility for the Advancement of Geoscience (GAGE) operated by the EarthScope Consortium (<https://www.unavco.org/software/geodetic-utilities/plate-motion-calculator/plate-motion-calculator.html>).

Numerous studies have been carried out on the deformation along the Eurasia-Nubia plate boundary zone in this region, such as Koulali et al. (2011), who established west-southwest movements with respect to Eurasia ($\sim 2\text{--}3$ mm/yr) in the southwestern part of the Betic Cordillera. The Betic-Rif deformation zone is controlled by slab rupture and Alboran Domain collision (Mancilla et al. 2015). In the eastern Betic Cordillera, within the complex general context of extension and westward displacements, there are moderate active compressive tectonics (Palano et al. 2013; Galindo-Zaldivar et al. 2015), where part of the convergence between Nubia and Eurasia is accommodated by shortening (Borque et al. 2019). In the western Betic Cordillera, the development of the Gibraltar Arc, the tectonic belt connecting the Betic and Rif Cordilleras surrounding the Alboran Sea, continues at present (Gonzalez-Castillo et al. 2015), and the displacement pattern is in agreement with a clockwise rotation of the tectonic units in the northern branch of the Gibraltar Arc. On the other hand, Galindo-Zaldivar et al. (2022) established the present-day interaction of the rollback tectonics of the Betic-Gibraltar-Rif slab in the western part of the Gibraltar Arc, with indentation tectonics affecting the eastern and southern areas. The Betic-Rif deformation zone and hypothetical Eurasia-Nubia plate boundary, both based on Mancilla et al. (2015) and personal communication with Sánchez-Gómez M (2022), are denoted in the map figures with a magenta and black line, respectively.

2.3 GPS data

At the time of this study, all available data from the Topo-Iberia CGPS network cover the interval 2008–2019. Over time, some stations have been dismantled or have suffered incidents that remain unresolved, and as a consequence, the continuity of data spans varies significantly between stations (Fig. 2.2 top).

Blewitt and Lavallée (2002) established the relationship between the data span and the effect of annual signals in velocity estimation. The recommended standard minimum data span for velocity solutions intended for tectonic interpretation or for establishing a reference frame is 2.5 years, and the velocity bias is a minimum at integer-plus-half years. Although the available data span is long, these recommendations have been taken into account. Therefore, the available span is shortened as necessary, with a priority of eliminating the periods of malfunction (Fig. 2.3) with the help of a previous data quality check carried out using TEQC software (Estey and

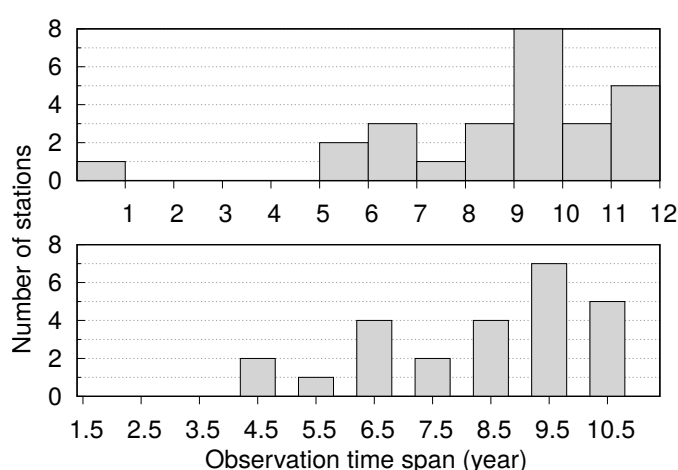


Fig. 2.2 Number of Topo-Iberia CGPS stations as a function of observation time span considering all the available data on control date 2020-02-11 (top) and considering the data selected for processing (bottom)

Meertens 1999). Fig. 2.3 shows, for the first time, a global view of the data quality from the Topo-Iberia stations for the processed period based on the maximum number of complete observations recorded in 72,122 RINEX (Receiver Independent Exchange) v. 2.11 formatted files. The average of the complete observations recorded at each Topo-Iberia station is in the range of 21,640–24,489. The number of stations as a function of the selected spans is shown in Fig. 2.2 (bottom), highlighting the largest number of sites over 9.5 years of observation. All stations together form a dataset spanning from 2008-04-09 to 2019-10-29, resulting in a total of 11.6 years. Details on available and processed data spans are shown in Table S1 of Supplement 1 (SI_1).

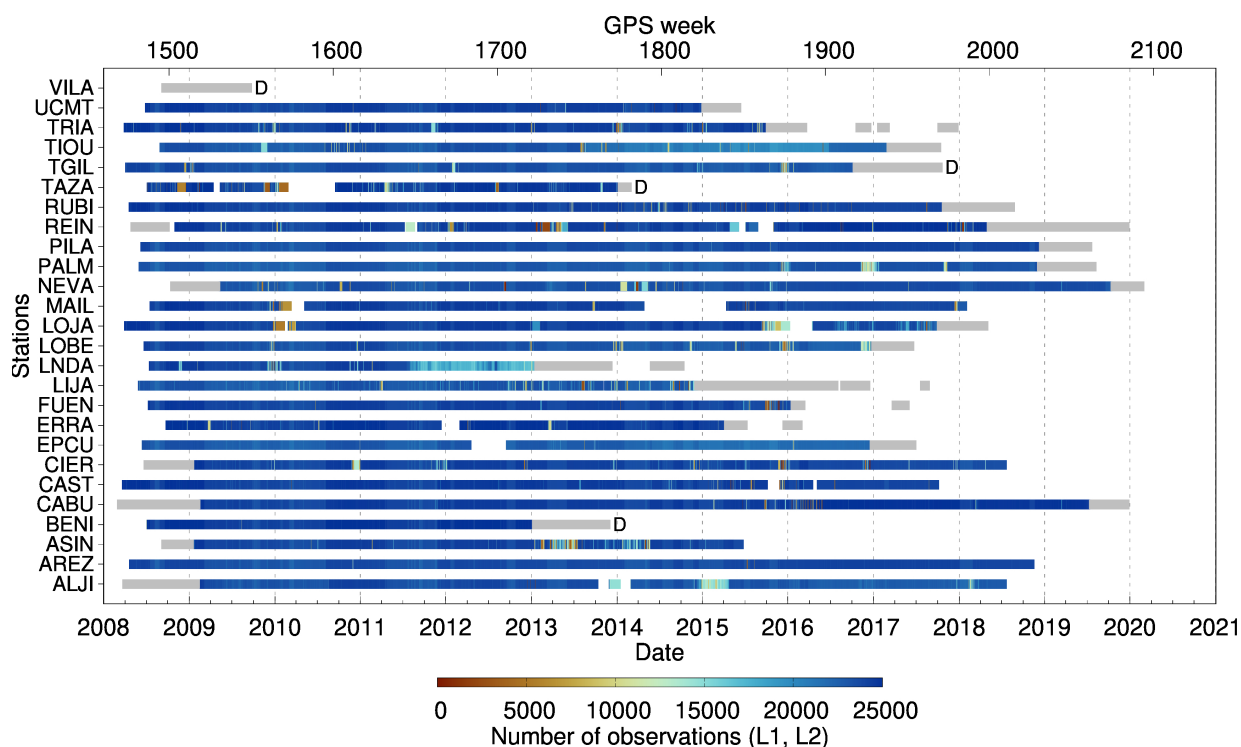


Fig. 2.3 Selected data spans to processing and maximum number of complete observations recorded at every Topo-Iberia CGPS station. Letter D means dismantled. Spans in gray color correspond to discarded data whose quality control can be seen in Fig. 2.12 (Appendix) and Fig. S1 (SI_1)

Continuously operating reference stations (CORS) from the EPN are also included in this analysis to tie the velocity solution into a global reference frame. A set of ten or more well-distributed sites with small uncertainties is sufficient to obtain a robust frame realization (Herring et al. 2018). To select the best reference stations, an interactive tool provided by EUREF (http://www.epncb.oma.be/_productsservices/ReferenceFrame) was used. Thirteen stations were selected between defined stations as recommended to be reference stations for the given span: ALAC, ALME, BELL, CACE, CANT, CASC, HERS, MELI, RABT, SALA, VALE, VIGO, and YEBE. All of them, except BELL, CACE, CASC, and MELI, are classified by EUREF (2021) as class C0, being the most stable and reliable stations in the EPN. The other four stations are class C1 and are still very stable. The CORS set was completed with the MAS1 and NOT1 stations in the IGS14 Core network (International GNSS Service), resulting in fifteen reference stations (Fig. 2.1).

2.4 Data processing strategy

GPS data are processed using a three-step approach similar to the approach described by Dong et al. (1998) and (Herring et al. 2018). In the first step, daily loosely constrained estimates of station coordinates and their covariances are obtained from doubly differenced GPS phase observables (GAMIT) or from PPP using undifferenced observables from just a single GPS receiver (GipsyX). In the second step, time series (*glred*) in a consistent reference frame (IGb14) are generated by minimizing each day for the selected CORS set (*glorg*). Outliers and offsets due to earthquakes or equipment changes, as well as periodic signals, are corrected to obtain clean time series. Additionally, in this step, the loosely constrained solutions from GAMIT and GipsyX were combined for each day, generating their time series. In the third step, all data are combined (*globk*) into a single solution applying generalized constraints (*glorg*) in the position and velocity to define a uniform reference frame while estimating an overall network translation and rotation (Helmert parameters). Both the second and third steps follow an iterative process. The first time series was stabilized (reference frame definition) using only the well-defined CORS, but the time series that best represents the final velocity solution is the one that is stabilized using all sites in the solution (Herring et al. 2015, 2018) (Figs. S9–S21 in SI_1). Thus, the first velocity solution obtained is used as a priori information for the next iteration, and all sites were used for stabilization. All the time series and velocity solutions are realized in a no-net-rotation (NNR) International Terrestrial Reference Frame (IGb14). Finally, positions, velocities, and uncertainties with respect to the Eurasian- and Nubian-fixed reference frames were estimated by fixing the set of CORS located on the stable part of the plates (*glorg*). Fig. 2.4 depicts the process flow diagram of the processing strategy described above. Some particular aspects of each strategy are discussed below. Details of the GAMIT and GipsyX processing specifications are presented in Tables S2 and S3 (SI_1).

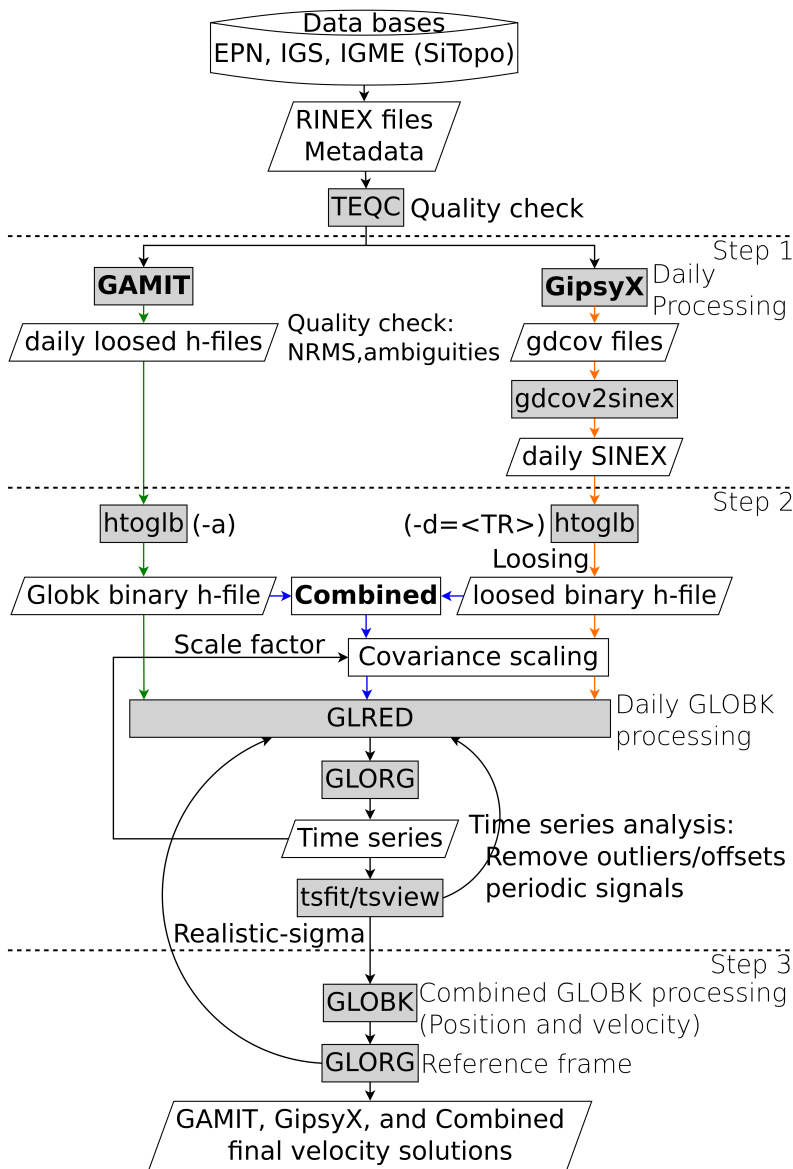


Fig. 2.4 GPS data processing flow. Boxes in gray contain the main programs that carry out the processing. The curved line indicates an iteration. The process flow is identical for all three strategies (in bold) from the *glred* module. The scale factor is determined from the GAMIT and GipsyX (unscaled) time series

2.4.1 GAMIT strategy

The Topo-Iberia stations (25) plus the additional CORS (15) are processed simultaneously in only one regional network (40) using GAMIT version 10.71 (Herring et al. 2018). Daily station positions and atmospheric delays are estimated from an ionosphere-free linear combination of GPS phase observables using the double-differencing technique to eliminate phase biases in the satellite and receiver clock oscillators. Some of the main models and processing parameters selected in this strategy are shown in Table 2.1. The GAMIT solutions are obtained in daily ASCII *h-file* format that are passed to GLOBK, where the final solution is determined. The integer phase ambiguities are successfully resolved (fixed) with an average of 96.1% for wide-lane (WL) and 92.8% for narrow-lane (NL) and a normalized root-mean-square (NRMS) average of 0.18, which is an indicator of the quality of the solutions. A more detailed explanation of the resolved ambiguities is provided in Appendix (Fig. 2.13) and SI_1 (Fig. S2).

Table 2.1 Some models and processing parameters that differ and are common between GAMIT and GipsyX strategies. Details are given in Tables S2 and S3 (SI_1)

Processing Parameter	GAMIT	GipsyX
Strategy	Double-differencing (BASELINE mode)	Precise point positioning (single station PPP)
Data sampling	30 s cleaning / 2 min analysis	Decimated to 5 min
Elevation angle cutoff	10°	7°
Orbits and clocks	IGS final orbits	JPL final (fiducial-free) orbits and clocks
Atmospheric zenith delay and gradient estimates	Zenith wet delay parameterized by a piecewise-linear function with 2-h intervals and process noise uncertainty constraint of $20 \text{ mm}/\sqrt{h}$. One pair of gradients per day with a priori constraint of 30 mm at 10° elevation	Estimated every 5 min as a random-walk process noise of $3 \text{ mm}/\sqrt{h}$ in zenith wet delay and $0.3 \text{ mm}/\sqrt{h}$ in gradient
A priori atmospheric parameters	Meteorological data input from VMF1 with 50% relative humidity	Wet and dry nominal troposphere values from VMF1 for each station every 5 min
Second-order ionospheric corrections	IGS IONEX files (2nd and 3rd order)	JPL IONEX files
Ambiguity	Resolved in a baseline-by-baseline mode	Resolved using the Wide-Lane Phase Bias (WLPB) method (Bertiger et al. 2010)
Phase elevation weighting	Site dependent constant and $1/\sin$ (elevation angle) terms	
Antenna corrections	Absolute ant. phase center variations based on IGS14 model for both satellite and ground ant.	
Tropospheric mapping function	VMF1 dry and wet terms	
Solid Earth tide	IERS 2010 convention (IERS 2010)	
Earth pole tide	IERS 2010 convention	
EOP	IERS Bulletin A	
Ocean tidal loading	FES2014b model with center of mass correction (list values)	
Atmospheric nontidal loading	Not applied	
Atmospheric tidal loading	Not applied	

2.4.2 GipsyX strategy

Each of the 40 sites is separately processed with GipsyX version 1.7 (Bertiger et al. 2020) in PPP mode using ionosphere-free carrier phase and pseudorange observables. Some models and processing parameters are common to those used in GAMIT (Table 2.1). In this case, the integer phase ambiguities are successfully resolved with an average of 99.8% for all RINEX files, with 3832 the average number of the double differences that pass certain established criteria for ambiguity resolution. The GipsyX solutions are obtained in daily *gdcov*-file format, which is translated to the Solution Independent Exchange (SINEX) format file (IERS 2006) before being passed to GLOBK. A program called *gdcov2sinex.sh* was specifically created for this conversion. To make these SINEX files loosely constrained, the methodology described by Herring et al. (2015, 2016) is followed. Details about the ambiguity resolution and the loosening process are described in Appendix (p. 36) and SI_1 (Fig. S3). The conversion process and program code are provided in Supplement 2 (SI_2). For ease of use, the executable program file (.sh) is provided in Supplement 3 (zipped folder SI_3.zip).

2.4.3 Combined strategy

As described above, different models and processing parameters are used in GAMIT and GipsyX. Consequently, the noise models from both analyses differ, resulting in different position estimate standard deviations. For the individual final solutions to be comparable, their covariance matrices are rescaled to weight the solutions equally following the combination procedure established by Herring et al. (2016). Two modifications with respect to the original methodology have been introduced: the GAMIT solution is used unscaled, only the GipsyX solution is rescaled; and the appropriate scaling value is determined from the relationship between sigma values in the time series of both solutions. The rescaling process is described in Appendix (p. 37) and SI_1 (Fig. S4). For individual processing, scale factors for the GAMIT and GipsyX solutions are fixed to 1 and 3.6, respectively. When the results of both strategies are combined or, what is the same, two solutions for the same network of sites are combined, these factors are doubled so the solutions from individual strategies and their combination (Combined strategy) have similar standard deviations for the position estimates (Herring et al. 2016; personal communication with Floyd MA and Herring TA 2022).

2.4.4 Considerations for the vertical component

The precision of the GNSS vertical component is generally approximately 2–3 times lower than that of the horizontal component for various reasons, including the geometry and distribution of satellites and phenomena such as ocean loading and atmospheric delays. To improve the accuracy, some changes have been made to the default GAMIT configuration. The default map-

ping function used for modeling and estimation of the atmospheric delay is the global mapping function (GMF) from fitting numerical weather model (NWM) data over 20 years, sufficient for all but the most accurate studies of heights and for meteorological studies (Herring et al. 2018). However, the VMF1 model is used, providing a more accurate reconstruction of the NWM data. Since having the most accurate value of pressure, from local surface pressure measurements, for the a priori zenith hydrostatic delay (ZHD) was not possible, the next most accurate source was chosen, the VMF1 grid. In addition, zenith delays were estimated every 2 hours, although there is little increase in the accuracy of station heights, which greatly increases the processing time. Regarding ocean tide loading, the model with the best possible accuracy at the date of the study was used, the FES2014b model. The default GipsyX configuration was also changed with regard to the VMF1 and FES2014b models.

2.4.5 Time series analysis

The loose solutions previously obtained are considered individually using *glred* to generate the position time series of each station, with day-to-day repeatability, throughout the span considered in an adequate framework. The raw time series are analyzed to estimate and remove outliers, periodic terms, and discontinuities in an iterative process described in Appendix (p. 38) and SI_1. The analysis is realized using the *tsfit* GLOBK program, a command-line tool for fitting time series and generating statistics, and the *tsview* interactive MATLAB-based program (Herring 2003). Files generated with *tsfit/tsview* containing outliers, discontinuities, and periodic signals are input to GLOBK to obtain a combined solution and extract more refined positions and velocities. Finally, the noise in the GPS position time series is assumed to be a combination of white noise plus random-walk (RW) noise, which is accounted for using the *realistic-sigma* algorithm or First-Order Gauss–Markov Extrapolation (FOGMEX) algorithm (Herring et al. 2015; Floyd and Herring 2020). Raw and cleaned time series are shown in Figs. S9–S21 (SI_1).

2.5 Analysis of the final results and discussion

Once the GPS data processing described above was completed, estimates of the velocity field based on the final position time series analysis of the data were generated. In the analysis of the results, a distinction was made between the final position time series and the velocity solutions obtained with each strategy, and a comparison between them was made. It is important to note that the FOGMEX algorithm has not yet been applied to these final position time series, which are those stabilized with all the sites in the solution, i.e., the time series that best represent the final velocity solution. The combined solution corresponds to Figs. S9–S21 in SI_1. Finally, the new 3D velocity field of the Topo-Iberia network is compared with previous publications, and the main differences and similarities are highlighted.

2.5.1 Comparison of time series

The statistics (mean and median) of the weighted root-mean-square (WRMS) position residual scatter in the final fitting of the time series are similar in the three strategies, and the differences between them are on the order of a tenth of a mm. The means of the WRMS scatters of position in the north and east components in the time series for the three strategies are in the range of 0.6–0.7 mm and of 2.0–2.1 mm in the up component, indicating good repeatability. Comparison details are shown in Appendix (p. 43) and SI_1 (Fig. S22 and Table S6).

2.5.2 Comparison of velocity solutions

Uncertainties for rates quoted in the text are one-sigma and those shown in the figures are 95% confidence intervals unless stated otherwise. A previous comparison between GAMIT and GipsyX solutions without applying the realistic-sigma algorithm was used to check their degree of matching. Details about this comparison and the different *htoglb* options to loosen the constraints of the GAMIT and GipsyX solutions are described in Appendix (p. 44) and SI_1 (Fig. S23).

A comparison of the mean and RMS of the differences between the final velocity estimates obtained using the three different strategies is shown in Table 2.2. The FOGMEX algorithm is applied to these final velocity solutions to account for the long-period temporally correlated noise and obtain more realistic uncertainties. The agreement between the velocity estimates from each strategy is very good overall, with RMS of differences <0.2 mm/yr in the horizontal component and <0.3 mm/yr in the height component. The comparison of velocity estimates from the GAMIT and GipsyX solutions shows that they match at the level of 0.2 mm/yr in the north and east components and 0.3 mm/yr in height. These values are very similar to those resulting from comparing the Combined and GipsyX solutions, but when the Combined and GAMIT solutions are compared, the RMS of the differences decreases to 0.1 mm/yr in the horizontal and up components.

The final horizontal velocity solutions in a Eurasian-fixed reference frame are shown in Fig. 2.5. The Combined solution tends to have an intermediate position between the other velocity solutions, although closer to the GAMIT solution, as shown in the statistics in Table 2.2. The mean horizontal velocity uncertainty is 0.1 mm/yr for the three strategies. The Combined

Strategy 1	Strategy 2	ΔV_N		ΔV_E		ΔV_U	
		RMS	Mean	RMS	Mean	RMS	Mean
Combined	GAMIT	0.1	0	0.1	0	0.1	0
Combined	GipsyX	0.1	0	0.1	0	0.3	0
GAMIT	GipsyX	0.1	0	0.2	0	0.3	0.1

Table 2.2 Statistics of differences in the north, east, and up velocity components (mm/yr) between the final velocity solutions (Strategy 1 minus Strategy 2)

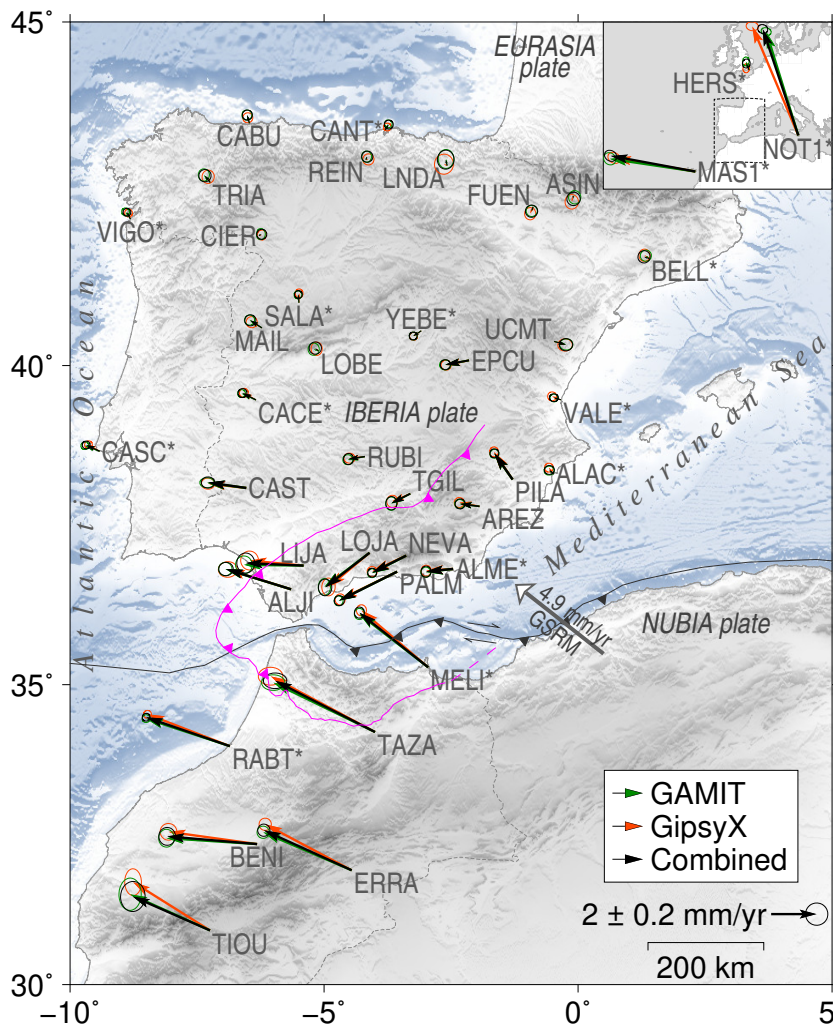


Fig. 2.5 Map of the horizontal velocities (95% confidence interval) of the Topo-Iberia CGPS network in a Eurasian-fixed reference frame from different strategies. The CORS used to define the framework are marked with an asterisk at the end of their name

horizontal velocity solution is presented as the new horizontal CGPS velocity field of the Topo-Iberia network based on 11 years (2008–2019). The velocities obtained for all stations used in this analysis are shown in Tables S7–S9 (SI_1). In addition, to facilitate plotting these velocities with GMT, an ASCII text file (hz_vel.dat) is provided in the zipped folder SI_3.zip. The expected velocities for the reference stations are known from data published by international organizations, such as the IGS and EPN. These velocities and coordinates have been used as a priori values so that the adjustment level indicates the validity of the results. The RMS of the adjustment in the horizontal velocity is <0.2 mm/yr, denoting an excellent fit (see details in SI_1, Figs. S26–S28).

The final vertical velocities depicted in Fig. 2.6 confirm that the values from the GAMIT and Combined strategies are quite similar, as indicated by the RMS of their differences (0.1 mm/yr in Table 2.2). In contrast, in the GipsyX strategy values, there are more differences in magnitude than the other strategies and the opposite results in 25% of cases. The vertical velocities are generally low, with a mean absolute value of 0.5 mm/yr and a mean uncertainty of 0.2 mm/yr for all strategies. The uncertainties are shown in Fig. 2.7, and a decreasing trend is observed as

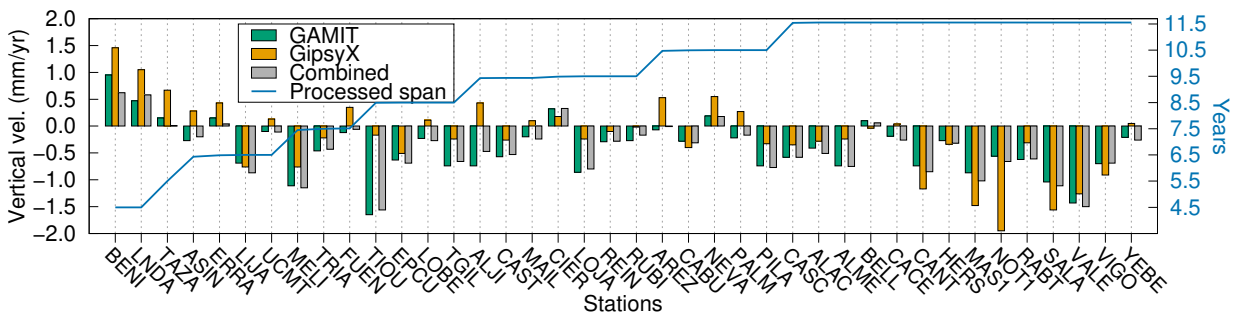


Fig. 2.6 Final vertical velocities obtained using different strategies sorted according to the processed span for each station. Positive and negative velocity values correspond to uplift and subsidence, respectively

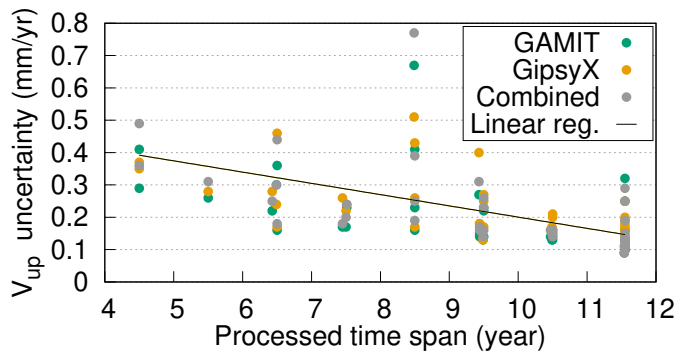


Fig. 2.7 Vertical velocity uncertainties obtained using each strategy as a function of the data span. The three linear regression lines overlap

the processed data span increases in a similar way for the three strategies, coinciding with their linear regression lines. The highest uncertainty in the graph corresponds to the TIOU station, with a data span of 8.5 years. Fifty percent of the Topo-Iberia stations have a data span of over 9.5 years, and according to the graph, this corresponds to an uncertainty of ~ 0.2 mm/yr, which is quite acceptable considering the low vertical velocities estimated.

The Combined vertical velocity solution is shown in Fig. 2.8 as the first vertical CGPS velocity field of the Topo-Iberia network. The vertical velocity solutions realized in the different reference frames are similar. Generalized subsidence is observed, except in a few cases, with the BENI and LND stations showing uplifts of 0.6 ± 0.5 and 0.6 ± 0.4 mm/yr, respectively. Coincidentally, the processed data spans from both stations are the shortest, 4.5 years (Fig. 2.6), and possibly a longer data span would be needed to obtain lower uncertainty and verify the uplift. Furthermore, the BENI station has been dismantled, resulting in a greater lack of information regarding what happened in its surroundings; hence, although the data recorded at this station were used in this study, the velocities from the BENI station cannot be presented herein with total confidence.

2.5.3 Comparison with previous publications

Garate et al. (2015) realized the velocity solution in the Eurasia fixed ITRF2008 frame; however, the new velocity solution was realized in IGB14 with respect to Eurasian- and Nubian-fixed reference frames. To compare the different fields, the ITRF2008 velocity solution is rotated and

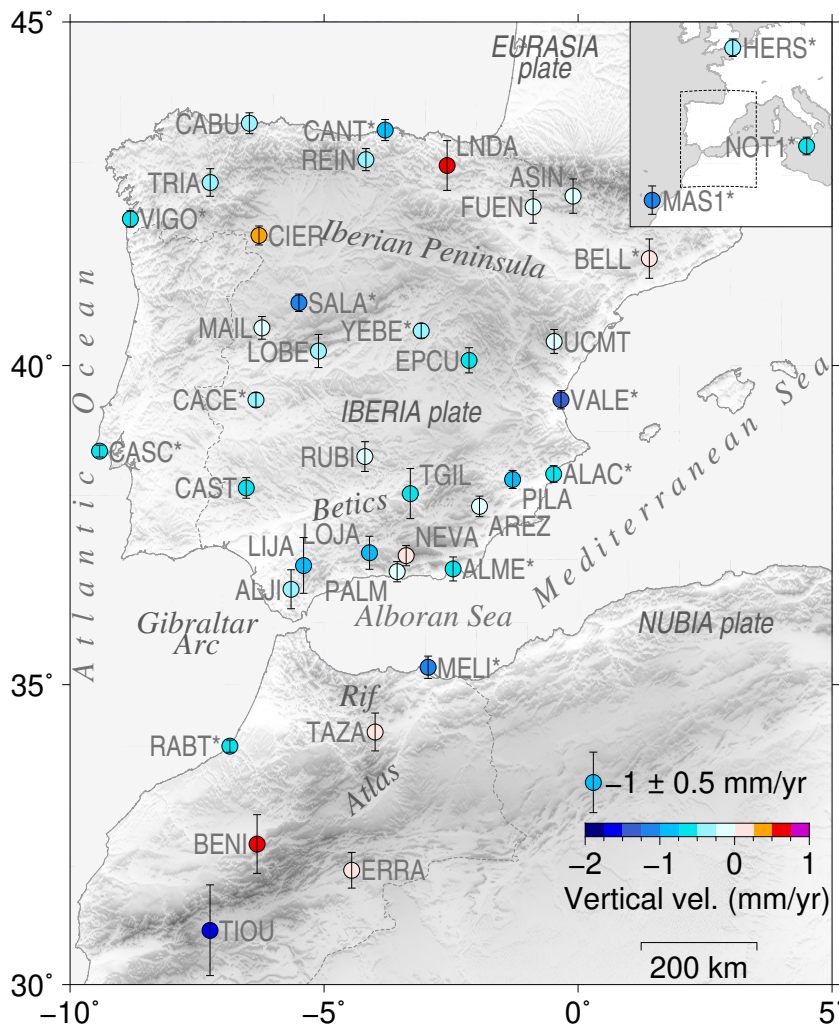


Fig. 2.8 Map of vertical velocities of the Topo-Iberia CGPS network and CORS used to define the framework (names ending with an asterisk). Positive and negative values correspond to uplift and subsidence, respectively. One-sigma uncertainties are represented by vertical error bars

translated into the reference frame of the new velocity solution using the *velrot* v.1.01 program. The resulting average RMS of the fit based on 33 common stations is 0.4 mm/yr, indicating a good adjustment. The new velocity solution is also compared with the velocity field presented by Koulali et al. (2011), although in this case, there are no Topo-Iberia stations in common. In this case, the RMS fit based on 11 common stations is 0.2 mm/yr, also indicating a good adjustment.

The new horizontal CGPS velocity solution is in general in good agreement with velocities published by Garate et al. (2015). The smallest residual displacements with respect to Eurasia are observed in northern Iberia. Their existing displacement values range from 0.1 mm/yr at ASIN in the northeast to 1.1 mm/yr at EPCU in the central zone (Table S8 of SI_1 and Fig. 2.9). The stations with the highest displacements are those deployed in Morocco and located on the Nubia plate, showing general northwestward displacements ranging from 3.7 to 4.9 mm/yr. The main differences are visible in the Betic Cordillera, specifically at the ALJI, LIJA, LOJA, and NEVA stations (Fig. 2.10 top), located in the Betic-Rif deformation zone.

Most of the displacements in the central and eastern Betics are westward, with a variable southwestward component. The AREZ and TGIL stations maintain the westward and south-

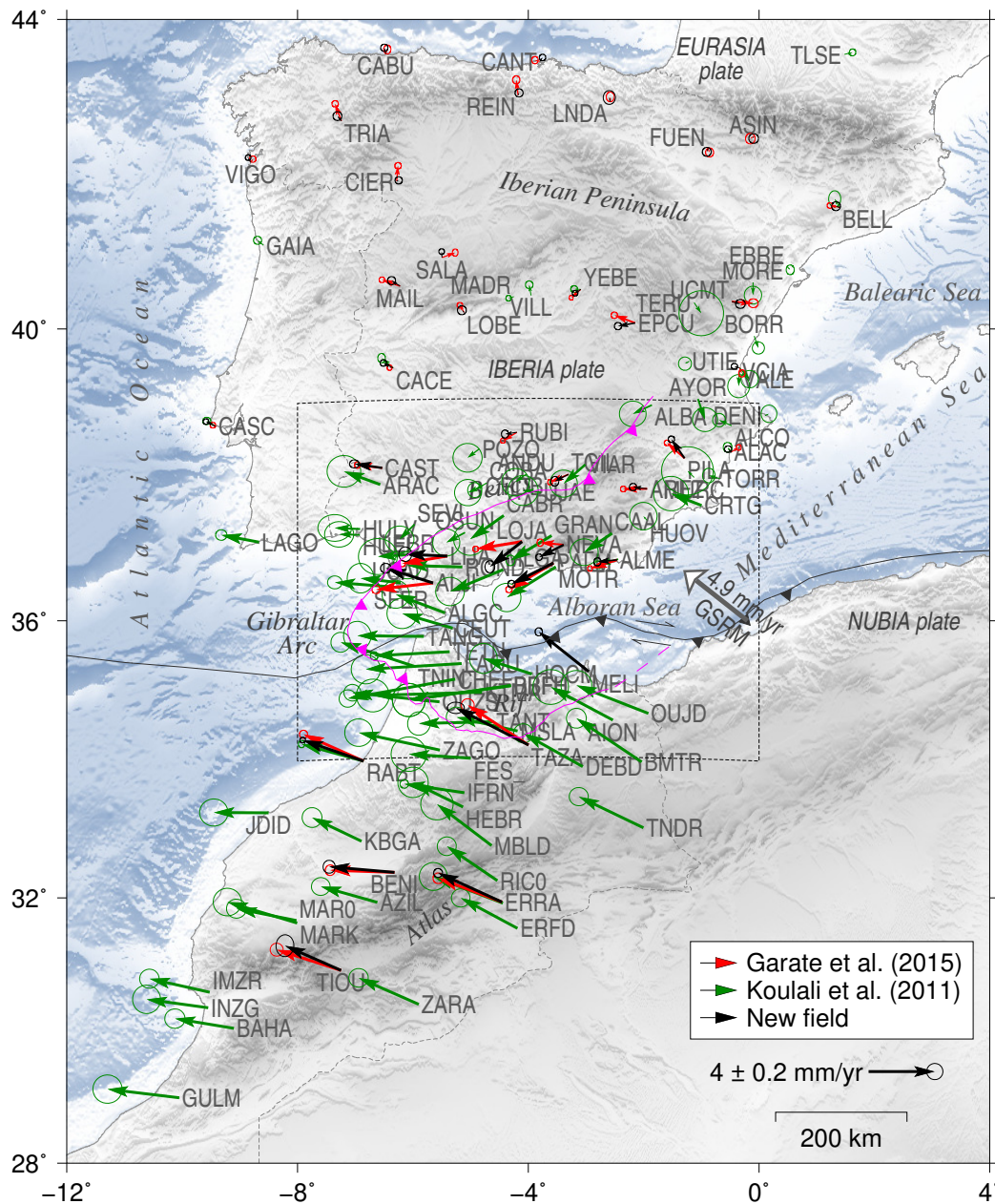


Fig. 2.9 Comparison between the new horizontal CGPS velocity field (95% confidence interval) and previous publications with respect to a Eurasian-fixed reference frame. Note that a factor of 0.5 has been applied to the velocity field uncertainties of Koulali et al. (2011) for figure clarity. The dashed black box represents the region enlarged in Fig. 2.10. Similar comparison with respect to Nubia is shown in Fig. S25 (SI_1)

westward displacements, respectively, presented in previous studies, but their velocities are even reduced by 76% in the case of TGIL, both being below 0.9 mm/yr. The PILA station (1.4 mm/yr) shows northwestward displacement in the eastern Betics, where part of the shortening between the Nubia and Eurasia plates is accommodated (Borque et al. 2019). The NEVA station (1.7 mm/yr) continues showing a displacement roughly parallel to the nearby GRAN station and the farthest CAAL station, as in Galindo-Zaldivar et al. (2015), coinciding exactly with the azimuth

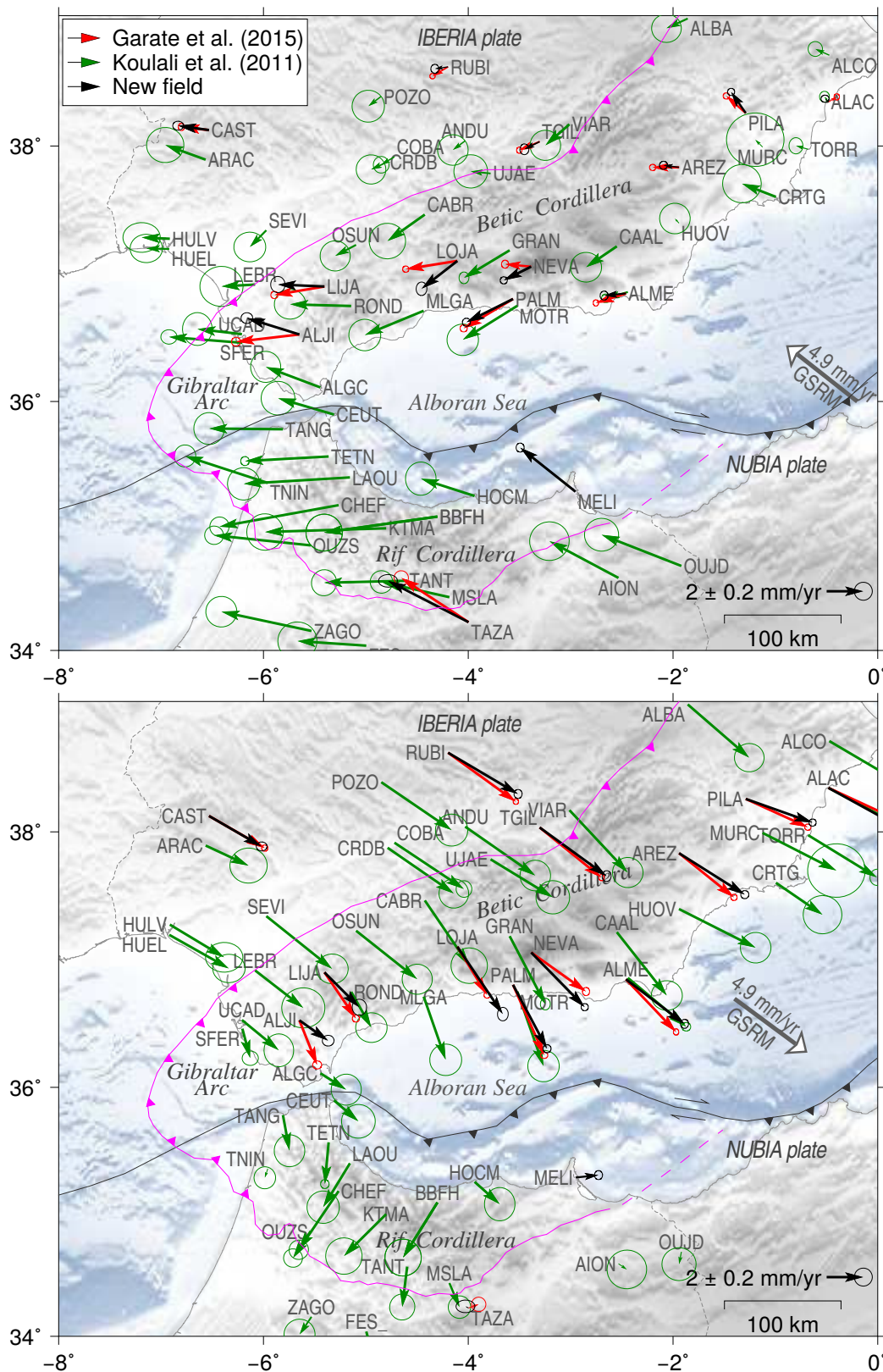


Fig. 2.10 Comparison between the new horizontal CGPS velocity field (95% confidence interval) and previous publications with respect to Eurasian- (top) and Nubian-fixed (bottom) reference frames. Note that a factor of 0.5 has been applied to the velocity field uncertainties of Koulali et al. (2011)

of the PALM station (2.8 mm/yr), but the stations as a whole show a higher southwestward component instead of purely westward motion. The LOJA station (2.5 mm/yr), in addition to presenting a reduction in velocity similar to the NEVA and PALM stations, also presents a higher southwestward component integrated into both stations and together with the CABR and MOTR stations of the velocity field of Koulali et al. (2011).

As previously published, displacements in the western Betic Cordillera show westward motion (Garate et al. 2015; Gonzalez-Castillo et al. 2015). At the LIJA station (2.5 mm/yr), there are no evident changes in motion due to its current uncertainty showing a westward displacement similar to the ROND and LEBR stations. Between the displacements of the Topo-Iberia stations in the western Betic, a maximum is reached at the ALJI station (3 mm/yr), showing present-day west-northwest ward motion rather than westward motion parallel to the LIJA station. The new displacement at the ALJI station, compared with the velocity field of Koulali et al. (2011), is in harmony with the ALGC and UCAD stations, being even more evident with respect to the Nubian-fixed reference frame (Fig. 2.10 bottom). This new direction supports the conclusion of Gonzalez-Castillo et al. (2015) that a clockwise block rotation occurs at present in the northern branch of the tectonic belt Gibraltar Arc. According to the new data presented in this study, this region is currently undergoing a northwest-southeast convergence rate of 3.5 ± 0.1 mm/yr with respect to Nubia. The displacements as a whole are also in agreement with the tectonic model involving rollback and indentation tectonics in the Gibraltar Arc proposed by Galindo-Zaldivar et al. (2022).

It might be believed that the origin of the discrepancies described above could be related to different criteria followed by the authors in the time series analyses, but the case of the NEVA station is remarkable, presenting a new direction of displacement. The NEVA time series have been very stable with the different criteria used, keeping the result constant, without information gaps in the metadata and without unknown strange behaviors during the long activity period (10.5 years). Therefore, the new southwest displacement at the LOJA station, more or less parallel to the NEVA and PALM stations, can be considered coherent. In addition, the data span of the LOJA and ALJI stations analyzed in this work has been extended from 4 to 9.5 years, allowing a more precise determination of their present-day displacements.

With respect to the vertical velocity field, in addition to the higher uncertainties associated with this component, it must be considered that the results presented by different publications usually come from methodologies differing in, among others, processing software, noise model or stations defining the reference system. As a consequence, the vertical velocity estimates presented tend to have quite a few differences. All of this makes a detailed comparison of the velocity at each station less conclusive than whether or not there is an agreement between regions of subsidence or uplift. On the other hand, the density of the Topo-Iberia network and CORS used in this study, although covering the study area, does not allow for establishing rates of subsidence or uplift with confidence for the entire Iberian Peninsula and Morocco. It should

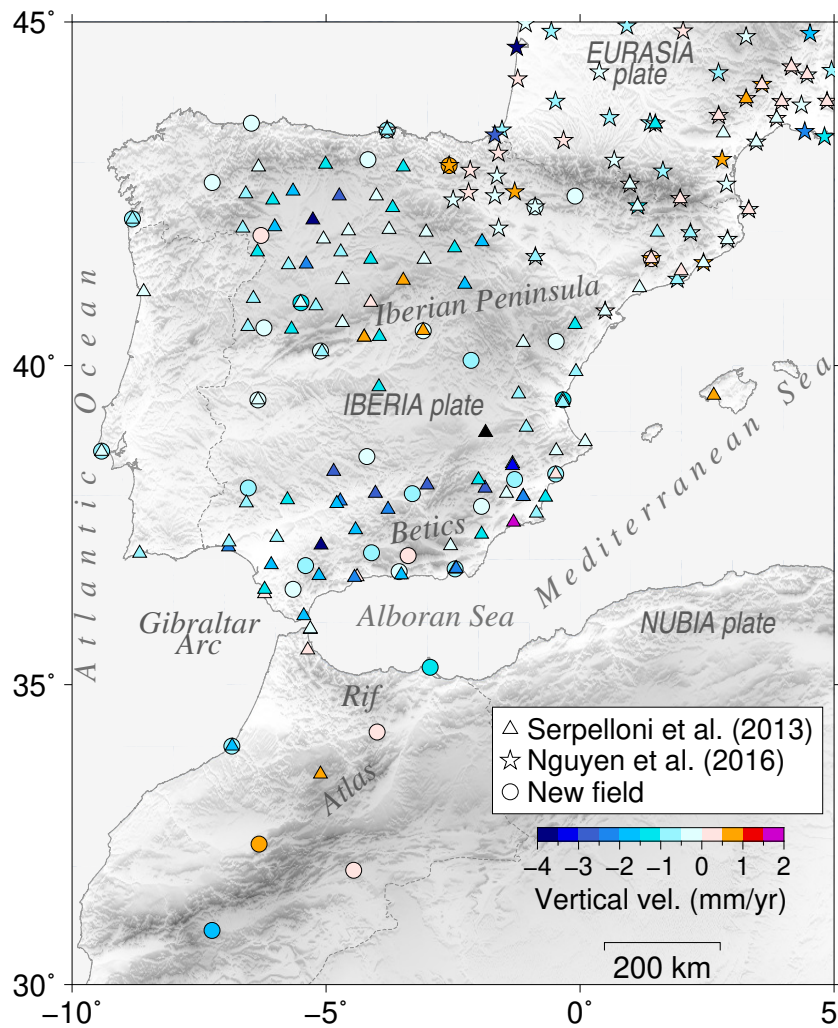


Fig. 2.11 Comparison between the new vertical CGPS velocity field and previous publications. Positive and negative values correspond to uplift and subsidence, respectively. Uncertainties are not shown for figure clarity (values listed in Serpelloni et al. 2013, Table S2, and Nguyen et al. 2016, Table 3). A black triangle symbol in the eastern Iberian Peninsula exceeds the color scale bounds and corresponds to a velocity value of -9.3 mm/year

also be noted that the vertical velocities determined are so small that they may not imply subsidence or uplift. However, as in previous publications, general subsidence is observed in the Iberian Peninsula (mean value of 0.5 ± 0.1 mm/yr) except at some isolated stations (Fig. 2.11). A mean subsidence velocity of 0.6 ± 0.1 mm/yr is located in the southern Iberian Peninsula and approaches zero close to the southern Pyrenees, in agreement with Serpelloni et al. (2013), although they establish subsidence rates ~ 2 mm/yr higher than those in this work. They did not use Topo-Iberia stations, and although they present a dense spatial distribution of stations, they only covered the central and southeastern regions. The velocity rates close to zero in the Pyrenees also coincide with those presented by Nguyen et al. (2016), where there are four stations in common and the estimated velocity coincides at two of them (LNDA and FUEN), which could confirm the uplift at the LNDA station.

2.6 Summary and conclusions

Topo-Iberia network data available up to 2019, with 50% of stations having over 9.5 years of data, have been processed, presenting a new 3D velocity field based on 11 years.

A quality check was carried out on the entire network, from which the optimal data spans to be processed were determined. In addition, a global vision of the data quality from the Topo-Iberia stations is presented for the first time.

GAMIT/GLOBK and GipsyX were used with the intention of having different analyses to compare and avoid possible errors introduced during processing while maintaining the premise of using different GNSS processing techniques. To make the individual solutions comparable, the methodology described by Herring et al. (2016) was followed, but in this case, only the GipsyX solution, and not the GAMIT solution, was rescaled by a factor obtained from the relation between the sigma values in the time series of both solutions. The *final* velocity solutions were not combined or averaged, but the two independent loosely constrained solutions from GAMIT and GipsyX were merged using a kalman filter (GLOBK). This required converting the GipsyX solutions to SINEX files, and a new program specifically created for it called *gdcov2sinex.sh* is provided.

The means of the WRMS scatters of position in the north and east components in the time series for the three strategies are in the range of 0.6–0.7 mm and of 2.0–2.1 mm in the up component, indicating good repeatability.

A new horizontal CGPS velocity field of the Topo-Iberia network based on 11 years (2008–2019) has been presented. The mean horizontal velocity uncertainty (1σ) is low, 0.1 mm/yr. The new velocity field is in good agreement with the results of previous publications, except for some discrepancies in the Betic Cordillera, where the new horizontal velocities are lower. The smallest and highest residual displacements with respect to Eurasia occur in northern Iberia and Morocco, respectively. The stations in the Betic central sector present a higher southwestward component instead of purely westward motion. The main discrepancy in the western Betic Cordillera is observed at the ALJI station, where a maximum is reached (3 ± 0.1 mm/yr), showing present-day west-northwestward rather than westward motion. The results support the conclusion of Gonzalez-Castillo et al. (2015) that a clockwise block rotation occurs at present in the northern branch of the Gibraltar Arc. The velocities indicate a northwest-southeast convergence rate of 3.5 ± 0.1 mm/yr with respect to Nubia. The displacements as a whole are also in agreement with the tectonic model involving rollback and indentation proposed by Galindo-Zaldivar et al. (2022).

A vertical CGPS velocity field of the Topo-Iberia network has been presented for the first time. The vertical velocities are low for the three strategies (a mean absolute value of 0.5 mm/yr and a mean uncertainty of 0.2 mm/yr). Considering the limitations of the vertical component estimation and that the vertical velocities determined are so small that they may not imply sub-

sidence or uplift, general low subsidence is observed in the Iberian Peninsula, as in previous publications, except at some isolated stations, such as the LNDA station, which shows an uplift of 0.6 ± 0.4 mm/yr. A mean subsidence velocity of 0.6 ± 0.1 mm/yr is located in the southern Iberian Peninsula and approaches zero close to the southern Pyrenees. The results offered additional information on the vertical velocity in the Iberian Peninsula and Morocco, complementing the few studies that have estimated it.

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Data Availability GNSS data provided by the EPN can be accessed from <https://epncb.eu/ftp/obs/> and https://epncb.eu/_networkdata/stationlist.php. Topo-Iberia network GPS data were provided by IGME (<https://www.igme.es>), but restrictions apply to the availability of these data due to the internal privacy policies of the Topo-Iberia team and are not publicly available. GNSS products used with GipsyX provided by JPL are available at https://sideshow.jpl.nasa.gov/pub/JPL_GPS_Products/Final/. GAMIT VMF1 files are available at <ftp://everest.mit.edu/pub/GRIDS/>, and those for GipsyX are available at https://vmf.geo.tuwien.ac.at/trop_products/GRID/2.5x2/VMF1/STD_OP/. The GPS data were processed on two desktop computers running Debian GNU/Linux 10 (<https://www.debian.org>). Maps were created using GMT software version 5.4.5 (Wessel et al. 2013), graphs were created using Gnuplot version 5.2 (<http://www.gnuplot.info>), and figures were edited using Inkscape version 0.92.4 (<https://inkscape.org>). The Scientific color map roma (Crameri 2021) was used in Fig. 2.3 to prevent visual distortion of the data and exclusion of readers with color-vision deficiencies (Crameri et al. 2020). Supplement 3 provided is a zipped folder containing the executable program file *gdcov2sinex.sh*, and the ASCII text file *hz_vel.dat* for direct use in GMT. Additional data and resources used in this work are indicated in the main body.

Supplementary Information This article contains supplementary material (3 supplements) available at <https://rdcu.be/dfCAR> and <https://doi.org/10.1007/s10291-023-01484-8>. Part of this material has been included in the following Appendix.

Appendix

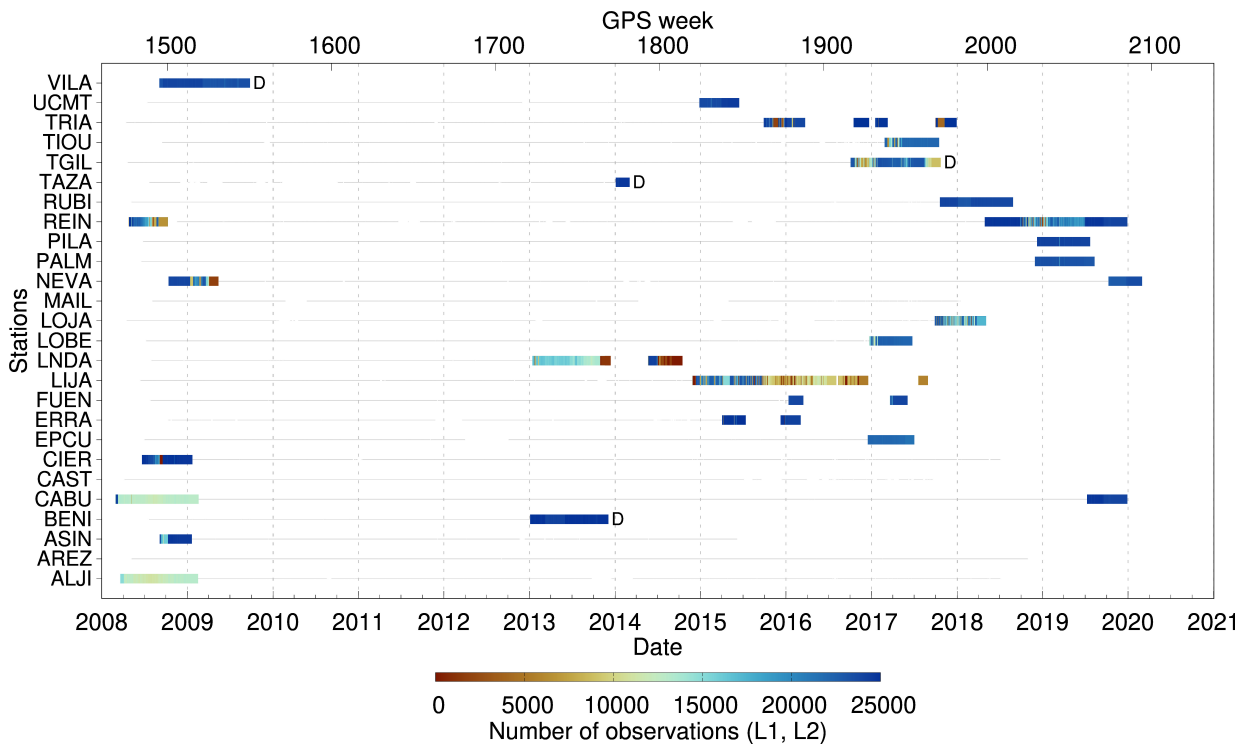


Fig. 2.12 Discarded Topo-Iberia data spans and quality check based on the maximum number of complete observations recorded. Letter D indicates dismantled

GAMIT strategy

The Topo-Iberia stations (25) plus the additional CORS (15) are processed simultaneously in only one regional network (40) using GAMIT version 10.71 (Herring et al. 2018). Being the number of sites minor than ~ 50 in daily GAMIT processing, it is not necessary to use sub-networks for the processing to be more efficient and accurate. The regional solution uses 24-hour RINEX-formatted data sampled at 30 seconds being quality-checked using TEQC. The daily station positions and atmospheric delays are estimated from the ionosphere-free linear combination GPS phase observables using double-differencing techniques to eliminate phase biases in the satellite and receiver clock oscillators. The satellite orbit parameters are fixed to the IGS final values, and the Earth Orientation Parameters (EOP) are interpolated from the IERS Bulletin A (BASELINE mode in GAMIT software). The second and third-order ionospheric corrections

computed from the Ionosphere Map Exchange (IONEX) files are applied. The ocean tidal loading effects are accounted for using the FES2014b model including corrections for the center of mass motion. The ocean loading displacement coefficients for each of the sites are provided by Bos and Scherneck (2021), i.e., it is a list of values specific to a location, and not a grid. The Vienna Mapping Function (VMF1) grid (Boehm et al. 2006) is used for the a priori hydrostatic and wet troposphere delay components, and to model the zenith delay variance. The integer phase ambiguities are resolved in a baseline-by-baseline mode. The constraints to a priori coordinates values are between 0.05 m for some reference sites chosen to enhance the ambiguity resolution and 100 m for remaining sites, thus generating loosely constrained variance-covariance matrices and solutions by a weighted least squares algorithm.

The ambiguities are successfully resolved with an average of 96.1% for wide-lane (WL) and 92.8% for narrow-lane (NL) (Fig. 2.13 top), which is an indicator of the solution quality. More than 90.9% of WL ambiguities and more than 85.3% of NL ambiguities are resolved in 95% of the daily solutions. Another quality indicator of the daily GAMIT solutions is the square root of the chi-squared per degree of freedom ($\sqrt{(\chi^2/f)}$), referred to as the normalized root-mean-square (NRMS). In practice, with the default weighting scheme to account for temporal correlations, a good solution usually produces a NRMS of ~ 0.2 (Herring et al. 2018). It can also be seen in Fig. 2.13 that the values obtained are in the range (0.16–0.19) with an average of 0.18. The number of stations used in each daily GAMIT solution shown in Fig. 2.13 (bottom) evinces the variation of the Topo-Iberia stations number over time, since the number of CORS is more or less fixed (15).

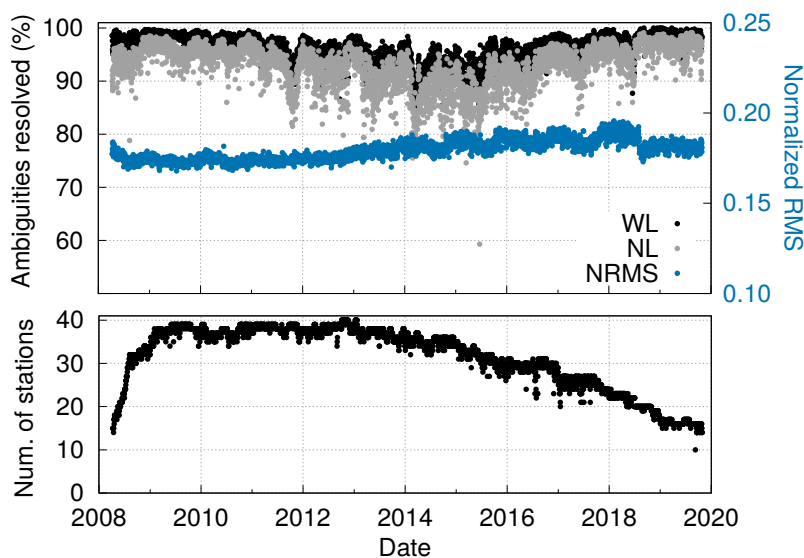
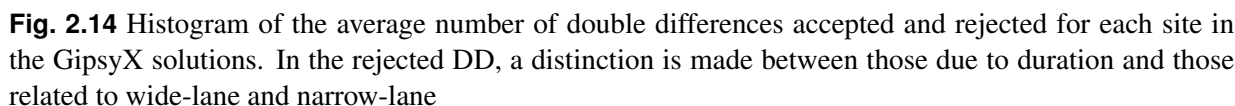


Fig. 2.13 Percentage of wide-lane (WL) and narrow-lane (NL) integer phase ambiguities fixed in each daily GAMIT solution, and its NRMS (top). Number of stations used in each daily solution (bottom)

GipsyX strategy

Each of the 40 sites is separately processed with GipsyX software version 1.7 (Bertiger et al. 2020) in precise point positioning (PPP) mode using ionosphere-free carrier phase and pseudo-



Several statistics are generated as part of the GipsyX ambiguity resolution process in the *ambres.stats* file, including the number of double differences (DD) accepted and rejected for each test considered (duration, wide- and narrow-lane) (see Fig. 2.14). In this way, the DD are rejected due to duration too short, and in the case of WL or NL due to bad DD, large sigma, and low confidence. The integer ambiguities are successfully resolved with an average of 99.8% for all RINEX files, with 3832 the average number of the DD that passed all tests.

Using the same method as the GAMIT h-files, the daily SINEX files are passed to GLOBK to obtain the final solution. In both cases, it is necessary to convert the files into GLOBK binary h-files. The GAMIT h-files contain loosely constrained solutions and full variance covariance matrices. The GipsyX-derived SINEX files come from separate PPP runs using fiducial-free prod-

ucts, so there are no parameters linking the positions between stations, and therefore, there is no covariance between their positions. To make these SINEX files loosely constrained and complete the covariance matrix, the methodology described by Herring et al. (2015, 2016) is followed. A covariance matrix is added to the block diagonal covariance matrix in the SINEX files, allowing the system to rotate and translate. This rotation and translation is accomplished with the *htoglb* GLOBK program (with option `-d=<TR>`) by adding 10 mas^2 in rotational variance and 1 m^2 in translation variance to the covariance and converting the SINEX files into binary h-files at the same time. In this way, the minimum constraint solutions are *loosened* so that they can rotate and translate in GLOBK.

Combined strategy

As described above, different models and processing parameters are used in GAMIT and GipsyX. Consequently, the noise models from both analyses differ, resulting in different position estimate standard deviations. For the individual final solutions to be comparable, their covariance matrices are rescaled to weight the solutions equally following the combination procedure established by Herring et al. (2016). The scale factors are determined such that the average value of the chi-squared per degree of freedom (χ^2/f) of the fit to the coordinate difference at the reference frame stations is near unity. Using the chosen GAMIT processing mode (BASELINE) and default reweighting scheme of the *autcln* program, the error budget is conservative, and the mean NRMS values obtained in the time series are $\sim 0.6\text{--}0.8$. Since the problem of individual solutions being comparable reduces to a problem of the relative weight of one solution with respect to the other, rather than rescaling both as in Herring et al. (2016), the GAMIT solution is used unscaled, and only the GipsyX solution is rescaled. In addition, to obtain an appropriate scaling value, the relationship between sigma values in the time series of both solutions is studied. Analyzing the histograms in Fig. 2.15, the GipsyX position estimates have a standard deviation ~ 1.9 times smaller than the GAMIT values. This sigma factor corresponds to a scale factor of 3.6, since it is necessary to square the value before applying it, i.e., the GipsyX h-files are downweighted by 3.6 in covariance (a factor of 1.9 in uncertainty). A sigma factor of ~ 2 between the GAMIT and Gipsy solutions was also determined in the study realized by Floyd et al. (2020). Once the GipsyX h-files are processed using GLOBK applying the scale factor (GipsyX rescaled), their sigma values are approximately in alignment with the GAMIT/GLOBK solution, as shown in the histograms.

For individual processing, scale factors for the GAMIT and GipsyX solutions are fixed to 1 and 3.6, respectively. When the results of both strategies are combined or, what is the same, two solutions for the same network of sites are combined, these factors are doubled so the solutions from individual strategies and their combination (Combined strategy) have similar standard deviations for the position estimates (Herring et al. 2016; personal communication with Floyd MA and Herring TA 2022).

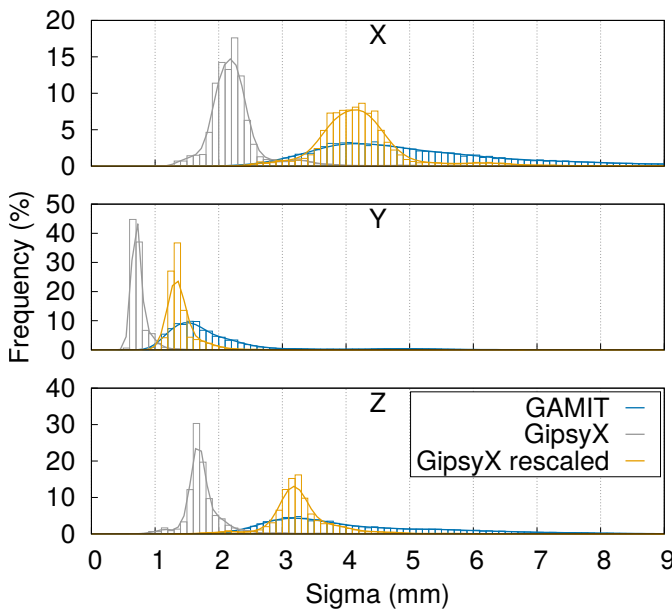


Fig. 2.15 Normalized histograms and kernel density estimates (curved lines) of sigma values in the GAMIT and GipsyX time series

Time series analysis

Prior to any velocity estimation, it is necessary to estimate and subtract non-secular (no tectonic) motions that can affect the stations, which by definition of the ITRF framework must be linear. The raw time series are analyzed to estimate and remove outliers, periodic terms, and discontinuities in an iterative process briefly described below. The analysis is realized using the *tsfit* GLOBK program, a command-line tool for fitting time series and generating statistics, and the *tsview* interactive MATLAB-based program (Herring 2003), since the point-by-point visual inspection is impractical in long and continuous time series. The files generated with *tsfit/tsview* containing outliers, discontinuities, and periodic signals are input to GLOBK to obtain a combined solution and extract positions and velocities more refined.

Outliers

The outliers are detected and eliminated using two automatic procedures (max-sigma and n-sigma). Any position estimate whose uncertainty is more than 2, 2, and 3 cm in east, north, and up, respectively, is removed (max-sigma), as well as the points that exceeded the 2-sigma value after detrending the data. Although the final result corresponds to this n-sigma criterion, the analysis has also been carried out using the 3-sigma criterion to verify and compare the results, which should be quite similar. Small values of this criterion allows for more precise results but can also cause all data to be deleted, and even more if there are non-secular motions not detected correctly. Considering only the known information from the station metadata, a preliminary analysis is carried out with both n-sigma criteria revealing notable discrepancies in the horizontal velocity at some Topo-Iberia stations (Fig. 2.16 left). The results shown correspond to the GAMIT/GLOBK strategy, but these are also similar using the GipsyX and Combined

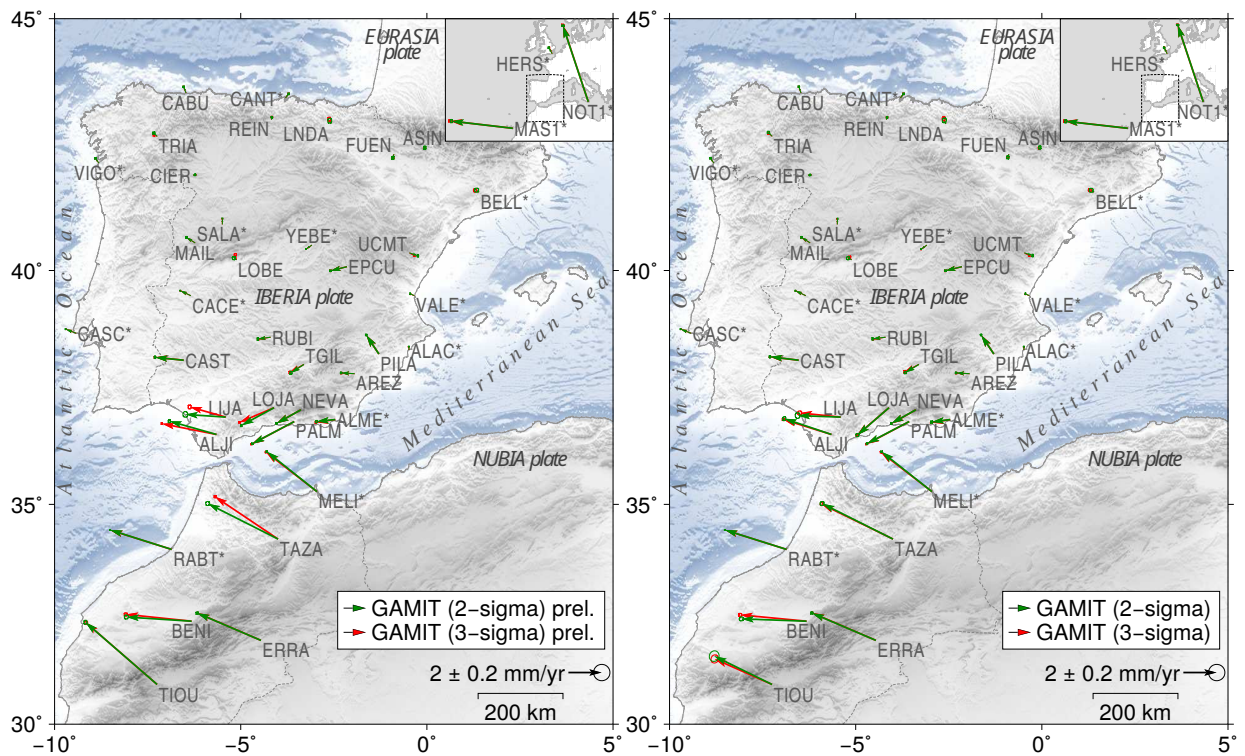


Fig. 2.16 Map of the horizontal velocities from the GAMIT solution obtained using 2- and 3-sigma criteria in a Eurasian-fixed reference frame. The CORS used to define the framework are marked with an asterisk at the end of their name. (Left) Preliminary analysis. (Right) Second analysis, once outliers or data segments are removed, offset breaks added, and periodic signals estimated

strategies. The stations showing more discrepancies are ALJI, LIJA, LOJA, and TAZA. These relative differences are due to that some data segments are considered outliers using the 2-sigma criterion, resulting in a different velocity direction that the direction obtained using the 3-sigma criterion. Although these stations could have time series with acceptable statistical values, a further analysis is required. In a second analysis, some data segments have been excluded which could be related to malfunctions due to battery problems in winter periods already detected at other Topo-Iberia stations (García-Armenteros 2020), but the cause is unknown in most of them. An example can be seen in Figs. 2.17a,b where a data segment is shown, which has been deleted in Figs. 2.17c,d. It can be verified after its deletion how the resulting velocities are similar using both criteria. After the second analysis, the greatest velocity discrepancies disappear or are reduced (Fig. 2.16 right). Uncertainties for rates quoted in the text are one-sigma and those shown in the figures are 95% confidence intervals unless stated otherwise.

Discontinuities

A discontinuity can occur due to events such as earthquakes, hardware or antenna changes, and other causes of unknown origin in the station environment, which produce abrupt and permanent position changes. In the preliminary analysis, only the offsets due to known equipment

changes were considered, and once these were corrected, other offsets could be detected and corrected adding breaks. Some of these breaks correct obvious jumps to naked eye, and in other cases they correct small offsets (amplitude of some mm) improving the linearity in some of the velocity components and decreasing the time series statistics. For example, comparing the Figs. 2.17e,f it can be seen that when the 2-sigma criterion is used, a data segment in 2008 is automatically deleted as it is considered an outlier, causing the discrepancy in the horizontal velocity direction shown above in Fig. 2.16 left. In Figs. 2.17g,h an offset break has been added after a small gap correcting the loss of the data segment and the velocity discrepancy between both n-sigma criteria.

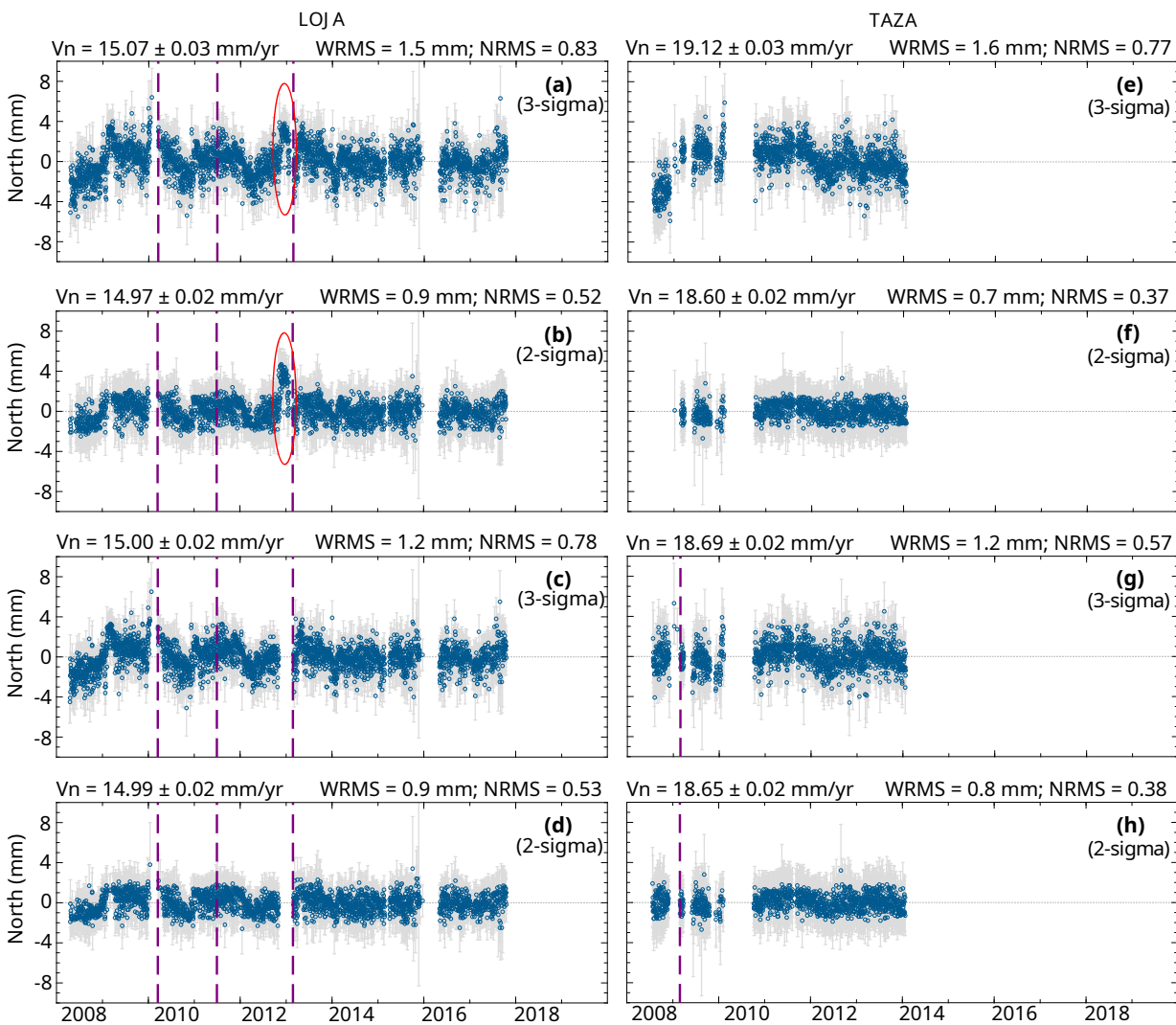


Fig. 2.17 LOJA (left) and TAZA (right) position time series of the residual north component analyzed using different n-sigma criteria in the IGB14 reference frame. The outliers and offsets were removed, the linear trends and periodic signals were estimated. The daily positions are shown in blue with error bars in grey. The deleted data segment is marked with a red ellipse, and the magenta dashed lines represent equipment changes or added offset breaks

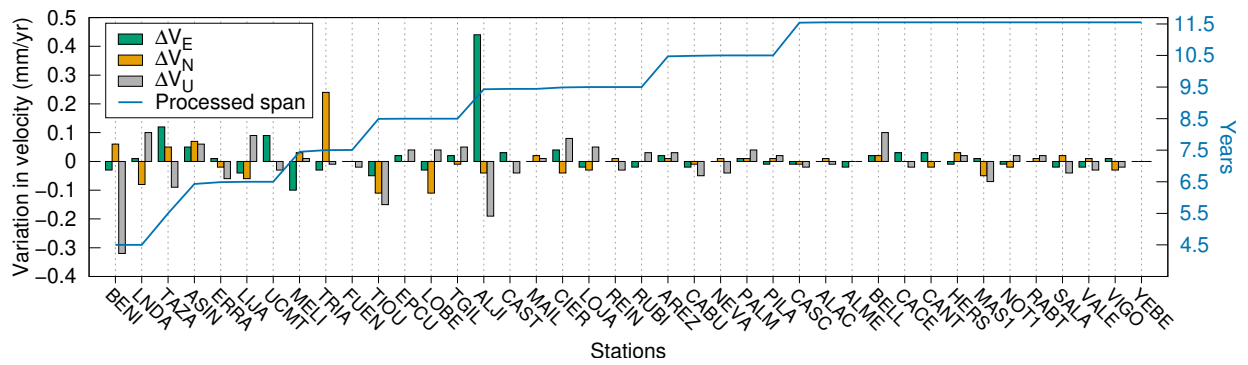


Fig. 2.18 Differences between the velocity component estimates considering and without considering the seasonal signals, and sorted according to the processed span for each station

Strategy	ΔV_N (mm/yr)		ΔV_E (mm/yr)		ΔV_U (mm/yr)	
	RMS	Mean	RMS	Mean	RMS	Mean
GAMIT	0.05	0.00	0.08	0.01	0.08	-0.01
GipsyX	0.06	0.01	0.06	0.01	0.08	0.00
Combined	0.06	0.00	0.08	0.01	0.05	0.00

Table 2.3 Statistics of differences in north, east, and up velocity component estimates considering and without considering the seasonal signals for each strategy

Periodic signals

The periodic signals can affect the three components of GPS time series being their frequency spectrum dominated by annual and semi-annual periods (seasonal signals). When the data were selected for processing, the effect of these signals in the estimation of the velocities (Blewitt and Lavallée 2002) was taken into account selecting data spans of integer-plus-half years and longer than 4.5 years. Although the velocity bias could be minimum, the annual and semi-annual periods (sine and cosine terms) are estimated from the time series using *tsfit/tsview*. Moreover the seasonal signals constitute a source of noise for the velocity estimation, therefore the elimination of these signals facilitates detecting anomalous data segments and smaller offsets (amplitude of some mm) masked in the time series noise.

A comparison has been realized between the velocity estimates considering and without considering the annual and semi-annual terms in the time series, and the results obtained using GAMIT/GLOBK are shown in Fig. 2.18. Except for a few stations, it is observed that the variation in velocity is minimal, particularly in periods over 8.5 years. Table 2.3 summarizes the statistics of the differences obtained between both solutions for the three strategies showing similar and low values. This low affectation of estimating the seasonal signals was expected according to the length of the data spans and the precautions taken in their selection. Furthermore, whether or not to consider this estimation does not affect the velocity uncertainties. The prominent east velocity variation at the ALJI station (Fig. 2.18) is studied in detail in Fig. 2.19. The annual frequency has been the most detected (top right) being its amplitude in the east component of ~ 1.5 mm, five times greater than in the north component. When the seasonal signals are estimated and

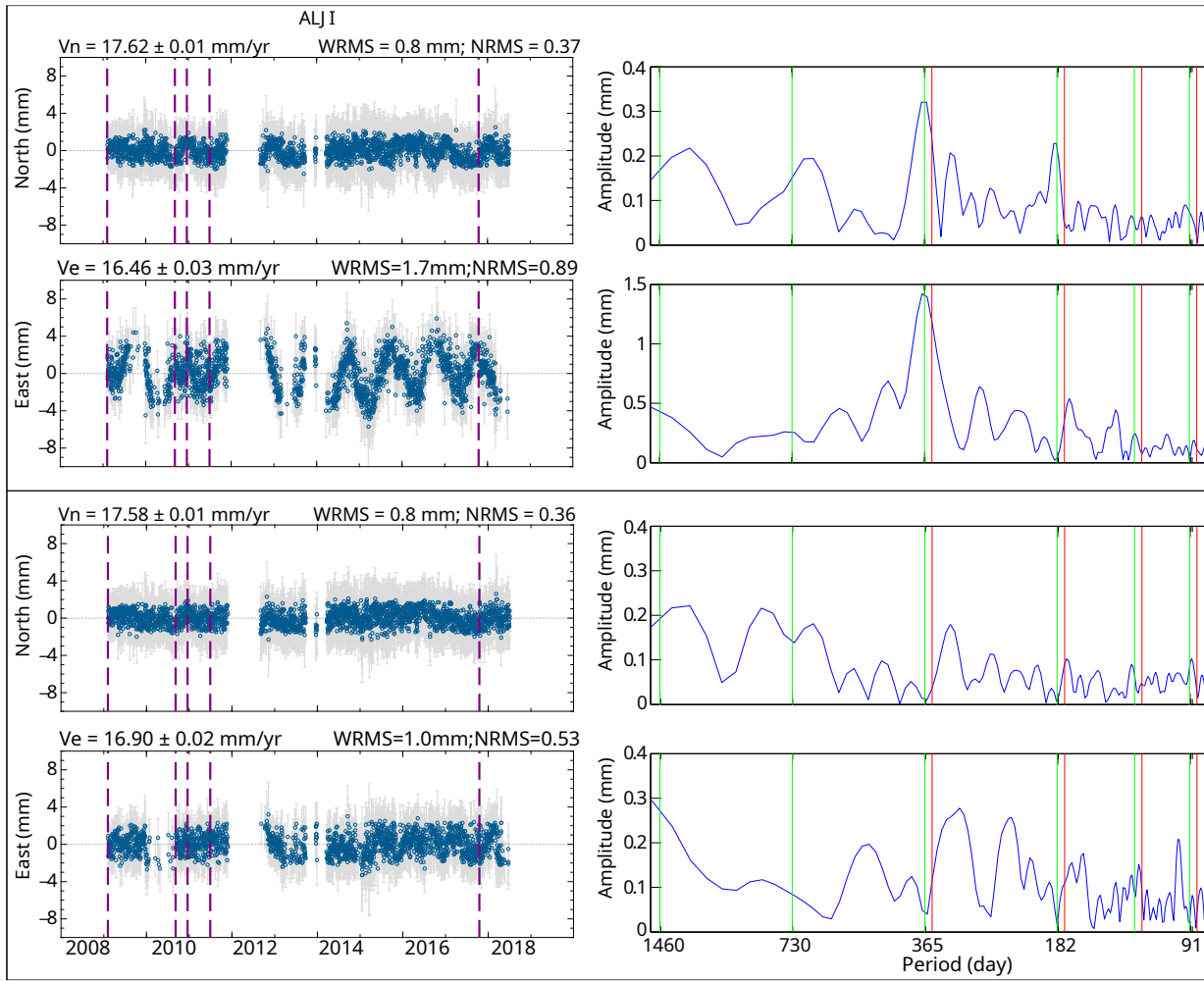


Fig. 2.19 (Left) ALJI residual north and east components time series considering (bottom) and without considering (top) the annual and semi-annual terms in the IGB14 reference frame. The outliers and offsets were removed and the linear trends estimated. The daily positions are shown in blue with error bars in gray. The magenta dashed lines represent equipment changes or added offset breaks. (Right) Correspondence in the frequency spectrum obtained using *tsview*. This figure corresponds to the Fig. S8 (Supplement 1) and has been cropped on the right for annotations clarity

removed (bottom left), the annual frequency is almost completely removed resulting in the mentioned velocity variation in the east component. Therefore, although it is shown that the effect of the periodic signals has been minimal, estimating them is advisable as shown in the case of the ALJI station.

Noise model

In the analysis realized, the noise in the GPS position time series is assumed to be a combination of white noise plus random-walk (RW) noise. The long-period temporally correlated noise is accounted for using the *realistic-sigma* algorithm or *First-Order Gauss–Markov Extrapolation* (FOGMEX) (Herring et al. 2015; Floyd and Herring 2020) to determine a RW noise term and

add it to the error model used by GLOBK. The FOGMEX algorithm is an option implemented in *tsfit* and previously proposed and referred to as the *RealSigma* option by Herring (2003). The RW values are generated for each site by the analysis of the position residuals from fitting their time series. A minimum RW process noise value of $0.05 \text{ mm}^2/\text{yr}$ is imposed in each station. The median RW values obtained in the north, east and up components are 0.06, 0.06 and $0.09 \text{ mm}^2/\text{yr}$, respectively, from the Combined strategy. Similar values were obtained from the GAMIT and GipsyX strategies except in up component, which are 0.12 and $0.11 \text{ mm}^2/\text{yr}$ respectively. The maximum horizontal random-walk (HRW) process noise value is obtained at the TIOU station ($0.3 \text{ mm}^2/\text{yr}$), therefore, there have not been stations with high process noise values that could contaminate nearby stations. The RW process noise values obtained are incorporated into the kalman filter (GLOBK) after the last iteration of the process flow (Fig. 2.4) to estimate the final velocities and obtain more realistic uncertainties.

A comparison between the globk velocity solutions applying and without applying the FOGMEX algorithm was realized to quantify their impact on the velocity uncertainties. Table 2.4 shows that the increase in the uncertainties is similar for the three strategies.

Strategy	$\Delta\sigma_N$ (mm/yr)		$\Delta\sigma_E$ (mm/yr)		$\Delta\sigma_U$ (mm/yr)	
	RMS	Mean	RMS	Mean	RMS	Mean
GAMIT	0.08	0.07	0.07	0.07	0.10	0.08
GipsyX	0.07	0.06	0.07	0.07	0.09	0.08
Combined	0.06	0.06	0.07	0.07	0.08	0.07

Table 2.4 Statistics of the differences in velocity uncertainties (1σ) applying and without applying the FOGMEX algorithm for each strategy

Comparison of time series

The statistics of the final time series generated using each strategy are summarized in Table 2.5 and Fig. 2.20. The median horizontal WRMS scatters are less than or equal to 0.9 mm for all strategies, with 0.5 mm being the lowest value for the GipsyX east component and 0.6 mm for the remaining strategies in the north and east components. The median up WRMS scatters are less than or equal to 2.1 mm, with the lowest value for the Combined strategy. The means in the north and east components are 0.7 mm for all strategies, indicating good repeatability.

Strategy	North (mm)		East (mm)		Up (mm)	
	Median	Mean	Median	Mean	Median	Mean
GAMIT	0.6	0.7	0.6	0.7	1.9	2.1
GipsyX	0.6	0.7	0.5	0.6	2.1	2.2
Combined	0.6	0.7	0.6	0.6	1.8	2.0

Table 2.5 Statistics of the WRMS position residual scatter in the final fitting of the time series for each strategy

When the combination of the h-files is performed, *globk* computes the χ^2 increment that occurs if the data from the new h-file are added to the solution. If this value exceeds a tolerance

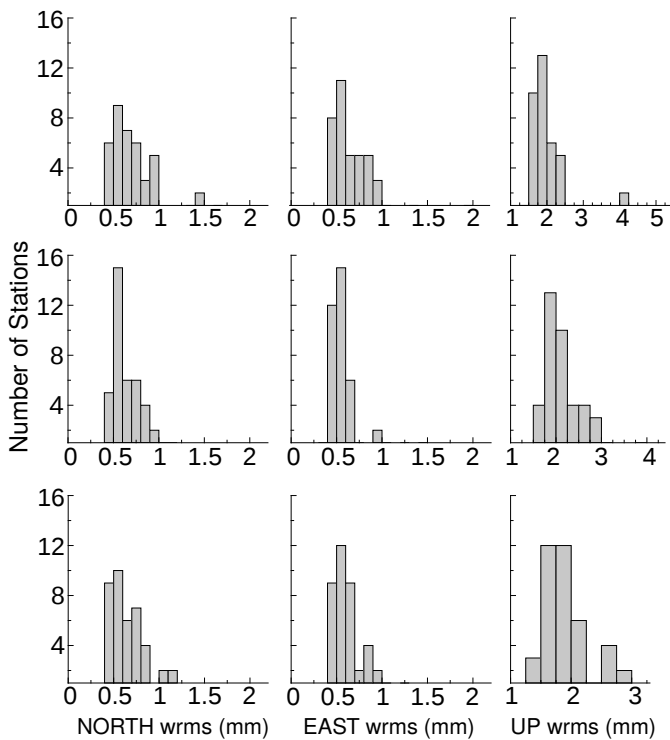


Fig. 2.20 GAMIT (top), GipsyX (middle), and Combined (bottom) solution histograms of the north, east, and up WRMS position residual scatter. Linear trends, outliers, offsets and periodic signals were estimated and removed from the time series

given, the data are not included (Herring et al. 2015). As a consequence, the number of daily combined solutions is less than the daily individual solutions from GAMIT or GipsyX. Moreover, the error bars in the time series from the Combined strategy are slightly larger than those in the other strategies, most notably in the up component. After the time series analysis is performed (estimation and elimination of outliers, periodic terms, discontinuities, and detrending), the final number of daily positions in the Combined strategy is less than in the GAMIT and GipsyX strategies. Possibly this is the reason why the up WRMS in the Combined strategy is lower. In general, the statistics are similar in the three strategies, and the differences between them are on the order of a tenth of a mm.

Comparison of velocity solutions

A comparison between GAMIT and GipsyX solutions without applying the realistic-sigma algorithm was used to check their degree of matching. In Fig. 2.21 (left), some discrepancies in the direction of the velocity vectors are observed, which are more visible at the NOT1 and southern stations with higher velocities. In principle, it could be interpreted that there is a slightly clockwise rotation in the GipsyX velocity solution with respect to the GAMIT solution, except at the NOT1 station, which has a counterclockwise rotation. In the standard GAMIT processing (BASELINE mode), the h-files are converted into GLOBK binary h-files using *htoglb* with the default options, i.e., applying a rotational and translational variance to the covariance to loosen the minimum constraint solutions (automatic loosening of rotational and translational constraints). If the translation (Helmert parameters) is then estimated in *glorg*, it is not necessary

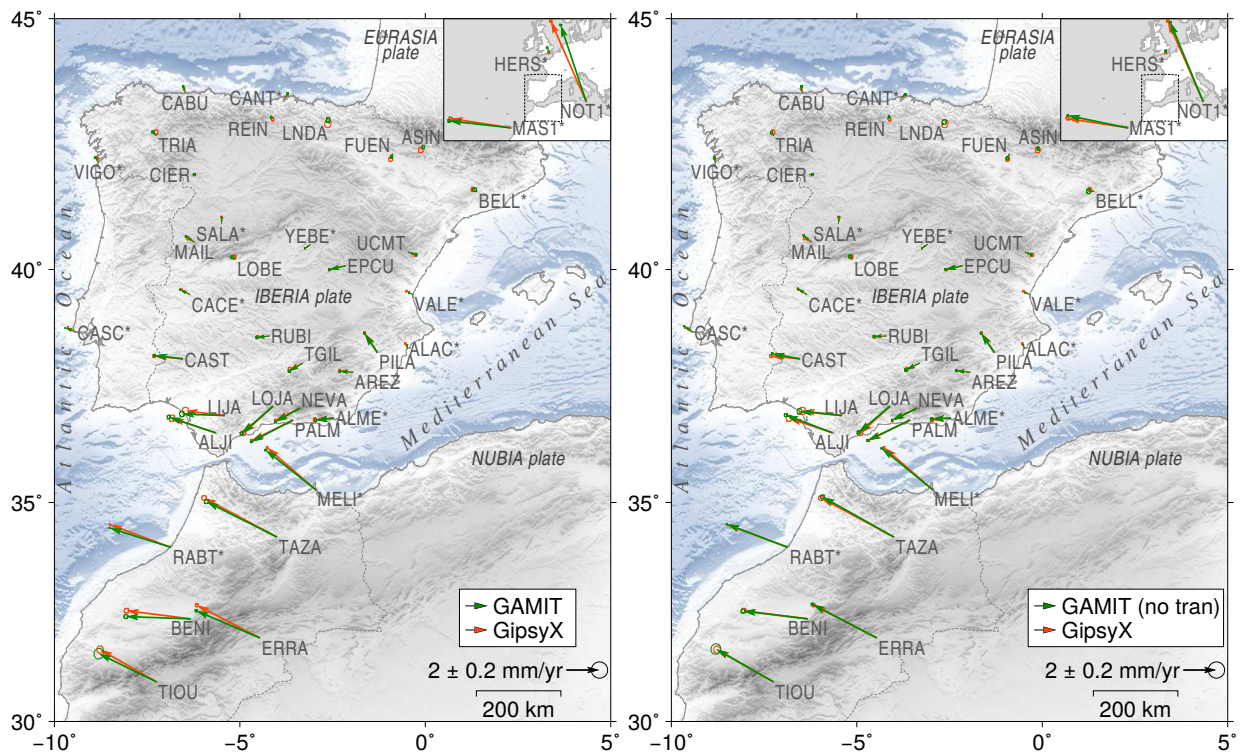


Fig. 2.21 Map of the Eurasian-fixed horizontal velocities (95% confidence interval) from the GAMIT and GipsyX solutions with translation estimation made explicit in *globk.cmd* (left) and without it (right). The CORS used to define the framework are marked with an asterisk at the end of their name

to make it explicit in *globk.cmd* (*globk* command file) since doing so will have little effect. In the analysis carried out, a combination of GAMIT and GipsyX was the goal; therefore, to facilitate the subsequent combination of h-files, the automatic loosening of constraints is not applied to the GAMIT solution (option -a in *htoglb*). In this case, if the intent is translation estimation, it is necessary to make it explicit in *globk.cmd*, and the result will be similar to standard GAMIT processing.

On the other hand, the GipsyX SINEX files do not contain EOP information (see details in Supplement 2) and were converted by applying rotational and translational constraint loosening, so the EOP and translation estimation will have no effect when performing a GipsyX-only solution. In the Combined solution, the translation estimation will have an effect when there are GipsyX and GAMIT h-files on the same day, since these second files contain EOP information (personal communication with Floyd MA and Herring TA 2022). To ensure that GAMIT and GipsyX solutions are in conditions as similar as possible for *comparison purposes only*, it is necessary not to make the translation explicit in the *globk.cmd* for the GAMIT solution (Fig. 2.21 right). The velocity solutions match in a remarkable way considering that both come from independent processing. The RMS of the differences in the north and east velocity components between both velocity solutions is 0.08 and 0.07 mm/yr, respectively. The velocity solutions are also similar with respect to their one-sigma uncertainties (RMS of their differences in the north

and east are 0.02 and 0.01 mm/yr, respectively). The discrepancies found could be related to the different effects resulting from the translation estimation on each velocity solution and the lack of EOP information in the GipsyX SINEX files.

As indicated, the described process was carried out only to make a comparison between individual solutions. In the GLOBK processing and subsequent combination of h-files, the automatic loosening of constraints is not applied for the GAMIT solution (option -a in *htoglb*) (see Fig. 2.4), and the estimation of translation is made explicit in *globk.cmd*.

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Quality assessment of the Topo-Iberia CGPS stations and data quality's effects on postfit ionosphere-free phase residuals

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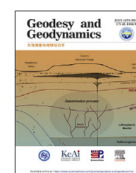
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Quality assessment of the Topo-Iberia CGPS stations and data quality's effects on postfit ionosphere-free phase residuals

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Abstract

This paper analyzed GPS data from the Topo-Iberia network spanning almost 12 years (2008–2020). The data quality information for all 26 Topo-Iberia stations is provided for the first time, complementing the Spanish Geological Survey's storage work. Data analyses based on quality indicators obtained using TEQC have been carried out. The guidelines and data quality information from the IGS stations have been considered as the quality references, with the stations ALJI, EPCU, and TIOU standing out as the worst stations, while on the contrary, FUEN, PALM, PILA, and TRIA meet the quality requirements to become an IGS station. The relationship between the GPS data quality and their GAMIT- and GipsyX-derived postfit ionosphere-free phase residuals has also been investigated, and the results reveal an inversely proportional relationship. It has been found that the stations showing an increase in elevation of the horizon line, also show an increase in cycle slips and multipath, are among the poorest quality stations, and among those with the highest postfit RMS of phase residuals. Moreover, the evolution of the vegetation around the antenna should be considered as it could cause a progressive loss of quality, which is not complying with the IGS standards. The quality assessment shows that the Topo-Iberia stations are appropriate for geodetic purposes, but permanent monitoring would be necessary to avoid the least possible loss of data and quality. In addition, a method to characterize the GNSS data quality is proposed.

Keywords GPS data quality's effects · IGS quality standard · Postfit LC phase residual · Quality assessment · Topo-Iberia CGPS network

3.1 Introduction

One application of the Global Navigation Satellite System (GNSS) networks geodynamics is to measure crustal deformation. The implementation of GNSS networks on a global, national, and regional scale, as well as their densification, have allowed the study of tectonic plate displacements, displacements due to active faults, subsidence, and earthquakes, among others. The GNSS technique, specifically the Global Positioning System (GPS), was one of the methodologies used to take crustal deformation measurements in the project Geosciences in Iberia: Integrated studies of topography and 4-D evolution ‘Topo-Iberia’ (Gallart 2006). For this purpose, a Topo-Iberia network composing 26 continuously operating GPS stations (CGPS), covering the Spanish part of the Iberian Peninsula and Morocco was established, complementing existing networks. The network was fully operational in December 2008, and the Spanish Geological Survey (IGME) implemented the Topo-Iberia Information System (SiTopo) to store the data. The maintenance and control of the stations are distributed among institutions that formed the Consolider Topo-Iberia team (Fig. 3.1).

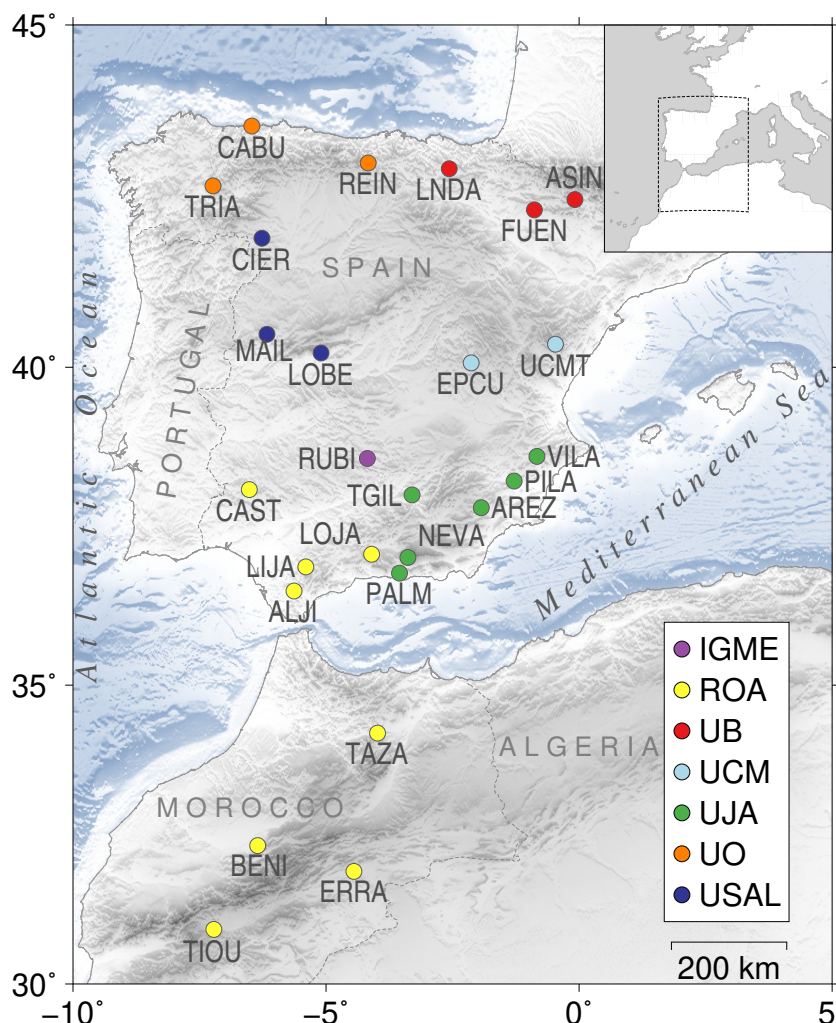


Fig. 3.1 Deployment of the Topo-Iberia CGPS stations in function of the institution in charge. The shaded-relief image of the Earth illumination from the south is at 1 arc minute resampled from the SRTM15+V topography database (Tozer et al. 2019) plotted with Generic Mapping Tools (GMT) software (Wessel et al. 2013)

The quality of the permanent GNSS networks for geodetic purposes depends on the equipment installed, the stability of the monument supporting it, and the physical location of the station. The Topo-Iberia station equipment was installed on the ground, and the antennas were primarily installed on concrete pillars anchored on rocky outcrops to maximize the stability following criteria recommended by UNAVCO (Gárate et al. 2008). All Topo-Iberia stations were initially outfitted with Trimble NetRS dual-frequency receivers and Trimble GNSS Choke-Ring antennas, using SCIGN radomes only in those places where environmental conditions advise it (Table 3.1). The communication with the stations is via a GPRS modem, and the power supply is carried out by a solar panel and two batteries, except for the station NEVA which is connected to the internet via a wired connection and to the power grid at the Sierra Nevada Observatory (Granada).

The data quality information is essential in the GNSS networks to ensure that the stations work properly and the data are appropriate for geodynamic studies. Example of this information type is provided by international services such as the EUREF Permanent GNSS Network (EPN) (EUREF 2021) and the University NAVstar CONSORTIUM (UNAVCO) over the Plate Boundary Observatory (PBO) network (UNAVCO 2021) or some study on quality data from GNSS stations (Hernández-Andrade et al. 2022). There is currently no information on data quality from the Topo-Iberia CGPS stations except for the study on 6 stations and a global view of the quality carried out by García-Armenteros (2020); García-Armenteros (2023). For this reason, the present work aims to assess the GPS data quality and provide the quality information for all 26 Topo-Iberia stations, thus complementing the IGME's storage work. Moreover, as in previous studies (Hernández-Andrade et al. 2022; García-Armenteros 2020), quality thresholds established by the International GNSS Service (IGS) are taken as quality references, evaluating whether the Topo-Iberia stations would have sufficient quality to become an IGS station.

García-Armenteros (2023) provided a new 3D crustal velocity field in the Iberian Peninsula and Morocco based on eleven years (2008–2019). The GNSS data processing software used was GAMIT version 10.71 (Herring et al. 2018) that applying the double-differencing technique, and GipsyX version 1.7 (Bertiger et al. 2020), applying the PPP technique. In the case of GAMIT, the Topo-Iberia stations (25) plus additional continuously operating reference stations (CORS) (15) were processed simultaneously in only one regional network (40). The satellite orbit parameters were fixed to the IGS final values, and the Earth Orientation Parameters (EOP) were interpolated from the International Earth Rotation and Reference Systems Service (IERS) Bulletin A (BASELINE mode in GAMIT). In the case of GipsyX, each of the 40 sites was separately processed using ionosphere-free carrier phase and pseudorange observables. JPL's final non-fiducial GNSS products (antenna models, ephemerides, clocks, and EOP) were used. Details of the GAMIT and GipsyX processing specifications were given by García-Armenteros (2023, Tables S2-S3 SI_1). The present work also intends to study how the quality of the GPS data affects the results of their processing, i.e., the relationship between the GPS data quality and the one-way postfit

Table 3.1 Topo-Iberia CGPS stations. 4-char ID, geographic position, location, installation/dismantling date (Year–Day Of Year), last antenna and receiver installed, and institution in charge. Geographic position taken from García-Armenteros (2023)

ID	Lon (°)	Lat (°)	Location	Install / Dismantle	Antenna Dome	Receiver	Inst. ¹
ALJI	-5.64938	36.52989	Sierra del Aljibe, Cádiz (ES)	2008–101 / -----	TRM29659.00 NONE	Trimble NetRS	ROA
AREZ	-1.94046	37.83543	Sierra del Almiraz, Murcia (ES)	2008–116 / -----	TRM29659.00 NONE	Trimble NetRS	UJA
ASIN	-0.09868	42.51661	Asín de Broto, Huesca (ES)	2008–269 / -----	TRM29659.00 SCIT	Trimble NetRS	UB
BENI	-6.31859	32.37679	Beni-Mellal (MA)	2008–204 / 2013–318	TRM29659.00 NONE	Trimble NetRS	ROA
CABU	-6.47000	43.56897	Faro Cabo Busto, Asturias (ES)	2008–078 / -----	TRM29659.00 SCIS	Trimble NetRS	UO
CAST	-6.53214	38.12273	Castillo de Segura, Badajoz (ES)	2008–069 / -----	TRM29659.00 NONE	Trimble NetRS	ROA
CIER	-6.28065	41.94113	Villardeciervos, Zamora (ES)	2008–191 / -----	TRM29659.00 SCIS	Trimble NetRS	USAL
EPCU	-2.14646	40.07955	Polytechnic School of Cuenca (ES)	2008–185 / -----	TRM29659.00 SCIS	Trimble NetRS	UCM
ERRA	-4.45606	31.93879	Errachidia (MA)	2008–156 / -----	TRM29659.00 NONE	Trimble NetRS	ROA
FUEN	-0.88541	42.36022	Fuencalderas, Huesca (ES)	2008–205 / -----	TRM29659.00 SCIT	Trimble NetRS	UB
LIIJA	-5.40379	36.90624	Sierra de Lijar, Cádiz (ES)	2008–043 / -----	TRM29659.00 NONE	Trimble NetRS	ROA
LNDA	-2.57827	42.96005	Landa, Alava (ES)	2008–214 / -----	TRM29659.00 SCIT	Trimble NetRS	UB
LOBE	-5.11040	40.22045	Lobera, Avila (ES)	2008–191 / -----	TRM29659.00 SCIS	Trimble NetRS	USAL
LOJA	-4.10635	37.10727	Loja, Granada (ES)	2008–069 / -----	TRM29659.00 NONE	Trimble NetRS	ROA
MAIL	-6.22369	40.56916	Maillo, Salamanca (ES)	2008–218 / -----	TRM29659.00 SCIT	Trimble NetRS	USAL
NEVA	-3.38564	37.06262	Sierra Nevada, Granada (ES)	2008–291 / -----	TRM29659.00 SCIS	Trimble NetRS	UJA
PALM	-3.56230	36.80904	Sierra los Guájares, Granada (ES)	2008–157 / -----	TRM29659.00 NONE	Trimble NetRS	UJA
PILA	-1.28943	38.25431	Sierra de la Pila, Murcia (ES)	2008–165 / -----	TRM29659.00 NONE	Trimble NetRS	UJA
REIN	-4.17707	43.04594	Reinosa, Cantabria (ES)	2008–137 / -----	TRM29659.00 SCIS	Trimble NetRS	UO
RUBI	-4.19657	38.60935	Cabezarrubias, Ciudad Real (ES)	2008–127 / -----	TRM29659.00 NONE	Trimble NetRS	IGME
TAZA	-3.99644	34.22953	Taza, Fes (MA)	2008–204 / 2014–044	TRM29659.00 NONE	Trimble NetRS	ROA
TGIL	-3.30256	38.03424	Torreperogil, Jaén (ES)	2008–099 / 2017–277	TRM29659.00 NONE	Trimble NetRS	UJA
TIOU	-7.24520	30.92363	Tiouine (MA)	2008–156 / -----	TRM29659.00 NONE	Trimble NetRS	ROA
TRIA	-7.24144	42.71481	Triacastela, Lugo (ES)	2008–106 / -----	TRM29659.00 SCIS	Trimble NetRS	UO
UCMT	-0.47217	40.36378	Mosqueruela, Teruel (ES)	2008–197 / -----	TRM29659.00 SCIS	Trimble NetRS	UCM
VILA	-0.84750	38.64050	Sierra de la Villa, Alicante (ES)	2008–253 / 2009–249	TRM29659.00 NONE	Trimble NetRS	UJA

¹Institution in charge: Spanish Geological Survey (IGME), Spanish Navy Observatory (ROA), University of Barcelona (UB), Complutense University of Madrid (UCM), University of Jaén (UJA), University of Oviedo (UO), University of Salamanca (USAL)

ionosphere-free linear-combination (LC) phase residuals derived from both methodologies.

3.2 Data and methodology

All Topo-Iberia GPS data available on February 11, 2020 are analyzed in this study resulting in 77506 RINEX (Receiver Independent Exchange) formatted files. The quality-controlled data span from 2008-03-19 to 2020-02-10, a total of 11.9 years, and the LC phase residuals analyzed correspond to the GPS data processing (García-Armenteros 2023) from 2008-04-09 to 2019-10-29, a total of 11.6 years. Details on the data extent for each station are shown in Table 3.5 (Appendix) and Table S1 of Supplementary Information (SI).

To evaluate obstacles that may prevent the reception of the signal, QC2Sky software (Roggero 2010) is used to display the qc out-files from TEQC software (Estey and Meertens 1999). TEQC is a GNSS observation processing software that provides data quality information, such as the multipath effect, signal-to-noise ratio (SNR), and cycle slips. The satellite azimuth/elevation sky plots at the observation time in the Cartesian coordinate system are represented using QC2Sky, and a chromatic scale indicates the output values of the quality parameters. The existing obstacles are identified by their projection in this coordinate system. The sky plots on consecutive days are similar since the multipath effect produced by the station environment is usually permanent and characteristic of the site. Therefore, a complete cycle of the GPS constellation is sufficient to obtain the occlusion horizon of the station. Thus, the analysis was performed over 24 hours of observation with 30 seconds sampling interval in the first activity days. A zero cut-off elevation angle was set to obtain an overview of all observations on the horizon.

The GPS data from the Topo-Iberia stations are stored in native formats and RINEX version 2.11 (Gurtner and Estey 2012). The fact that these stations register only GPS observations, using this RINEX version and not new versions, allows the data quality check using TEQC, and no more modern software is necessary. The daily qc-reports obtained in the qc-full mode contain the parameters or indicators on which the quality check is based, corresponding to an elevation mask of 10° by default: maximum number of observations (OBS) as the number of actual complete observations that were counted for each frequency above the elevation mask angle, integrity (INT) or completeness in the recording of observations as a percentage of the number of complete observations recorded with respect to the number of expected or possible observations, cycle slips as the number of cycle slips per 1000 observations (CSR), and the root-mean-square (RMS) of multipath effect on L1 (MP1) and L2 (MP2) averaged over the observation interval. In the TEQC software, an observation complete for the GPS constellation is to have both observables, pseudorange and phase, on the frequency L1 and at least one other frequency for a satellite (Estey 2018). Knowing these daily quality parameters allows for monitoring the station's behavior over time. This information is integrated into historical quality plots and complemented with information from the site logs (change of antenna, receiver, firmware, etc.). A detailed analysis of

the station's behavior, and the quality throughout its activity period, requires in-depth knowledge of everything that happens at the station and its surroundings, maintenance, etc., beyond what is reflected in the *site logs*. This was only possible for the 6 stations under the UJA's control (García-Armenteros 2020). To assess the data quality from all 26 stations, some analyses have been carried out based on statistics of the quality indicators.

Data quality information from the IGS stations has been taken as a quality reference. A distinction has been made between some recommended (REC) guidelines regarding the data quality applicable both to current active IGS stations and to proposed stations (IGS 2015; Johnston et al. 2017), the quality threshold at more than half of the IGS stations (RF1), and the quality threshold at 2/3 of the IGS stations (RF2) (IGS 2017) shown in Table 3.2. In the case of the GPS constellation, the minimum number of observations expected at one station recording data at 30 seconds intervals during 24 hours is 20000. Since this indicator is not explicitly stated among the recommendations of the IGS (2015), it has been considered only in the thresholds RF1 and RF2.

Threshold	OBS	INT (%)	MP1 (m)	MP2 (m)	CSR
REC	-	95	0.3	0.3	1
RF1	20000	-	0.4	0.6	5
RF2	20000	-	0.5	0.75	10

Table 3.2 Quality indicator values for each IGS threshold

Regarding the study of the relationship between the data quality and the LC phase residuals, the postfit RMS scatter of phase residuals for each station has been extracted from the daily GAMIT's output file autcln.post.sum, and from the GipsyX's output file Summary obtained in the GPS processing by García-Armenteros (2023). Finally, the possible relationship between these results and those from the analyses based on statistics of the quality indicators has been studied.

3.3 Results and discussion

3.3.1 Stations quality

Fig. 3.2 shows an example of the satellite azimuth/elevation sky plots from the stations EPCU, LOBE, and TGIL obtained using QC2Sky. The sky plots from each Topo-Iberia station are provided in SI (Figs. S1–S3). The horizon of occlusion at each station is below 10° on the first activity days, there being no important obstacles except in the case of the stations ALJI, LIJA, NEVA, PALM, and TIOU. Nevertheless, these 5 stations have a wide enough horizon to record the necessary observations.

The RINEX signal strength indicators are standardized with the interval 0–9, with 1 the minimum possible signal strength and 9 the maximum possible (0 indicates that the value is

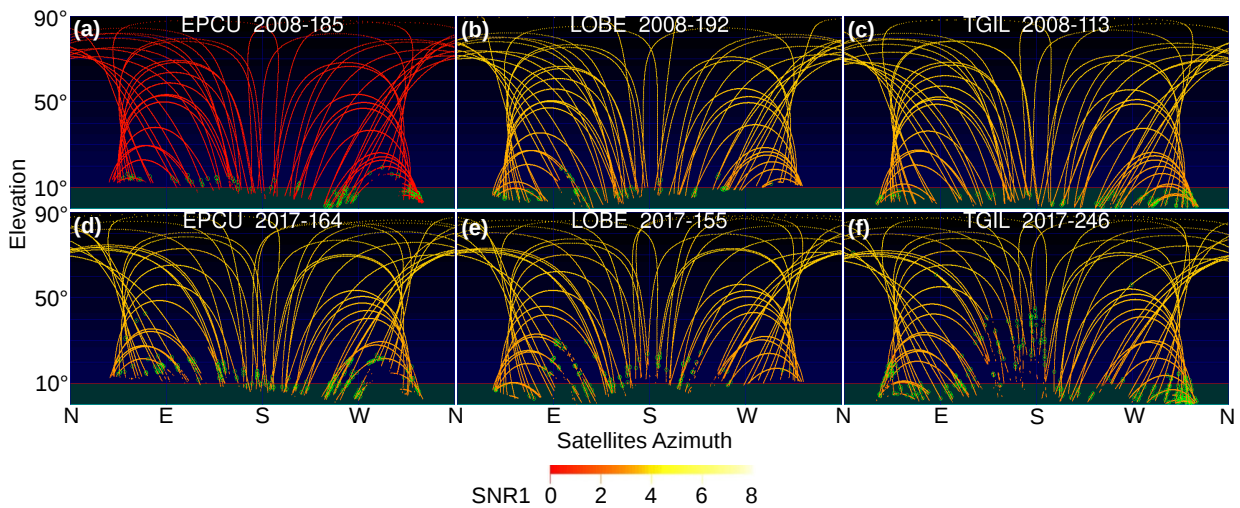


Fig. 3.2 Sky plots from (a–c) EPCU, LOBE, and TGIL stations on the first and (d–f) last activity days. Text in white corresponds to the station name and observation date (Year–DOY). Green dots represent the cycle slips, and the color of the satellite paths correspond to the signal-to-noise ratio value in L1 (SNR1) according to the chromatic scale modified from Roggero (2010)

unknown). The dBHz range that corresponds to each indicator, as well as the value that is considered good, has changed over time and different thresholds for good SNR can be found in the literature. Moreover, the recommended value of SNR is not explicitly stated in the IGS guidelines. In this study, the latest standardized SNR indicators established in the RINEX formats have been considered, being the value indicator 5 the threshold for good tracking corresponding to 30–35 dBHz (Romero 2020). All Topo-Iberia stations, except EPCU and UCMT, have shown a mean signal strength in L1 (SNR1) in the range of 44–47 dBHz (indicator 7), i.e., it is above the threshold for good SNR. On the other hand, it must be taken into account that the QC2Sky software resamples the SNR values from TEQC outputs in the interval 0–8, as can be seen on the chromatic scale in Fig. 3.2. The mean SNR1 at the stations EPCU and UCMT is about 6 dBHz, i.e., the minimum possible signal strength. However, it increased at the station EPCU, remaining stable since 2015 (Fig. 3.2d). In neither of the cases does the variation of the SNR value corresponded to the variation of the remaining quality parameters. A high SNR value indicates a strong signal, but a low SNR value indicates a weak signal or close to the noise floor, which may be difficult for the receiver to track (Bilich 2006). It is well known that the carrier phase multipath is directly related to the SNR, but these two stations show a multipath effect similar to that of most stations. The low SNR value at the station UCMT is presumably due to the antenna being installed a few meters from a very small-aperture terminal (VSAT) satellite antenna that increases the noise floor. Instead, the EPCU’s antenna is installed on a university campus, an environment that could have temporarily affected it similarly.

To assess the stability of the occlusion horizon, the sky plots on the first and last days of activity have been compared. In some cases, the last days do not reach 24 hours of operation, and the sky plots correspond to a few days before. In general, the occlusion horizon has remained

stable over time, except at the stations CIER, EPCU, LOBE, and TGIL. The change has been more evident at some stations such as TGIL, where elements of anthropic nature were added, or at LOBE where an increase in the elevation of the horizon line is observed in the southern zone, as well as an increase in the cycle slips (Fig. 3.2e). These changes in the occlusion horizon are related to alterations in the quality parameters analyzed below.

3.3.2 GPS data quality

Fig. 3.3 shows for the first time an overview of the quality based on the number of observations recorded from all 26 Topo-Iberia stations, whose data were available on the control date 2020-02-11. The periods with incomplete or missing files, or poor quality, are easily identified. This quality check was considered in the Topo-Iberia network processing by García-Armenteros (2023). When the data were selected for processing, the effect of the periodical signals in the estimation of velocities established by Blewitt and Lavallée (2002) was considered by selecting data spans of integer-plus-half years and longer than 4.5 years, so that the affectation was the least possible. In this way, the available span was shortened as necessary, with a priority of eliminating the periods of malfunction, such as the initial period of the stations ALJI and CABU, or the final period of LIJA. It is also observed that there are 4 dismantled stations on the control date. The absence of data for some stations is because they had not been sent to the IGME where they are centralized, and does not imply that the stations are inactive.

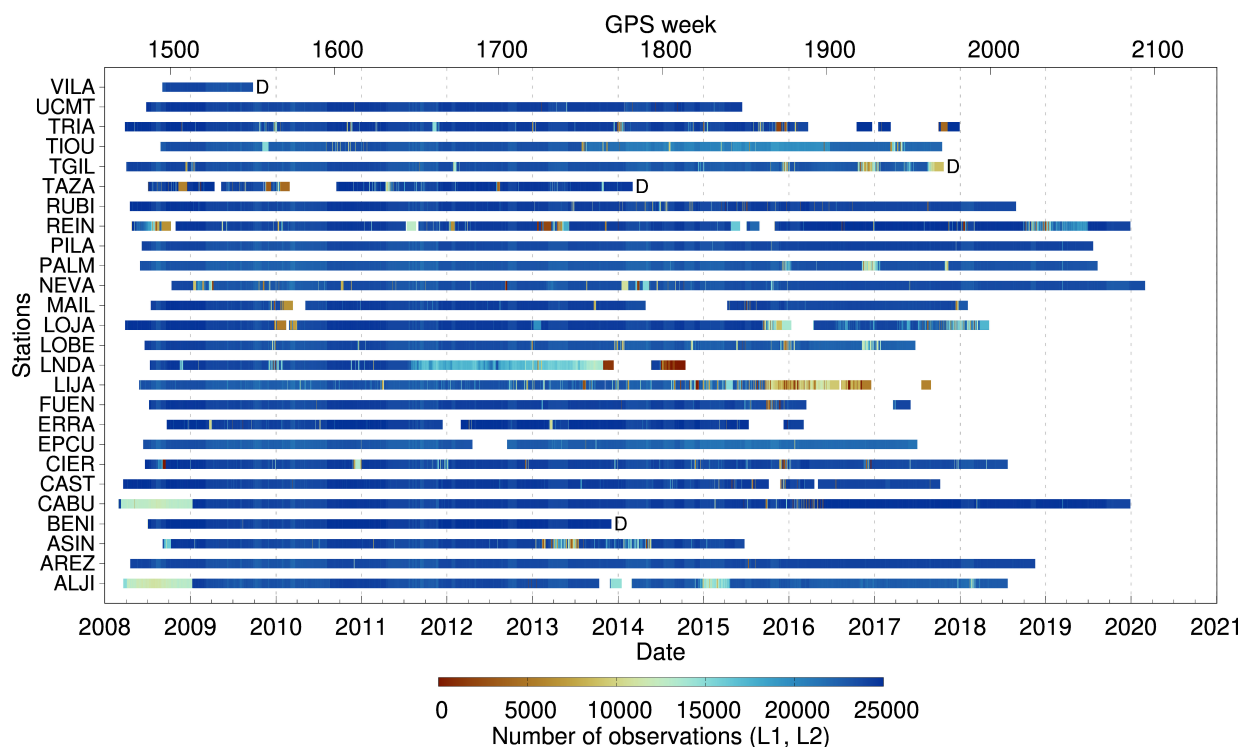


Fig. 3.3 Maximum number of complete observations recorded at each Topo-Iberia CGPS station throughout its activity period. The letter D indicates dismantled

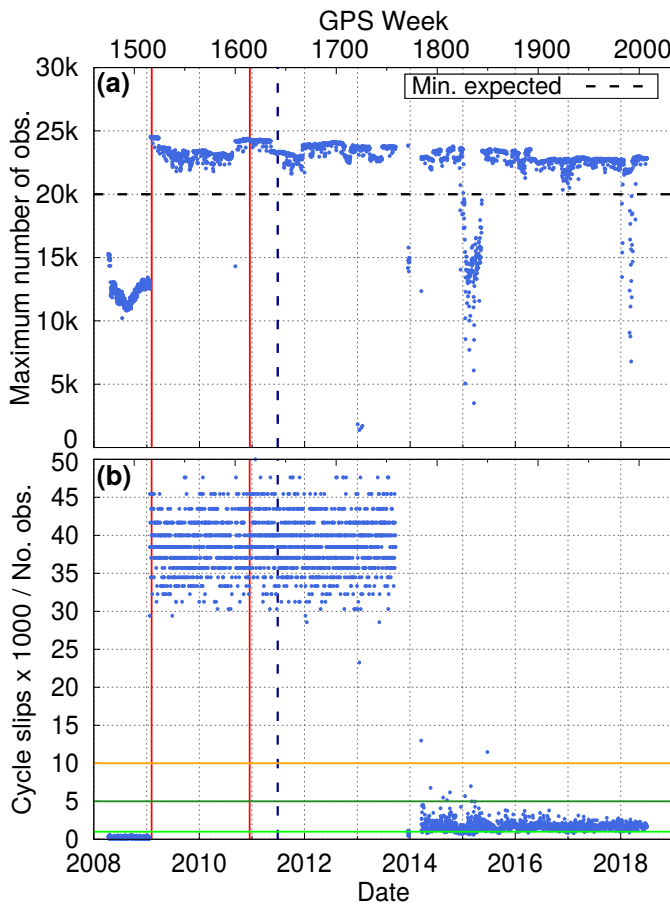


Fig. 3.4 Example of the GPS data quality information for the station ALJI: (a) maximum number of observations registered, and (b) number of cycle slips per 1000 observations. The green, dark green, and orange horizontal lines correspond to the IGS quality thresholds REC, RF1, and RF2, respectively. The red and blue vertical dashed lines correspond to antenna and receiver change

Fig. 3.4 shows an example of the multi-year or historical quality plot of some quality parameters obtained using TEQC for the station ALJI. The historical quality plots for each Topo-Iberia station with the full data quality information are also shown for the first time, and due to the great number of plots, they are provided in SI (Figs. S4–S29).

To analyze the data quality from the Topo-Iberia stations, basic statistics of the quality indicators have been calculated for each station. 39 RINEX files were not included in the quality plots nor in the statistics calculation for providing anomalous information. More details about them are shown in Tables S2–S3 of SI. The analyses of the data quality based on these statistics are presented below.

3.3.2.1 Analysis based on median

The median value, and not the average, was chosen since it is less affected by relatively short time spans with respect to the complete time series, where a station with extremely high or small values would have great influence on the average value. An example of this can be seen at the station ALJI showing an average value of 19.4 and a median of 3 in CSR (Table S4 of SI) due to high values over a period of time (Fig. 3.4b). Using the median value, it is known that 50% of the ALJI data are below 3 in CSR, thus showing the quality of a time series portion, which would not be possible to know using the average value.

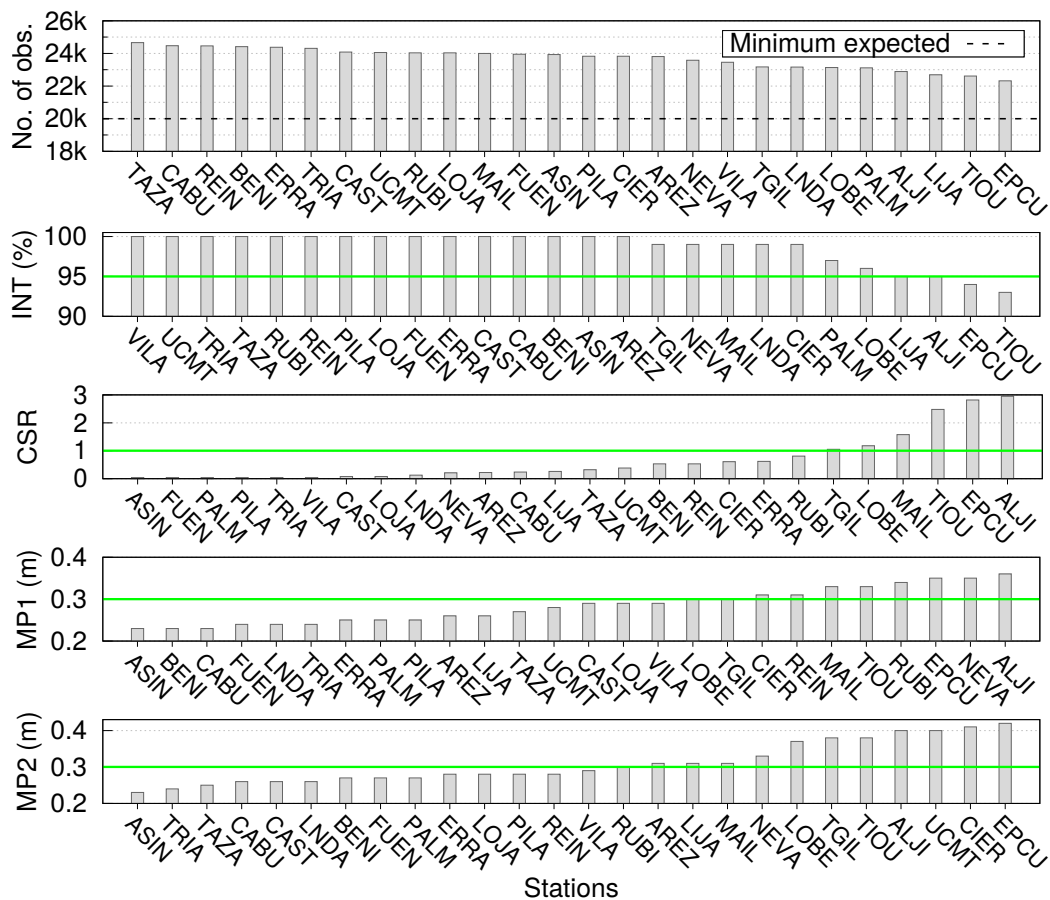


Fig. 3.5 Median value of the quality indicators analyzed for each Topo-Iberia station in the period from 2008-03-19 (DOY 079) to 2020-02-10 (DOY 041), and sorted in decreasing quality from left to right. The green horizontal lines correspond to the IGS recommended quality threshold (REC)

The median values of the quality indicators for each Topo-Iberia station are shown in Fig. 3.5. The record of the observations at all stations is above the minimum expected value (20000), corresponding to the minimum median value (22324) to the station EPCU. Regarding integrity, only 2 stations do not meet the IGS recommended value (95%), EPCU and TIOU, although with very close values, 94% and 93% respectively. 20 stations present the median integrity value $\geq 99\%$, which reflects high performance on this indicator for the whole network. The recommended value in the cycle slips per 1000 observations (1 CSR) is not met at only 6 stations, including again to EPCU and TIOU. The worst result corresponds to the station ALJI which presents high CSR values for almost half of the activity period due to unknown causes. As noted above, the quality plots are complemented with information from the site logs, and the sudden increase in the cycle slips and number of observations in 2009 at the station ALJI are presumably related to an antenna change. In contrast, there is no information about what might have happened in the station environment to explain the sudden decrease of the cycle slips in 2013. Regarding the multipath on L1, 8 stations do not meet the recommended value (0.3 m), and again ALJI is the station with the highest median MP1 value. However, station NEVA does not meet it either,

achieving good results in the remaining indicators throughout its activity period, with increases in the winter seasons (Appendix Fig. 3.12 and SI Fig. S19), which have been related to snow cover (García-Armenteros 2020). Finally, regarding the indicator MP2, 11 stations do not meet the recommended value (0.3 m). It should be noted that this analysis has been carried out with the statistical median, i.e., with the value corresponding to 50% of the data from each station for its entire period of activity. The stations that do not meet the IGS recommended values (REC), on the contrary, they meet the other less restrictive quality thresholds. That is, considering the median value of the quality indicators, all Topo-Iberia stations have better or equal quality than more than half of the IGS stations (threshold RF1 in Table 3.2).

3.3.2.2 Analysis based on compliance percentage

Another analysis has been carried out considering the level or percentage of compliance with the IGS thresholds in each quality indicator and for each station. Table 3.3 shows the percentage of available data from each station that meets each quality threshold. Thus, the station ALJI shows a median of 0.36 m in the indicator MP1, not meet the threshold REC, and actually, 8% of its data meet it. In the same way, the station UCMT, with a median of 0.40 m in the indicator MP2 and not meeting the threshold REC; 0% of its data meet it instead almost 100% of its data meet all quality thresholds for the remaining indicators. Considering the Topo-Iberia network as a whole, site NET* in the Table 3.3, it is observed that the lowest compliance percentages in the threshold REC correspond to the indicators MP1 and MP2 with 68% and 58%, respectively.

Considering all the indicators together, the mean percentage of compliance for each station is

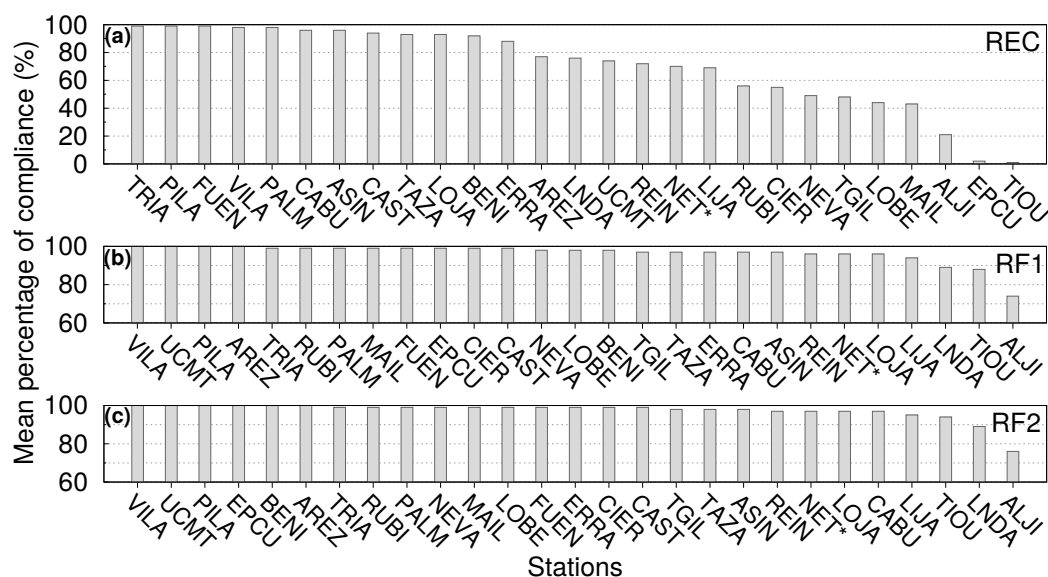


Fig. 3.6 Mean percentage of compliance with the IGS quality thresholds: (a) REC, (b) RF1, and (c) RF2. NET* corresponds to the Topo-Iberia network as a whole. The stations are sorted in decreasing percentages

also shown in Fig. 3.6. It is evident that with the threshold REC, the two worst stations are TIOU and EPCU, below 2% compliance, followed by ALJI with 21%. Moreover, ALJI and TIOU are the stations that show the lowest percentage of compliance in the threshold RF1, 74% and 88%, respectively. Half of the Topo-Iberia stations have a percentage of compliance with the threshold REC greater than 76%, and at 7 of them it is greater than 95%. The network meets the thresholds REC and RF1 with 70% and 96%, respectively.

Table 3.3 Percentage (%) of compliance with the quality indicators according to the IGS thresholds defined in Table 3.2 for each Topo-Iberia station. The site NET* represents the network as a whole

Site	OBS	INT	MP1			MP2			CSR			ALL ²		
	RF1-2 ¹	REC	REC	RF1	RF2	REC	RF1	RF2	REC	RF1	RF2	REC	RF1	RF2
ALJI	87	68	8	57	66	0	100	100	10	52	52	21	74	76
AREZ	100	100	100	100	100	15	100	100	96	100	100	77	100	100
ASIN	92	92	99	99	100	100	100	100	96	100	100	96	97	98
BENI	100	100	100	100	100	100	100	100	71	95	100	92	98	100
CABU	91	93	100	100	100	93	100	100	99	100	100	96	97	97
CAST	98	100	82	100	100	100	100	100	96	100	100	94	99	99
CIER	97	99	41	100	100	0	100	100	82	100	100	55	99	99
EPCU	100	11	0	99	100	0	100	100	0	98	100	2	99	100
ERRA	98	99	100	100	100	93	100	100	62	91	98	88	97	99
FUEN	98	100	100	100	100	100	100	100	99	100	100	99	99	99
LIJA	82	50	100	100	100	43	100	100	84	97	98	69	94	95
LNDA	57	57	99	100	100	57	100	100	94	99	100	76	89	89
LOBE	96	78	59	100	100	0	100	100	40	99	100	44	98	99
LOJA	94	93	95	100	100	100	100	100	85	92	95	93	96	97
MAIL	98	99	11	100	100	49	100	100	15	99	99	43	99	99
NEVA	98	98	1	97	99	7	100	100	92	99	99	49	98	99
PALM	97	97	100	100	100	100	100	100	95	100	100	98	99	99
PILA	100	100	100	100	100	100	100	100	98	100	100	99	100	100
REIN	92	91	13	97	99	97	100	100	90	97	99	72	96	97
RUBI	98	100	10	100	100	53	100	100	64	100	100	56	99	99
TAZA	93	98	99	100	100	100	100	100	75	97	99	93	97	98
TGIL	94	92	52	99	100	0	100	100	48	97	100	48	97	98
TIOU	89	0	5	87	91	0	100	100	1	79	96	1	88	94
TRIA	96	100	100	100	100	100	100	100	99	100	100	99	99	99
UCMT	100	100	100	100	100	0	100	100	97	100	100	74	100	100
VILA	100	100	94	100	100	99	100	100	100	100	100	98	100	100
NET*	94	85	68	98	98	58	100	100	73	96	98	70	96	97

¹The threshold value of the observation number is the same for the quality references RF1 and RF2, therefore both columns are equal.

²Mean percentage of compliance considering all the indicators together.

3.3.2.3 Analysis based on discrete compliance criterion

Fig. 3.7 shows the results considering a stricter criterion, a discrete criterion of compliance based only on two values, 1 (meets the threshold) or 0 (does not meet the threshold). It has been

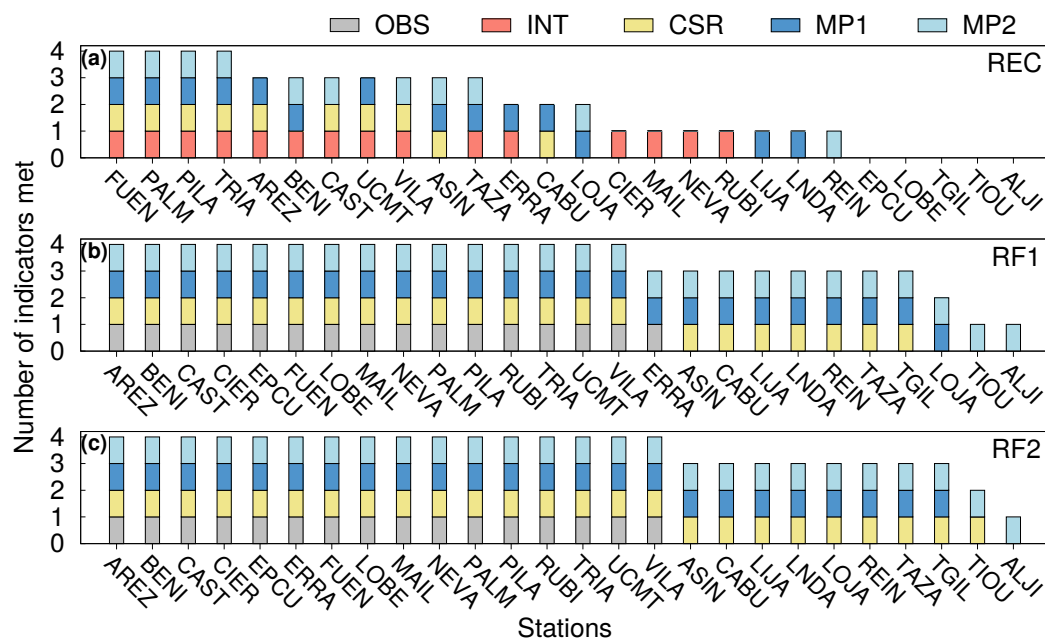


Fig. 3.7 Total number of indicators met by the Topo-Iberia stations for each IGS quality threshold considering a discrete criterion of compliance: (a) REC, (b) RF1, and (c) RF2. The stations are sorted according to the decreasing number of indicators met

Indicators met	Quality threshold		
	REC	RF1	RF2
0	5	0	0
1	7	2	1
2	3	1	1
3	7	8	8
4	4	15	16

Table 3.4 Number of stations according to the total number of indicators met for each IGS quality threshold

arbitrarily established that one station meets the quality threshold for an indicator if the compliance percentage of all available data is greater than 95%. In this way, the maximum value that can present for a station is 4, indicating that the station meets all the indicators for a certain quality threshold at least 95%. According to the results, 4 stations (FUEN, PALM, PILA, and TRIA) meet the guidelines to become an IGS station (IGS 2017) relative to the parameters considered in this study (INT, CSR, MP1, and MP2), and 5 stations do not meet it in any parameter (Fig. 3.7 and Table 3.4). Considering the next less restrictive threshold (RF1), 15 stations meet it, i.e., they have equal or better values than more than half of the IGS stations relative to the parameters considered (OBS, CSR, MP1, and MP2).

Among the 5 stations with zero indicators met in the threshold REC, the stations EPCU and LOBE stand out for meeting all the indicators in the other quality thresholds. The station LOBE, located in Sierra de Gredos Regional Reserve, began its activity period with all quality parameters within the threshold REC, except for MP2 (Appendix Fig. 3.13 and SI Fig. S16), and progressively worsening in a very similar way to the station TGIL (Appendix Fig. 3.14 and SI

Fig. S25). At other stations located in natural environments or with nearby trees, such as TGIL, this progressive and constant increase in multipath and cycle slips has been related to changes in the antenna environment, such as the growth of vegetation (Pirti 2008; Uzodinma and Nwafor 2018; García-Armenteros 2020). Moreover, if this growth also occurs next to the solar panel, it could cast a shadow on it. The station LOBE is surrounded by trees and initially showed an occlusion horizon below 10° , but it has been found that the horizon line increased in elevation in some areas (Fig. 3.2e). The increase of tree leafiness does not necessarily have to be the cause of a new horizon line by total occlusion of the GPS signal, but rather is more feasible the increase of the cycle slips number at higher elevations, as shown in Fig. 3.2. A progressive reduction in the number of recorded observations and the integrity value has also been observed, with notable decreases in the winter periods. This has been associated with poor battery performance issues at other stations, such as PALM. If this is combined with increase of shade hours on the solar panel, and the few sunlight hours available in these periods for recharging the batteries, it would cause a reduction in the receiver's operating time and sometimes malfunctions, as presumably happened at the station TGIL. The station EPCU is also located between trees at the Polytechnic School of Cuenca, showing the similar behavior to the station LOBE, although without worsening in winter periods. The 2 worst stations in the 3 quality thresholds are ALJI and TIOU, and although they meet the threshold RF1 in some of the analyses carried out, they present important anomalies for unknown reasons throughout their activity periods.

3.3.3 Data quality's effects on the phase residuals

The results of each daily GAMIT solution have been evaluated, in particular, the postfit RMS of one-way ionosphere-free phase residuals for the two best and two worst Topo-Iberia stations, i.e., the two stations with the lowest and the highest RMS value (Fig. 3.8). The GAMIT users will be familiar with evaluating the postfit RMS of the daily solutions based on the best and worst two stations, since this is provided in the GAMIT summary report, and Fig. 3.8 is the compilation of all them. The RMS values obtained are close to those expected in a typical project, 3-5 mm at the best sites and 7-9 mm at the worst, although slightly higher in the latter. Values between 10 and 15 mm indicate high but acceptable noise levels (Herring et al. 2018). The station TIOU presents the worst result, and its RMS value greater than 15 mm suggests receiver tracking problems, high values of multipath, or other problems of unknown origin, largely shown by its historical quality plot (Appendix Fig. 3.15 and SI Fig. S26).

Comparing these results with those obtained in the analysis based on median, the worst stations (TGIL, LOBE, ALJI, CIER, EPCU, and TIOU) are among the stations that present the worst quality in relation to the indicators studied (Fig. 3.5), and almost coincide in the case of the indicators INT, CSR, and MP2. In the same way, the best stations in the GAMIT solutions (lowest RMS) are also among those that present the best quality, especially in CSR. Compared with

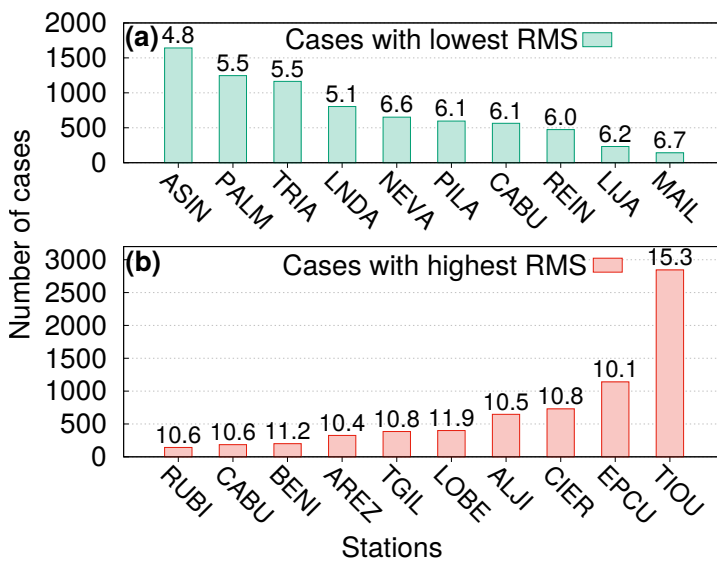


Fig. 3.8 Number of cases in which ten stations are among the (a) two best or (b) two worst Topo-Iberia stations in the daily GAMIT solutions. The number on the columns is the mean postfit RMS of LC phase residuals (mm) for the counted cases

the results from the analysis based on compliance percentage, the group of worst stations also corresponds almost entirely to the stations that show low compliance percentages with the quality threshold REC (Fig. 3.6a). Finally, compared with the results from the analysis based on discrete compliance criterion, this group of worst stations, except CIER, coincides exactly with the 5 stations that do not meet the threshold REC in any quality indicator (Fig. 3.7a). Furthermore, 3 stations (PALM, PILA, and TRIA) that meet the guidelines to become an IGS station relative to the quality indicators considered, i.e., with 4 indicators met, are considered the best stations in the daily GAMIT solutions. The station ASIN, the best in most cases with the lowest mean RMS (4.8 mm), is not among the stations that meet the threshold REC because the percentage of its data meeting the indicator integrity is 92%, and not 95%. The results reveal an inversely proportional relationship between the GPS data quality and the postfit phase residuals from their subsequent processing. A low data quality, i.e., low values in integrity, and high values in cycle slips and multipath, corresponds to high postfit RMS of phase residuals in the GAMIT solutions. This relationship is most evident considering the threshold REC as the quality reference.

The RMS scatter of LC phase residuals for each daily GipsyX solution were also evaluated. In this case, since each of the stations is separately processed, these are not grouped based on the two best or worst stations of each daily solution, but the mean RMS corresponding to the entire processed period for each station is calculated (Fig. 3.9). To facilitate comparison with the GAMIT results, these have also been represented in a similar way. Comparing Figs. 3.8 and 3.9, it is observed that the 3-4 best stations (lowest RMS), as well as the 6-7 worst stations (highest RMS), coincide in both processing strategies, although with some differences in the order. It is also observed that the RMS values from GipsyX are generally lower than those from GAMIT. It should be noted that although some models and processing parameters are common to both processing strategies, others differ, such as the elevation angle cutoff, orbits, clocks or ambiguity resolution method (Appendix Table 2.1; García-Armenteros 2023, Table 1), and even more re-

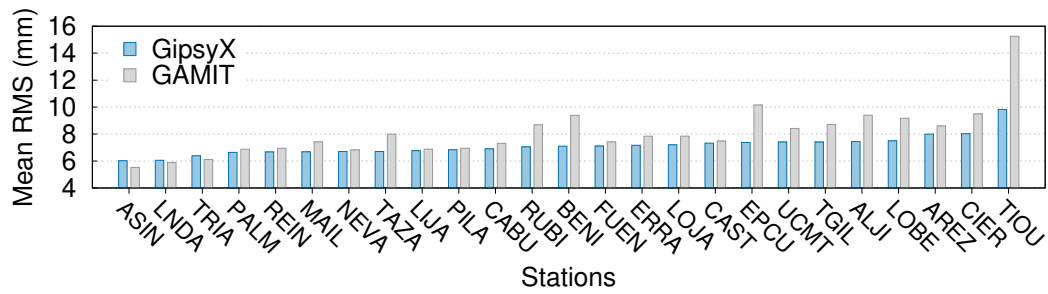


Fig. 3.9 Mean postfit RMS of LC phase residuals in the daily GAMIT and GipsyX solutions for each Topo-Iberia station. The stations are sorted by increasing RMS value from GipsyX

markable, each software has its characteristics inherent to the type of processing technique that it uses (Herring et al. 2018; Bertiger et al. 2020). Therefore, it is expected that the results will not be the same. However, the results obtained using GipsyX confirm the inversely proportional relationship between the postfit RMS of LC phase residuals and the GPS data quality.

On the other hand, among the group of the worst stations according to the RMS of phase residuals, there are the 4 stations (TGIL, LOBE, CIER, and EPCU) that show changes in the occlusion horizon, an increase in elevation of the horizon line (Fig. 3.2). The variation over time of their phase residuals obtained using GAMIT and GipsyX are shown in Fig. 3.10. As a sample of the variation over time of the quality parameters, the cycle slips (CSR) for the station TGIL and the multipath (MP1) for CIER are also shown. It is observed in the Figure how the

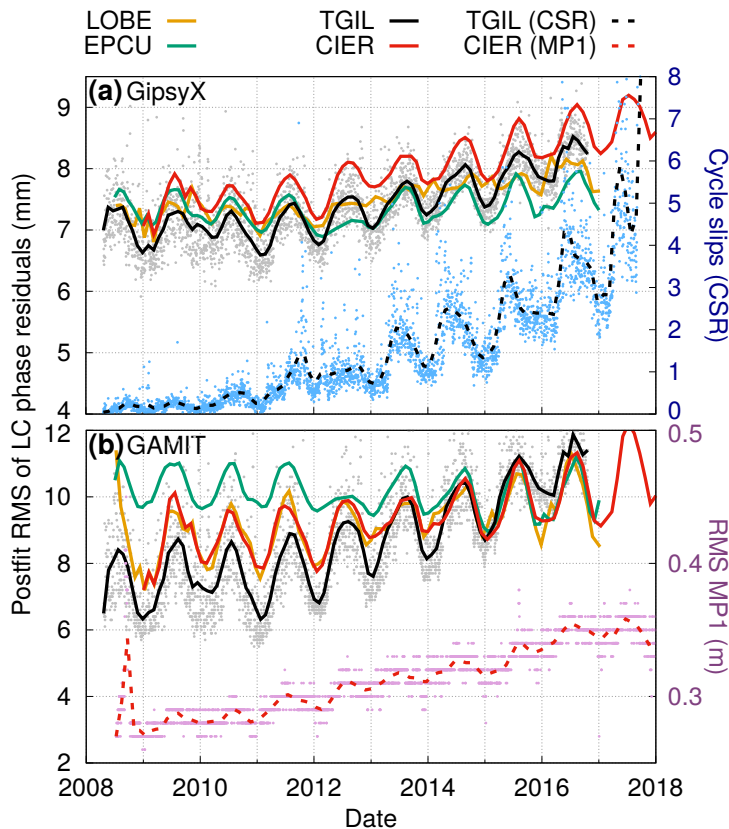


Fig. 3.10 Variation over time of the postfit ionosphere-free phase residuals derived from (a) GipsyX and (b) GAMIT, and a sample of the quality parameters for the four Topo-Iberia stations which have shown an increase in elevation of the horizon line. The point clouds are replaced by a Bezier curve for figure clarity, except for the station TGIL (in gray) and the parameters

evolution of the RMS of phase residuals is very similar in all stations and for both processing methodologies. All stations show a progressive increase in the phase residuals, except for the GAMIT-derived EPCU residuals, for which the increase is not as evident. Comparing the quality parameter evolution with the phase residual evolution at their corresponding station, a certain synchronism is observed, even more marked in the case of the parameter CSR. It should be noted that, in the case of the station TGIL, the line for CSR is longer than for the phase residuals because the late data span (Approximately 2017) was considered malfunctioning and discarded from the GPS processing. Similar consideration was given to the early period of the station CIER in relation to MP1. In this study, the changes in the occlusion horizon have not been expressly defined as a quality indicator, but presumably the changes in the antenna environment, such as the growth of nearby trees, increased leafiness, and other physical obstacles, cause the degradation of the tracking at low elevation entailing the elevation of the horizon line, and the increase in cycle slips, multipath, and scatter or noise.

3.3.4 Data quality characterization

The median statistic has the drawback that it provides information corresponding to only 50% of the data, and the remaining data could present a severe deterioration in the quality, as shown by the station ALJI data. Consequently, saying that all Topo-Iberia stations have better or equal quality than more than half of the IGS stations, considering the median value and the threshold RF1, is statistically correct but only occurs in 50% of the data and gives us a false sense of quality. Instead, the problem stations are evident using the analysis based on compliance percentage and even more considering all the indicators together as shown in Fig. 3.6a. The quality parameters have been analyzed individually, but it is possible that some station, such as UCMT, presents a high compliance percentage in all parameters except one, which does not imply poor quality. The total mean percentage of compliance for the station UCMT with the threshold REC is 74%. Therefore, considering all the indicators together provides an overview of the quality data. The analysis based on discrete compliance criterion, in addition to showing the data quality as the two previous analyses, also determines which stations meet the guidelines to become an IGS station in relation to certain quality parameters (Fig. 3.7 top). The stations that present poor quality or changes in the antenna environment are also easily identifiable due to the greater restrictiveness of this analysis, and it has been found that most of these stations do not meet any quality indicator with the REC threshold. On the other hand, not meeting all the quality indicators using this analysis does not imply that the station presents bad quality data, such as ASIN, which is the best station in most cases with the lowest mean postfit RMS of phase residuals. In the case of this station using the compliance percentage with the threshold REC and considering all the indicators together, the result is 96%, which is a very high percentage of total compliance.

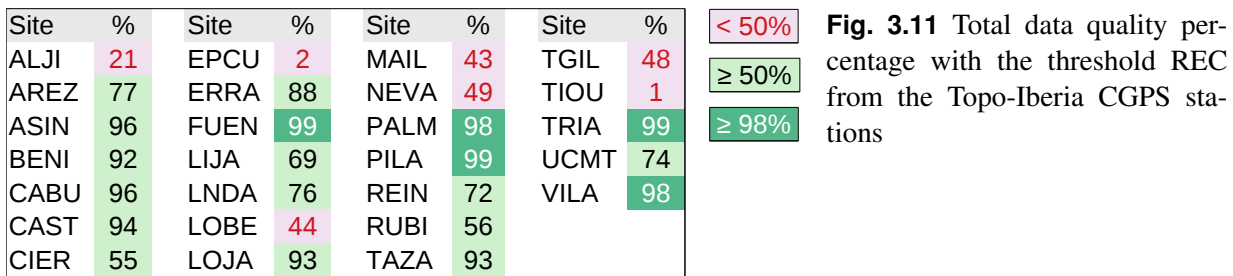
According to the results obtained from the Topo-Iberia CGPS network, the stations that meet

the quality requirements to become an IGS station correspond to a total mean percentage of compliance $\geq 98\%$ (Fig. 3.6a and Table 3.3). The stations with a compliance percentage above 50% have an acceptable quality. Below this level, it can be considered that the stations are problematic or that they present poor quality data, corresponding to high postfit RMS of phase residuals. For some of these poor quality stations, such as ALJI and LOBE, the time series analysis by García-Armenteros (2023) required further adjustments, including eliminating data segments considered outliers.

Considering all the abovementioned, one method to characterize the data quality is the combination of the last two statistics. Using the analysis based on compliance percentage, the total quality of the data can be established, as well as the stations whose results may be unreliable and which could require further attention in their subsequent time series analysis. Using the analysis based on discrete compliance criterion, the stations with problems and the stations that meet the guidelines to become an IGS station are easily identified.

According to the IGS guidelines (IGS 2015), in terms of data quality, a GNSS station is expected to have excellent tracking (number of observations $> 95\%$ of the expected), low multi-path (< 0.3 m), and a low number of cycle slips (< 1 per 1000 observations). In practice, the quality parameter values fluctuate, sometimes exceeding these established thresholds, resulting in a percentage of the data meeting the quality requirements and another not. Therefore, it would be useful if the IGS also establishes the appropriate compliance percentages and not only the threshold values. Currently, in addition to the quality plots from the EPN stations, the EUREF also provides the data quality percentage computed over the last 28 calendar days based on the number of observations with reference to the number of expected observations (http://www.epncb.oma.be/_networkdata/stationlist.php), but does not provide the percentage of total quality based on the quality parameters established by the IGS. This information would be helpful for users and provide it for the entire station activity period or for a specific span chosen by the user, thus helping to select the stations faster than based on the query of the quality plots.

Following the above criterion, Fig. 3.11 shows the total data quality percentage from the Topo-Iberia stations, i.e., the compliance percentage considering all the quality indicators related to the IGS guidelines (INT, MP1, MP2, and CSR). These values are valid for the quality-controlled data spans shown in Table 3.5 (Appendix) and Table S1 (SI). The values in green (total data quality percentage $\geq 98\%$) correspond to the stations that meet the quality requirements to become an IGS station, the values in light green ($50\% \leq \text{total percentage} < 98\%$) mean good or acceptable quality data, and the values in red (total percentage $< 50\%$) mean poor quality data or problem stations. The currently dismantled station VILA presents a very high percentage of total compliance but according to the analysis based on discrete compliance criterion, it is not one of the stations that met the guidelines to become an IGS station since the percentage of its data meeting the indicator MP1 is 94%, and not 95% which was arbitrarily set in this study.



3.4 Conclusions

Almost 12 years of data from the Topo-Iberia CGPS network have been quality-controlled spanning from 2008-03-19 to 2020-02-10. The GPS data quality information for all 26 Topo-Iberia stations is provided for the first time, complementing the IGME's storage work.

To analyze the stability and quality of the stations and their data, some parameters obtained using TEQC have been considered quality indicators (maximum number of observations, integrity, cycle slips, and multipath). Moreover, the guidelines and data quality information from the IGS stations have been taken as the quality references: as the first level of quality, the recommended guidelines to become an IGS station (REC); as the second level, the quality threshold at more than half of the IGS stations (RF1); and as the third level, the quality threshold at 2/3 of the IGS stations (RF2).

In general, the stations have not shown anomalous values for the multipath effect and SNR that could indicate a possible problem in their locations. The occlusion horizon is below 10°, except for some stations, but always with a horizon wide enough to record the necessary observations. The Topo-Iberia stations have shown a mean signal strength in L1 in the range of 44–47 dBHz, being above the threshold for good SNR, except the stations EPCU and UCMT whose mean SNR1 is about 6 dBHz.

Three analyses of the data quality based on basic statistics from the quality parameters have been carried out: one based on the median value, another based on the percentage of compliance with the quality thresholds, and another based on a discrete criterion of compliance. The stations ALJI, EPCU, and TIOU stand out as the worst stations in most analyses. The network meets the thresholds REC and RF1 with 70% and 96%, respectively, while the parameters with the lowest percentage of compliance with threshold REC correspond to MP1 and MP2 with 68% and 58%, respectively. According to the results, the stations FUEN, PALM, PILA, and TRIA meet the guidelines to become an IGS station.

The relationship between the GPS data quality and their GAMIT- and GipsyX-derived post-fit ionosphere-free phase residuals has been studied. The stations with the highest and lowest RMS scatter of LC phase residuals largely coincide in both processing methodologies. There is a great coincidence between the stations with the highest phase residuals and those considered poor quality in the different analyses. The results have revealed an inversely proportional

relationship between the postfit RMS scatter of LC phase residuals and the data quality. This relationship is more evident in the analysis based on the discrete criterion of compliance and considering the threshold REC as the quality reference, in which the best and worst stations almost completely coincide with the stations with the lowest and highest RMS scatter of phase residuals, respectively.

It has been found that the stations that show changes in the occlusion horizon (CIER, EPCU, LOBE, and TGIL), i.e., that show an increase in elevation of the horizon line, also present an increase in cycle slips and multipath, are in the group of the poorest quality stations established by the different analyses carried out, and are in the group of the stations that present the highest RMS scatter of phase residuals. Moreover, these stations present a similar variation over time of the postfit phase residuals, using GAMIT and GipsyX. This variation is markedly synchronized with the increase in cycle slips and multipaths, which in turn are presumably produced by a progressive change in the antenna environment (growth of vegetation, nearby trees, increased leafiness, etc.).

A progressive reduction in the number of recorded observations and the integrity, with notable decreases in winter periods, has been observed at some stations. This has been associated with poor battery performance issues and few hours of sunlight available during these periods for recharging by solar panel, ultimately leading to battery replacement as happened at the station PALM. It could be extrapolated to the remaining stations that have this type of power supply in common. Moreover, the problem is further aggravated if it coincides with the changes related to the vegetation mentioned above, but in this case, around the solar panel increasing the hours of shade on it, as also happened at the station TGIL. The data loss at the station LOBE is probably due to one or both of these causes.

The quality assessment shows that the Topo-Iberia CGPS stations and their emplacements are optimal for forming a network for geodetic purposes. However, the problems shown in some stations located in natural environments, reveal that the evolution of the nearby vegetation around the antenna and solar panel should be considered, as it could cause the progressive loss of data and quality, not complying with the IGS standards. It becomes necessary for the permanent monitoring of the stations, so that any change in the quality indicators or in the occlusion horizon can be detected, thus avoiding the least possible loss of data and quality.

Combining the analysis based on compliance percentage and the analysis based on discrete compliance criterion is proposed to characterize the GNSS data quality. In this way, the stations with problems and stations that meet the quality requirements to become an IGS station are easily identified, and a total data quality percentage is established for each station. According to the results obtained from the Topo-Iberia CGPS network, the stations whose total compliance percentage is below 50% can be considered problematic or poor quality stations, corresponding to high postfit RMS of phase residuals. It is also proposed that the institutions responsible for GNSS networks provide this total percentage in addition to the quality plots since the selection of

stations based on their quality percentage can be faster than the visualization of the quality plots. In this sense, it would also be necessary that the appropriate compliance percentages for the quality parameters, and not only the threshold values, be established in the IGS site guidelines.

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Data availability GPS data analyzed in this study were provided by the IGME (<https://www.igme.es>), but restrictions apply to the availability of these data due to the internal privacy policies of the Topo-Iberia team and are not publicly available. Derived data (qc reports and phase residual files) supporting the findings of this study are available from the corresponding author upon reasonable request. The remaining data generated are available in this article and its Supplement file. Maps were created using Generic Mapping Tools software version 5.4.5 (Wessel et al. 2013), graphs were created using Gnuplot version 5.2 (Williams and Kelley 2019), and figures were edited using Inkscape version 0.92.4 (Inkscape Project 2019). The Scientific color map roma (Crameri 2021) was used in Fig. 3.3 to prevent visual distortion of the data and exclusion of readers with color-vision deficiencies (Crameri et al. 2020). Additional data and resources used in this work are indicated in the main body.

Supplementary data Supplementary data to this article can be found online at <https://doi.org/10.1016/j.geog.2023.07.006>. Part of this material has been included in the following Appendix.

Appendix

Table 3.5 Quality-controlled and processed data spans from the Topo-Iberia CGPS network: 4-char ID of station, quality-controlled and processed data span, total years, and contained daily RINEX files. The data are sorted according to the quality-controlled years. The dates in bold are the lower and upper limits of the spans considering all stations. This information was taken from García-Armenteros (2023)

ID	Quality-controlled data			Processed data		
	Span (Year-DOY)	Years	RINEX	Span (Year-DOY)	Years	RINEX
VILA	2008-267 / 2009-248	0.9	348	- - -	- - -	- - -
BENI	2008-204 / 2013-317	5.3	1921	2008-204 / 2013-022	4.5	1633
TAZA	2008-205 / 2014-043	5.6	1496	2008-205 / 2014-023	5.5	1476
LNDA	2008-214 / 2014-269	6.2	1992	2008-214 / 2013-032	4.5	1616
ASIN	2008-269 / 2015-157	6.7	2372	2009-001 / 2015-157	6.4	2293
UCMT	2008-198 / 2015-146	6.9	2468	2008-198 / 2015-016	6.5	2338
ERRA	2008-286 / 2016-044	7.3	2200	2008-286 / 2015-099	6.5	2132
FUEN	2008-211 / 2017-135	8.8	2780	2008-211 / 2016-031	7.5	2719
EPCU	2008-185 / 2017-164	8.9	3069	2008-185 / 2017-003	8.5	2909
LOBE	2008-192 / 2017-155	8.9	3174	2008-192 / 2017-009	8.5	3042
TIOU	2008-260 / 2017-269	9.0	2931	2008-260 / 2017-074	8.5	2871
LIJA	2008-167 / 2017-222	9.2	2773	2008-167 / 2014-349	6.5	2264
TGIL	2008-113 / 2017-276	9.4	3420	2008-113 / 2016-296	8.5	3087
CAST	2008-100 / 2017-261	9.4	3071	2008-100 / 2017-261	9.4	3062
MAIL	2008-218 / 2018-014	9.4	2872	2008-218 / 2018-014	9.4	2872
TRIA	2008-107 / 2017-344	9.7	2846	2008-107 / 2015-290	7.5	2679
CIER	2008-193 / 2018-184	10.0	3501	2009-003 / 2018-184	9.5	3326
LOJA	2008-108 / 2018-105	10.0	3199	2008-108 / 2017-290	9.5	3045
ALJI	2008-101 / 2018-184	10.2	3493	2009-037 / 2018-184	9.4	3201
RUBI	2008-129 / 2018-220	10.3	3639	2008-129 / 2017-311	9.5	3416
AREZ	2008-130 / 2018-302	10.5	3818	2008-130 / 2018-302	10.5	3818
PILA	2008-179 / 2019-184	11.0	4023	2008-179 / 2018-361	10.5	3835
PALM	2008-171 / 2019-203	11.1	4042	2008-171 / 2018-353	10.5	3827
NEVA	2008-306 / 2020-041	11.3	3996	2009-119 / 2019-302	10.5	3729
REIN	2008-136 / 2019-343	11.6	3784	2008-324 / 2018-135	9.5	3103
CABU	2008-079 / 2019-343	11.7	4278	2009-030 / 2019-210	10.5	3829
Topo-Iberia	2008-079 / 2020-041	11.9	77506	2008-100 / 2019-302	11.6	72122

Site: **NEVA** - RINEX2 Network: Topo-Iberia System: GPS
 Period: 2008-11-01 (DOY 306) / 2020-02-10 (DOY 041)
 GPS Week: 1503 / 2092

- Antenna change
- Antenna/Receiver change
- - Receiver change (including firmware)
- - Battery change
- Dismantled site

Quality references:

- Recommended value to become an IGS stations
- Threshold value at more than 1/2 IGS stations
- Threshold value at more than 2/3 IGS stations

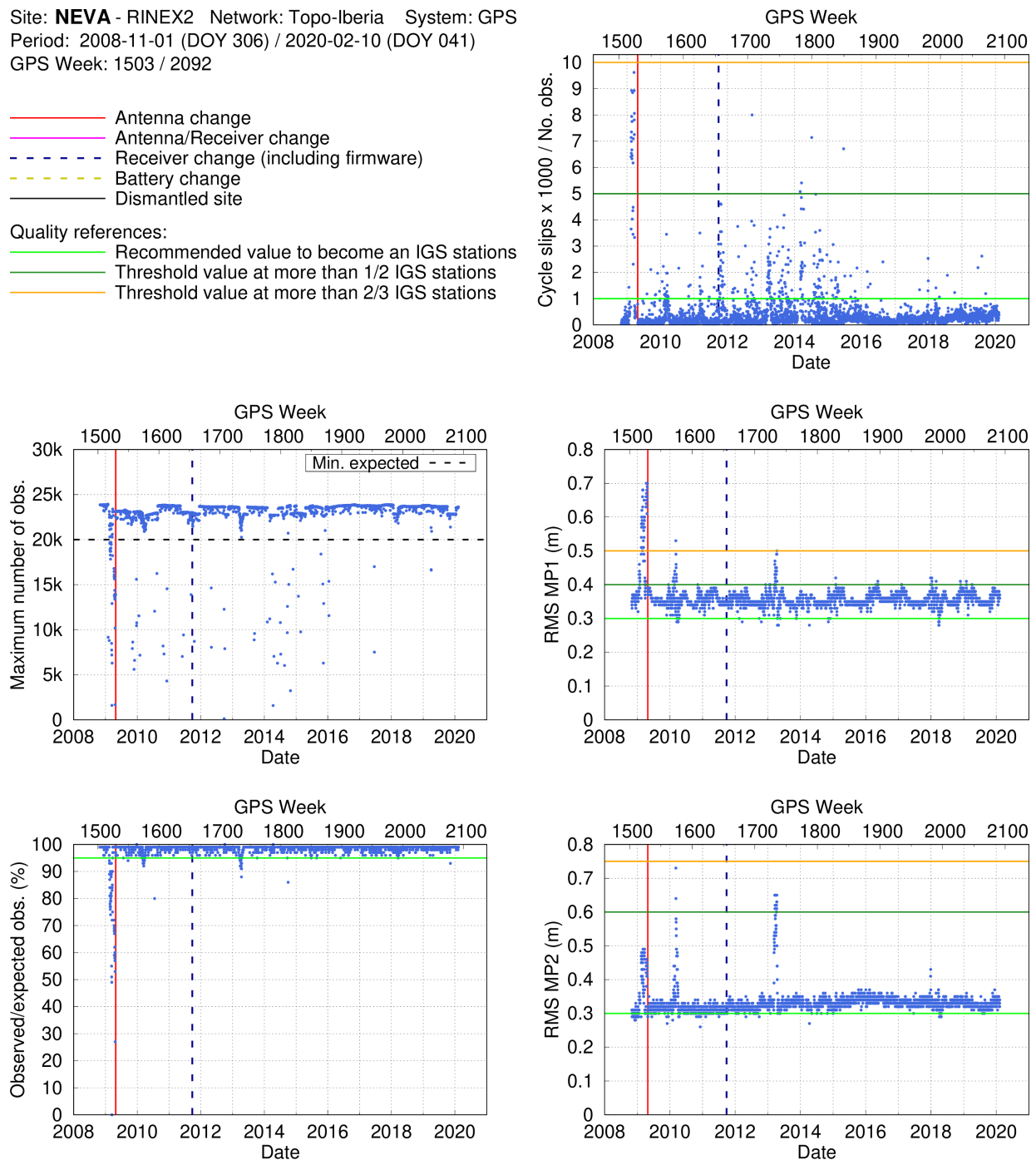


Fig. 3.12 Historical information on the data quality from the Topo-Iberia CGPS station NEVA

Site: **LOBE** - RINEX2 Network: Topo-Iberia System: GPS
 Period: 2008-07-10 (DOY 192) / 2017-06-04 (DOY 155)
 GPS Week: 1487 / 1952

- Antenna change
- Antenna/Receiver change
- - Receiver change (including firmware)
- - Battery change
- Dismantled site

Quality references:

- Recommended value to become an IGS stations
- Threshold value at more than 1/2 IGS stations
- Threshold value at more than 2/3 IGS stations

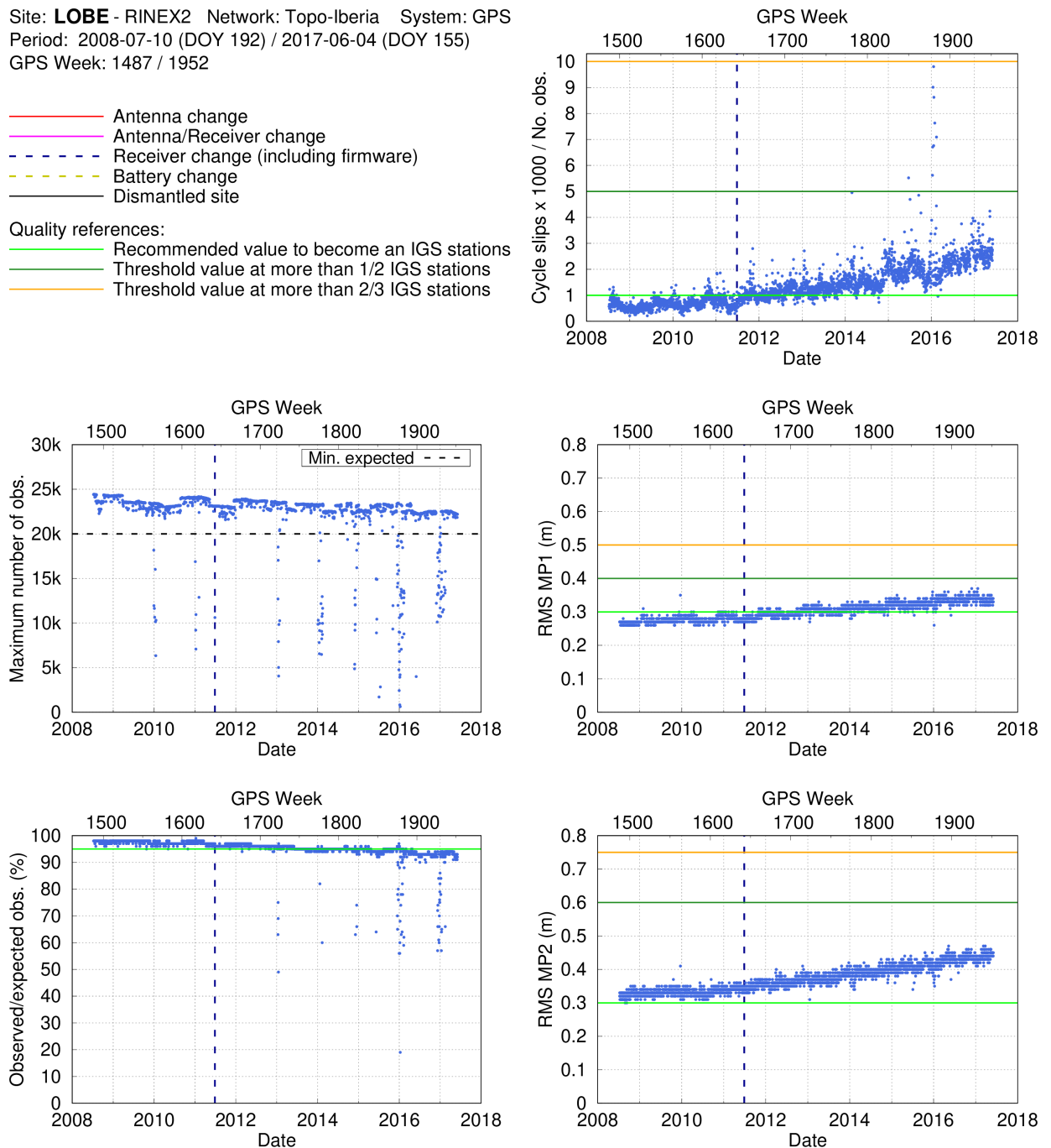


Fig. 3.13 Historical information on the data quality from the Topo-Iberia CGPS station LOBE

Site: **TGIL** - RINEX2 Network: Topo-Iberia System: GPS
 Period: 2008-04-22 (DOY 113) / 2017-10-03 (DOY 276)
 GPS Week: 1476 / 1969

- Antenna change
- Antenna/Receiver change
- - Receiver change (including firmware)
- - Battery change
- Dismantled site

Quality references:

- Recommended value to become an IGS stations
- Threshold value at more than 1/2 IGS stations
- Threshold value at more than 2/3 IGS stations

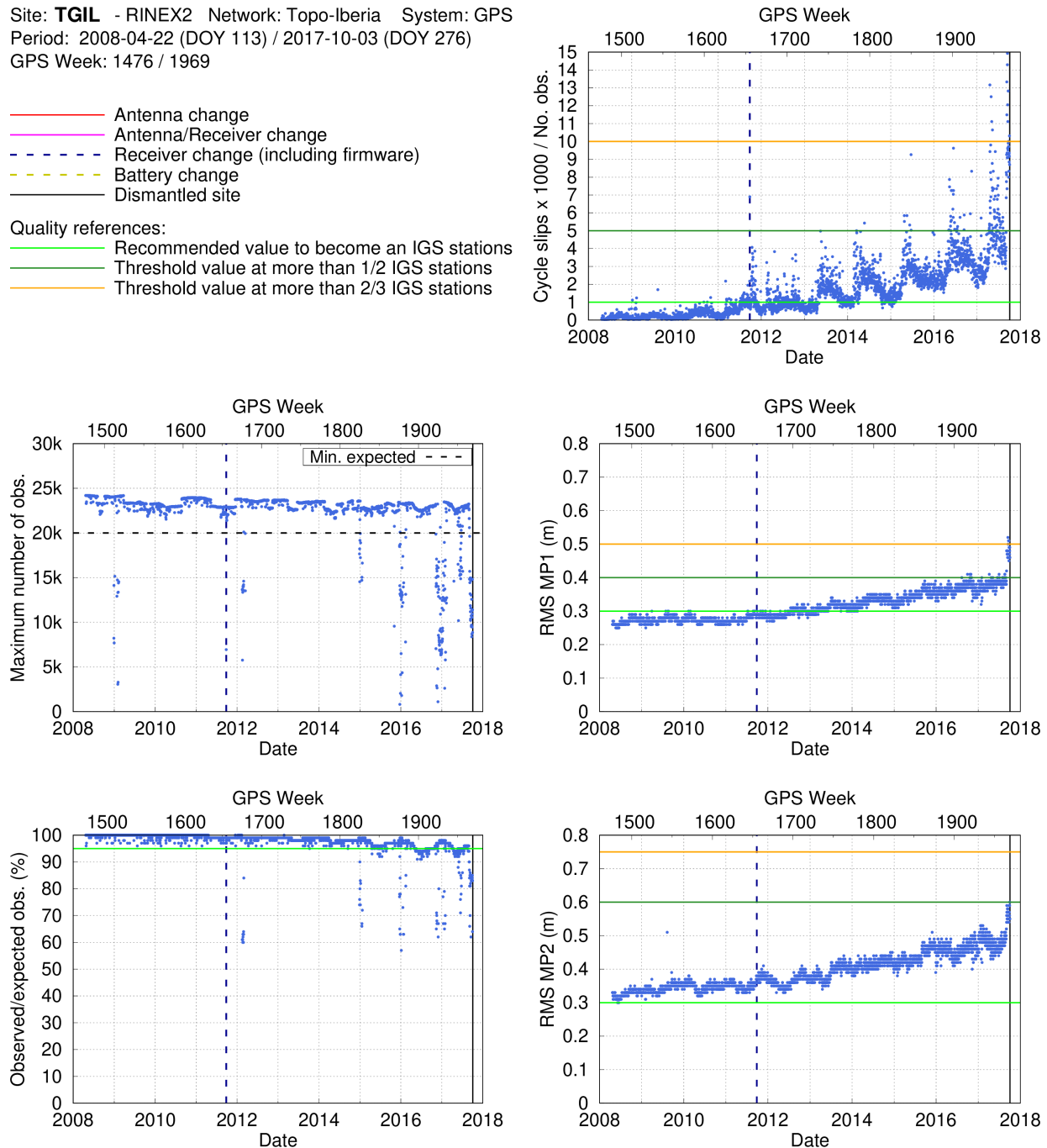


Fig. 3.14 Historical information on the data quality from the Topo-Iberia CGPS station TGIL

Site: **TIOU** - RINEX2 Network: Topo-Iberia System: GPS
 Period: 2008-09-16 (DOY 260) / 2017-09-26 (DOY 269)
 GPS Week: 1497 / 1968

- Antenna change
- Antenna/Receiver change
- - Receiver change (including firmware)
- - Battery change
- Dismantled site

Quality references:

- Recommended value to become an IGS stations
- Threshold value at more than 1/2 IGS stations
- Threshold value at more than 2/3 IGS stations

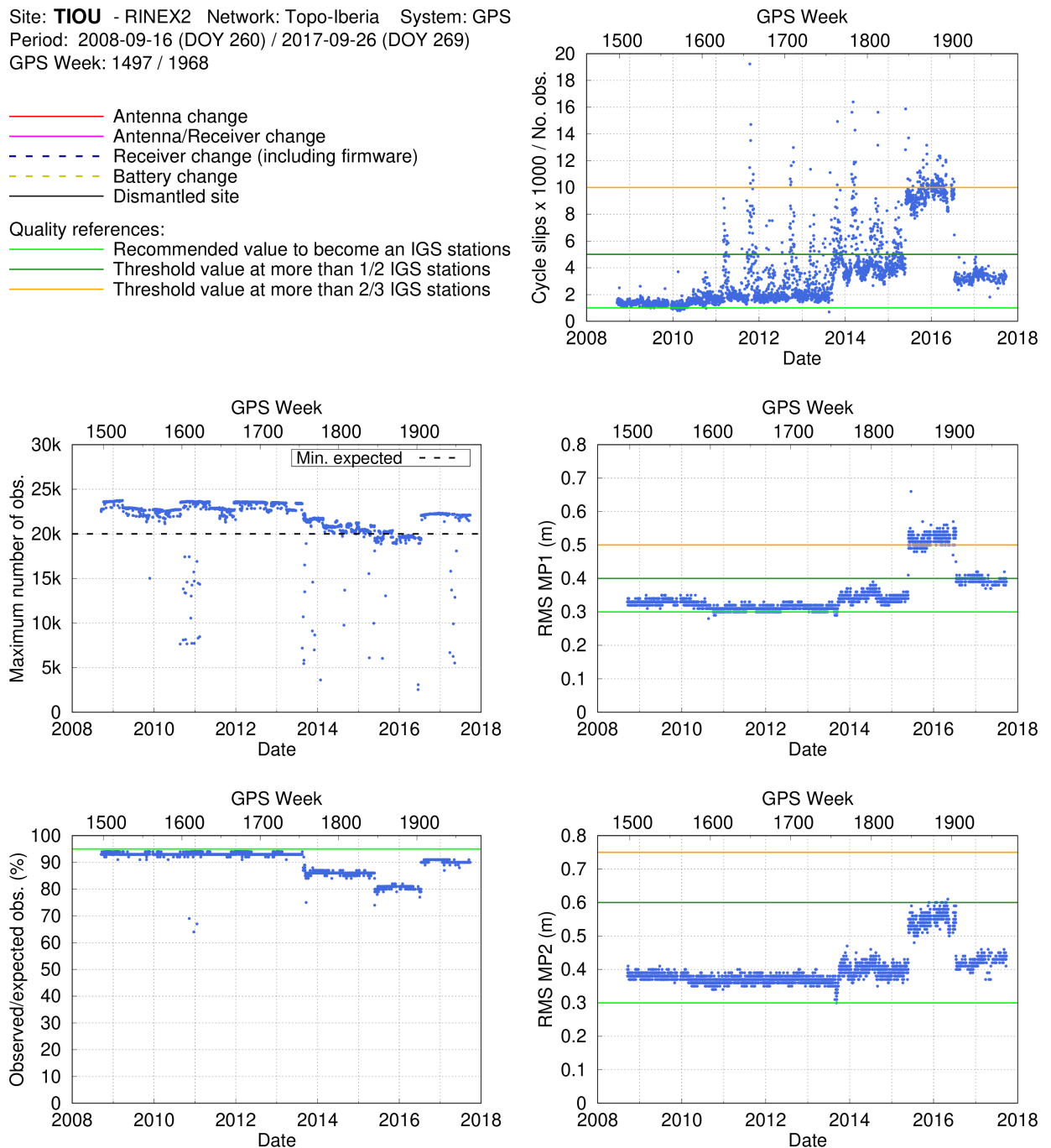


Fig. 3.15 Historical information on the data quality from the Topo-Iberia CGPS station TIOU

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Antenna environment's effects on elevation angle dependent ionosphere-free phase residuals, and geodetic monument noise in the Topo-Iberia CGPS network

Antenna environment's effects on elevation angle dependent
ionosphere-free phase residuals, and geodetic monument noise in the
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Abstract

The purpose of this study was determine for the first time the relationship between the antenna environment and the elevation angle dependent ionosphere-free phase residuals from the GAMIT/GLOBK processing of the Topo-Iberia network (2008–2019), as well as the relationship between the geodetic monument type used and noise. The pattern formed by the trace of the elmean residuals has been associated with the antenna environment characteristics, and five pattern types have been established. A diagram of pattern types has also been created for the first time that could be useful to select the optimal GNSS antenna environment. A new metric has been proposed to quantify the differences between patterns, the phase residuals pattern difference index (PRPDI), which has turned out to be a good tool to identify antenna environment changes, as well as the best and worst quality stations. According to the results, the highest PRPDI values correspond to the poorest quality stations and those that have shown changes in the occlusion horizon. The results also reveal that the smallest elmean phase residuals are produced by antenna environments with uneven ground and vegetation cover (RMS of 0.6 mm at ASIN station), and the highest residuals occur in environments associated with monuments on flat roof of buildings (RMS of 3.1 mm at BENI station). The Topo-Iberia stations with standard pillars on bedrock and shallow-drilled braced monuments present less noise than those with little pillars and monuments on buildings. The results regarding the least noisy monument types agree with those of previous publications. The Topo-Iberia monuments present a random-walk noise level adequate for a geodetic monument. No relationship between noise and geographical location of the sites has been observed, but between seasonal noise and the antenna environment.

Keywords Antenna environment · Elmean phase residuals pattern · GAMIT/GLOBK · Geodetic monument noise · PRPDI · Topo-Iberia CGPS network

4.1 Introduction

Elements to consider in relation to the quality of the permanent Global Navigation Satellite System (GNSS) networks for geodetic purposes include the station emplacement and the stability of the geodetic monument supporting the antenna. Moreover, the information on the GNSS data quality is essential to ensure that they are suitable for this purpose type and that the stations function correctly. The Topo-Iberia network is one of these networks established for geodynamic purposes, fully operational since December 2008 (Gallart 2006) and composed of 26 continuously operating Global Positioning System (CGPS) stations. The network maintenance and control is distributed among the institutions that formed the Consolider Topo-Iberia team (Fig. 4.1). The station equipment installation followed criteria recommended by the University Navistar Consortium (UNAVCO) (Gárate et al. 2008), and the antennas were mainly installed on concrete pillars on bedrock for added stability (Table 4.1). The original equipment consisted of Trimble NetRS dual-frequency receivers and Trimble GNSS Choke-Ring antennas, with SCIGN radomes where environmental conditions so recommended. The last GPS processing of the Topo-Iberia

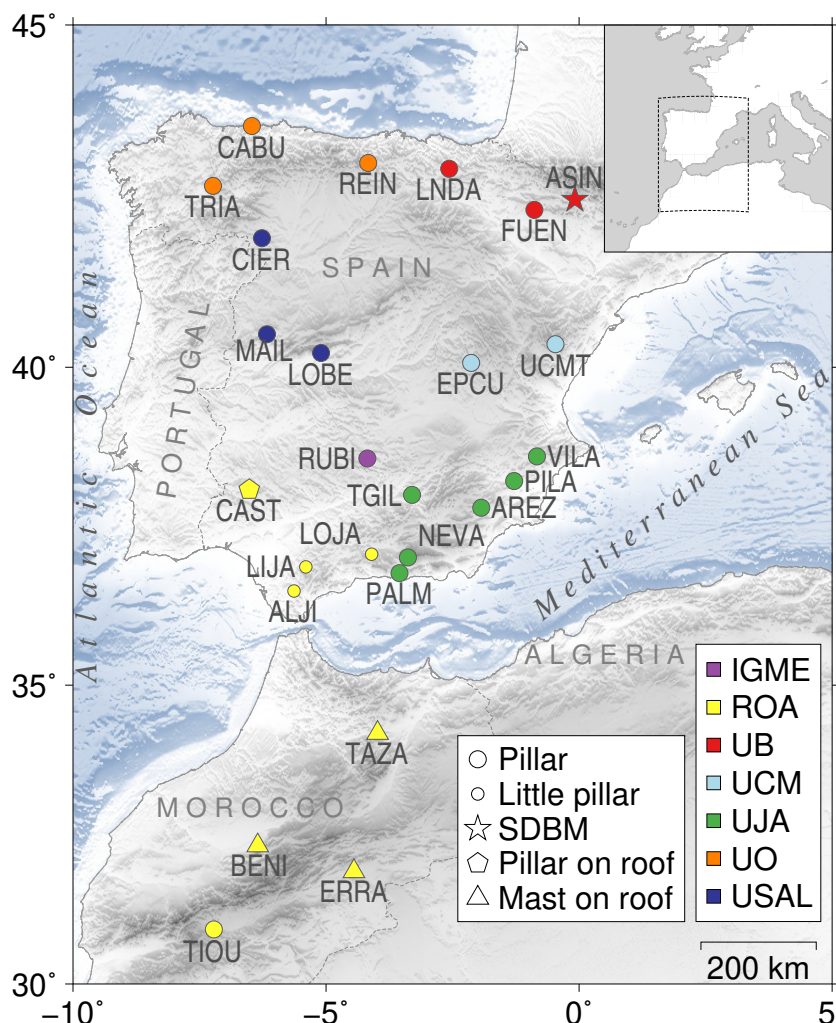


Fig. 4.1 Deployment of the Topo-Iberia CGPS stations in function of the geodetic monument type and institution in charge. The shaded-relief image of the Earth illumination from the south is at 1 arc minute resampled from the SRTM15+V topography database (Tozer et al. 2019) plotted with Generic Mapping Tools (GMT) software version 5.4.5 (Wessel et al. 2013)

network was carried out by García-Armenteros (2023a) providing a new 3D crustal velocity field in the Iberian Peninsula and Morocco based on 11 years (2008–2019). The GNSS processing software used was GAMIT version 10.71 (Herring et al. 2018) and GipsyX version 1.7 (Bertiger et al. 2020). Moreover, the quality assessment of almost 12 years of Topo-Iberia GPS data and the quality information for all 26 stations was provided by García-Armenteros (2023b), as well as the relationship between the GPS data quality and their GAMIT- and GipsyX-derived *postfit* ionosphere-free linear-combination (LC) phase residuals.

Table 4.1 Topo-Iberia CGPS stations. 4-char ID, geographic position, installation/dismantling date (Year-Day of Year), geodetic monument type, and institution in charge on control date 2020-02-11. The geographic positions are taken from García-Armenteros (2023a)

ID	Lon (°)	Lat (°)	Install/Dismantle	Monu. ¹	Inst. ²
ALJI	-5.64938	36.52989	2008-101/- - - - -	CPL	ROA
AREZ	-1.94046	37.83543	2008-116/- - - - -	CP	UJA
ASIN	-0.09868	42.51661	2008-269/- - - - -	SDBM	UB
BENI	-6.31859	32.37679	2008-204/2013-318	SMR	ROA
CABU	-6.47000	43.56897	2008-078/- - - - -	CP	UO
CAST	-6.53214	38.12273	2008-069/- - - - -	CPR	ROA
CIER	-6.28065	41.94113	2008-191/- - - - -	CP	USAL
EPCU	-2.14646	40.07955	2008-185/- - - - -	CP	UCM
ERRA	-4.45606	31.93879	2008-156/- - - - -	SMR	ROA
FUEN	-0.88541	42.36022	2008-205/- - - - -	CP	UB
LIJA	-5.40379	36.90624	2008-043/- - - - -	CPL	ROA
LNDA	-2.57827	42.96005	2008-214/- - - - -	CP	UB
LOBE	-5.11040	40.22045	2008-191/- - - - -	CP	USAL
LOJA	-4.10635	37.10727	2008-069/- - - - -	CPL	ROA
MAIL	-6.22369	40.56916	2008-218/- - - - -	CP	USAL
NEVA	-3.38564	37.06262	2008-291/- - - - -	CP	UJA
PALM	-3.56230	36.80904	2008-157/- - - - -	CP	UJA
PILA	-1.28943	38.25431	2008-165/- - - - -	CP	UJA
REIN	-4.17707	43.04594	2008-137/- - - - -	CP	UO
RUBI	-4.19657	38.60935	2008-127/- - - - -	CP	IGME
TAZA	-3.99644	34.22953	2008-204/2014-044	SMR	ROA
TGIL	-3.30256	38.03424	2008-099/2017-277	CP	UJA
TIOU	-7.24520	30.92363	2008-156/- - - - -	CP	ROA
TRIA	-7.24144	42.71481	2008-106/- - - - -	CP	UO
UCMT	-0.47217	40.36378	2008-197/- - - - -	CP	UCM
VILA	-0.84750	38.64050	2008-253/2009-249	CP	UJA

¹Monument type: CP (Concrete pillar on bedrock. Standard height or greater); CPL (Little concrete pillar on bedrock. Two bodies, height of 0.344 m); CPR (Concrete pillar on building roof); SDBM (Shallow-drilled braced monument on bedrock); SMR (Steel mast on building roof)

²Institution in charge: IGME (Spanish Geological Survey), ROA (Spanish Navy Observatory), UB (University of Barcelona), UCM (Complutense University of Madrid), UJA (University of Jaén), UO (University of Oviedo), USAL (University of Salamanca)

The residuals of the LC phase observations from GAMIT processing vary in azimuth and elevation above the horizon depending on the environment multipath effect around the antenna. Herring et al. (2016) found that this elevation dependence of the phase residuals, averaged over all azimuths, is useful for determining the phase modeling and multipath effect at each site. The multipath effect produced by the antenna environment is characteristic of the site and is generally more or less constant over time, which would allow to relate the phase residuals with a characteristic environment at each site. In the present work, it is intended to determine the relationship between the antenna environment and the elevation angle dependent mean (elmean) LC phase residuals, as well as with the GPS data quality from the Topo-Iberia stations. For this purpose, the data quality information and the GAMIT-derived phase residuals obtained by García-Armenteros (2023a,b) are used. This study is carried out on these stations for the first time, evaluating how the terrain type in which the antenna is located affects the positioning, its suitability for a geodetic station, whether the antenna environment is stable or not, and consequences. The station VILA is left out of this study since it was not processed due to its short activity period (348 days).

The geodetic monuments require high stability, but unfortunately it varies depending on the type of anchor used (e.g., bedrock, roof on building, mast on wall, etc.). This instability is considered an important source of noise. Studies on the noise from different types of monuments have shown its importance (Williams et al. 2004; Beavan 2005; Herring et al. 2016). To date, no study on the noise from the Topo-Iberia network monuments has been carried out, and doing so is also one of the purposes of the present work. This study is based on the background noise from the GPS position time series obtained by García-Armenteros (2023a), with which the possible relationship between the monument type and the noise is determined. Moreover, the part of the noise associated with periodic signals, the seasonal noise, is analyzed.

4.2 Data and methodology

The phase residuals analyzed correspond to the Topo-Iberia GPS data processing spanning from 2008-04-09 to 2019-10-29, a total of 11.6 years. Details on the data spans for each station were provided in Table 3.5 and García-Armenteros (2023b, Suppl. Table S1). Note that the processed period is smaller than the quality-checked period. The elmean phase residuals for each station have been extracted from the daily GAMIT output files *autcln.post.sum*.

4.2.1 Antenna environment and elmean LC phase residuals

By plotting the elmean phase residuals and connecting them, a certain pattern or *waveform* is revealed. As mentioned above, the phase residuals vary in azimuth and elevation above the horizon depending on the environment multipath effect, which is characteristic of the site. In this way, the created pattern is associated with the terrain type or environmental characteristics

of each site. The form of this pattern should be constant in time if the conditions at the antenna environment do not change, resulting in a pattern with well-defined traces regardless of whether the elmean phase residuals are high or low.

A new metric is proposed to quantify the differences between two consecutive yearly patterns, the phase residuals pattern difference index (PRPDI) expressed in mm:

$$PRPDI = \sqrt{\frac{1}{n} \sum_{i=1}^n \sum_{j=10}^{80} (\bar{X}_{w_j} - \bar{X}_{(w+52)_j})_i^2} \quad (4.1)$$

where $\bar{X}_{w_j}$ is the mean LC phase residuals averaged over each GPS week (w) in 1° elevation angle bins (j), and $\bar{X}_{(w+52)_j}$ is the value for the homologous week for the following year, and for the same elevation angle. The maximum elevation angle above the horizon considered in the comparison has been set at 80° , since the phase residuals have not been determined at high elevation angles in a homogeneous way for all cases, and their differences could contaminate the result of the remaining pattern. If the elevation mask is also taken into account, the pattern to be compared would correspond to that included in the range of elevation angles from 10° to 80° . For the matching between yearly patterns to be the maximum possible, and the difference index to be representative, the years composed of a few weeks have been discarded, most of which coincide with the initial or final year of the processed period for some stations. The higher the PRPDI value, the greater the differences between two patterns, and the worse defined is the trace formed by the combination of both. The closer to zero, the greater the similarity between two patterns, forming a well-defined combined pattern. This could also be interpreted as the antenna environment has been stable and there have been no external phenomena that cause notable variations in the elmean phase residuals.

The quality assessment by García-Armenteros (2023b) is used to analyze the possible relationship between the results presented herein and the data quality. This quality check (qc) was based on some quality indicators: maximum number of observations recorded, integrity as percentage of the number of complete observations recorded with respect to the number of expected observations, number of cycle slips per 1000 observations (CSR), and root-mean-square (RMS) of multipath effect on L1 (MP1) and L2 (MP2). Moreover, guidelines and data quality information from the IGS stations were taken as quality references. Specifically, the recommended guidelines (REC) to become an IGS station were taken as the first quality level or threshold (IGS 2015; Johnston et al. 2017).

4.2.2 Geodetic monument type and noise

The different geodetic monuments used in the Topo-Iberia network are analyzed based on the noise and basic statistics of the GPS position time series. Fifty percent of the Topo-Iberia

stations had a data span of over 9.5 years on the control date, which is a long period of time that allows analyzing the possible relationship. The time series analysis was realized using the *tsfit* GLOBK program (Herring et al. 2015), a command-line tool for fitting time series and generating statistics. The linear trends, outliers, offsets, and periodic signals (annual and semi-annual) were estimated and removed from the time series. The outliers were detected and eliminated by two automatic procedures, max-sigma and n-sigma. Any position estimate whose uncertainty was greater than 2, 2, and 3 cm in east, north, and up, respectively, was removed (max-sigma), as well as the points that exceeded the 2-sigma value after detrending the data. The noise in the GPS position time series was assumed to be a combination of white noise plus random-walk (RW) noise. The long-period temporally correlated noise was accounted for using the *realistic-sigma* algorithm (Floyd and Herring 2020) to get realistic uncertainties. The basic statistics of the position time series are extracted from the *tsfit* summary output file, and this file is used with the *sh_gen_stats* GAMIT/GLOBK script to generate the RW process noise values. Finally, the seasonal noise is determined by comparing the estimated RW noise considering and without considering the seasonal signals (annual and semi-annual terms) in the time series.

4.3 Results and discussion

4.3.1 Antenna environment's effects on the elmean LC phase residuals

The elmean residuals of the phase observations from the Topo-Iberia GPS data processing have been plotted, and depending on the resulting waveform or pattern, five types have been established into which the Topo-Iberia stations are grouped. A sample of them is shown in Fig. 4.2 corresponding to the first complete processed year (2009), except for the station ASIN whose graph corresponds to the year 2010 since there was an antenna change in 2009 that altered the pattern (see Fig. S1 in Supplement). The graphs for all Topo-Iberia stations and complete processed periods are shown in Appendix (Figs. 4.14–4.18), and a compilation of all yearly graphs is provided in Supplement (Figs. S1–S5). For integration of a station in a group, all processed years have been considered and not only the pattern obtained for one year. Moreover, the possible changes in the antenna environment due to natural causes (vegetation growth, snow, etc.) or anthropic nature, have been considered since they could cause a slightly different pattern from one year to another. The groups established in this study are the following:

- *Group 1* (ASIN). The azimuthal-averaged phase residuals are low at all elevation angles, i.e., the width of the pattern around the X axis is narrow, and there are no areas that stand out for presenting notable residuals (Fig. 4.2a). The antenna is installed on uneven ground with dense vegetation cover (bushy small scrub) resulting in a good scattering environment.
- *Group 2* (FUEN, LNDA, LOBE, PALM, PILA, REIN, RUBI, TGIL, and TRIA). The phase

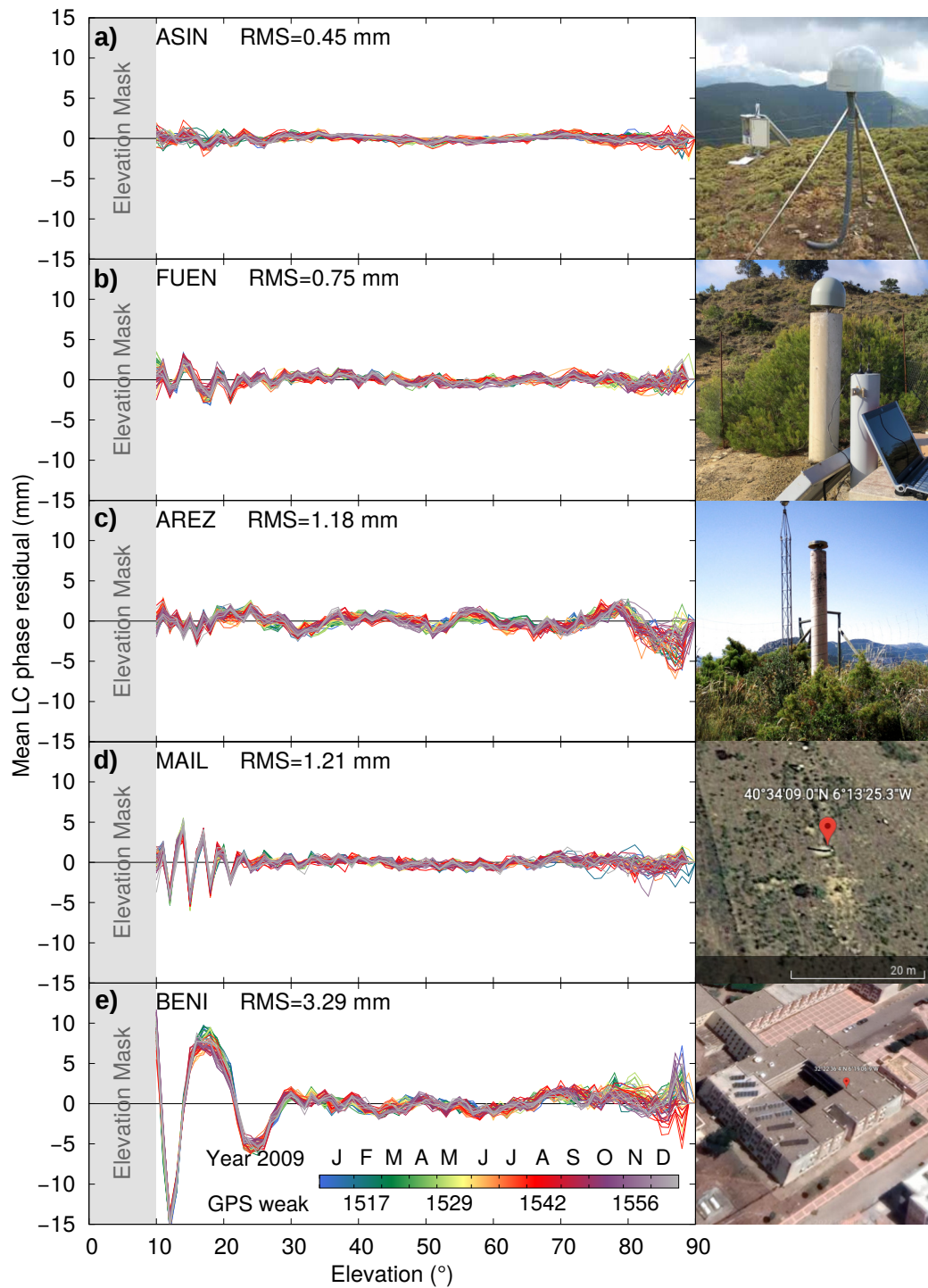


Fig. 4.2 Mean ionosphere-free phase residuals for all satellites, averaged over each week of 2009 (2010 in case of ASIN) in 1° elevation angle bins above the horizon (left), and antenna/site photograph (right) of a sample-station from each group established in this work. The mean RMS of phase residuals corresponds to the complete processed year. Photographs: the ASIN photo is modified from Asensio et al. (2010), the FUEN photo is courtesy of Giorgi Khazaradze (UB. Project NSOURCES PID2020-119772RB-I00), the MAIL and BENI photos are from Google Earth (<https://earth.google.com/web/search/40.56916,-6.22369> and <https://earth.google.com/web/search/32.37679,-6.31859>, respectively)

residuals are also low and the pattern width is narrow, but in this case the largest residuals occur at low elevation angles ($\sim 0^\circ$ – 20°) with a well-defined pattern (Fig. 4.2b). The antenna is installed on uneven ground with different types of vegetation cover. The highest residuals coincide with the presence of a small, more or less flat surface, or with a rocky outcrop around the antenna, that would favor the multipath effect from reflections off these surfaces at low elevation angles. It should be noted that the station PALM is located on a little flat rocky outcrop surrounded by uneven terrain, but when this terrain is very densely covered by vegetation, as shown the photograph in Fig. 4.17, the station presents a pattern and RMS very similar to the group 1 (see graphs in Suppl. Fig. S4 from 2016).

- *Group 3* (ALJI, AREZ, CAST, LIJA, LOJA, and UCMT). The phase residuals are greater and distributed throughout the entire range of elevation angles (Fig. 4.2c). The presence of rocky ground is notable, also combined with different types of vegetation cover. An exception in this group is the station CAST located on a castle (Fig. 4.15). The small horizontal surface on which the antenna is installed, and the artificial rocky surfaces with different planes of inclination around it, do not produce the characteristic effect of other antennas installed on buildings exposed below in group 5. Another particular case is the UCMT antenna installed on a flat artificial ground made up of small stones (Fig. 4.18). This ground type lacks the dispersive capacity of a natural ground without vegetation cover, as shown in group 2, increasing the phase residuals throughout the range of elevation angles. Moreover, being a flat surface, a greater multipath effect is produced at low elevation angles.
- *Group 4* (CABU, CIER, EPCU, MAIL, and NEVA). Two areas are clearly distinguished in the pattern (Fig. 4.2d). The area of low elevation angles ($\sim 0^\circ$ – 20°) is notable for presenting the greatest phase residuals with a well-defined pattern. Considering the trace in this area as a wave, it can be said that the waveform has higher frequency and amplitude than group 2. The remaining area shows low phase residuals, similar to those seen in groups 1 and 2. The stations have in common that the antenna is located on flat and uniform surfaces, with a large part of the area around antenna free of obstacles. The multipath effect associated with this specific environment is probably caused by the higher frequency and amplitude abovementioned. The uniform grassy ground, sparse vegetation, or without vegetation cover, depending on the case, causes the remaining pattern to present low phase residuals. A particular case in this group is the station NEVA showing a variable pattern over time depending on whether the ground is snow covered or not (Fig. 4.17). The pattern corresponding to the year 2017 has been taken as a sample, which has been divided into two: a pattern corresponding to the period without snow cover (Fig. 4.3 top), and another pattern corresponding to the snowy period (Fig. 4.3 middle). The ground without snow cover is a fairly flat ground without vegetation cover. Although there are some obstacles

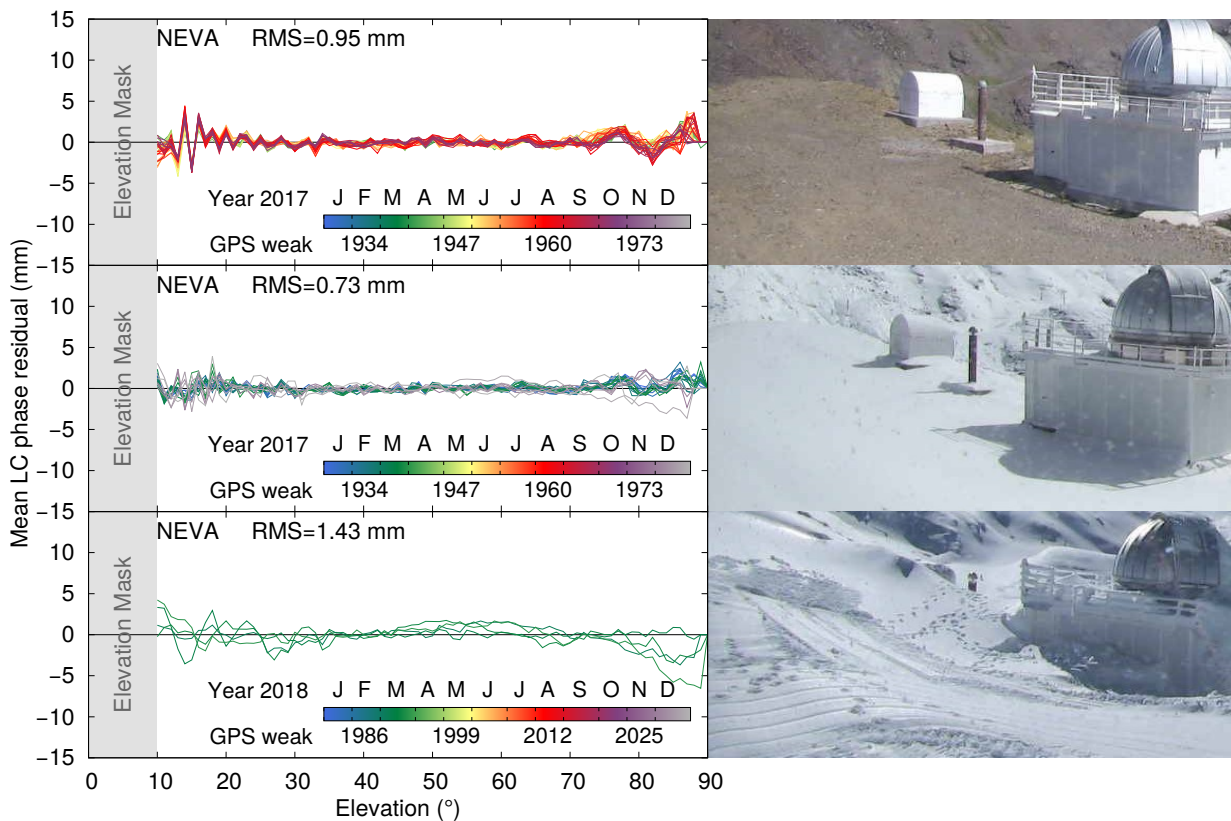


Fig. 4.3 Mean LC phase residuals for all satellites, averaged over each week in 1° elevation angle bins above the horizon (left), and photograph (right) of the station NEVA in different periods. (Top) Period from 2017-04-04 (DOY 94) to 2017-10-17 (DOY 290) and photo taken on 2017-07-14. (Middle) Remaining period of the year with snow cover and photo taken on 2017-10-19 (DOY 292), date of the first day in autumn with the ground completely covered. (Bottom) Period corresponding to March 2018 and photo taken on 2018-03-09 (DOY 68). The photographs are modified from the South Webcam of Sierra Nevada Observatory (<https://www.osn.iaa.csic.es/en/page/south-camera-osn>)

around the antenna, there is enough unobstructed flat surface to generate a small pattern with the characteristic high frequencies at low elevation angles, but of lower amplitude in this case. For this reason, the station NEVA has been included in this group and not in group 2. On the other hand, the pattern corresponding to the snowy period could be integrated in group 1 or 2 (with lower phase residuals), however, this pattern has the drawback that it also varies between different snowy periods. An example is the pattern corresponding to March 2018 (Fig. 4.3 bottom). The quantity of snow was very great on this date, the relatively flat surface became wavy, and the relative height of the antenna was reduced. As a consequence, the elmean phase residuals increased at different elevation angles and their RMS value doubled.

- *Group 5* (BENI, ERRA, and TAZA). The pattern shows the highest elmean phase residuals, and in some cases above 10 mm. Considering the waveform and comparing it with that of group 4, the frequency is smaller but the amplitude is increased considerably at elevations

up to $\sim 30^\circ$ above the horizon (Fig. 4.2e). The stations have in common that the antenna is installed on the flat roof of buildings, a poor-scattering environment. The station BENI is notable for presenting the highest phase residuals in the group (mean RMS of 3.1 mm for the span 2008–2013). Presumably this is because the antenna is installed in the central part of the roof, and therefore there is a greater extent of flat surface around the antenna that would reflect the GPS signal. Instead, the TAZA antenna is installed on the roof corner (Fig. 4.18), and the phase residuals are half (mean RMS of 1.6 mm, span 2008–2014).

A pattern type diagram of elmean phase residuals has been developed as a function of the vegetation cover and the extent of flat surface around the antenna, in combination with the presence of rocky ground (Fig. 4.4). The label (*no flat*) in the vertical categories indicates that there is no flat surface around the antenna. The *little flat surface or rocky outcrop* and the *uneven ground (no flat)* categories, differ in that the first presents a small flat surface that produces higher phase residuals at low elevation angles. The particular cases of the stations CAST and UCMT (group 3) are represented with the combination *artificial surface + little flat surface*. It can be seen that for the greatest elmean phase residuals to occur, associated with a high frequency (group 4) or high amplitude waveform (group 5), it is necessary a large extent of flat surface around the antenna that reflects the GPS signal at low elevation angles. Among the Topo-Iberia stations there has not been any case corresponding to the combination *scrub with shrubs + large flat surface*, but presumably it would also correspond to pattern type 4. In the same way, the combination of *uneven ground (no flat)* with different types of vegetation cover would also correspond to pattern type 1. This diagram depicts the antenna environment characteristics observed at the Topo-Iberia

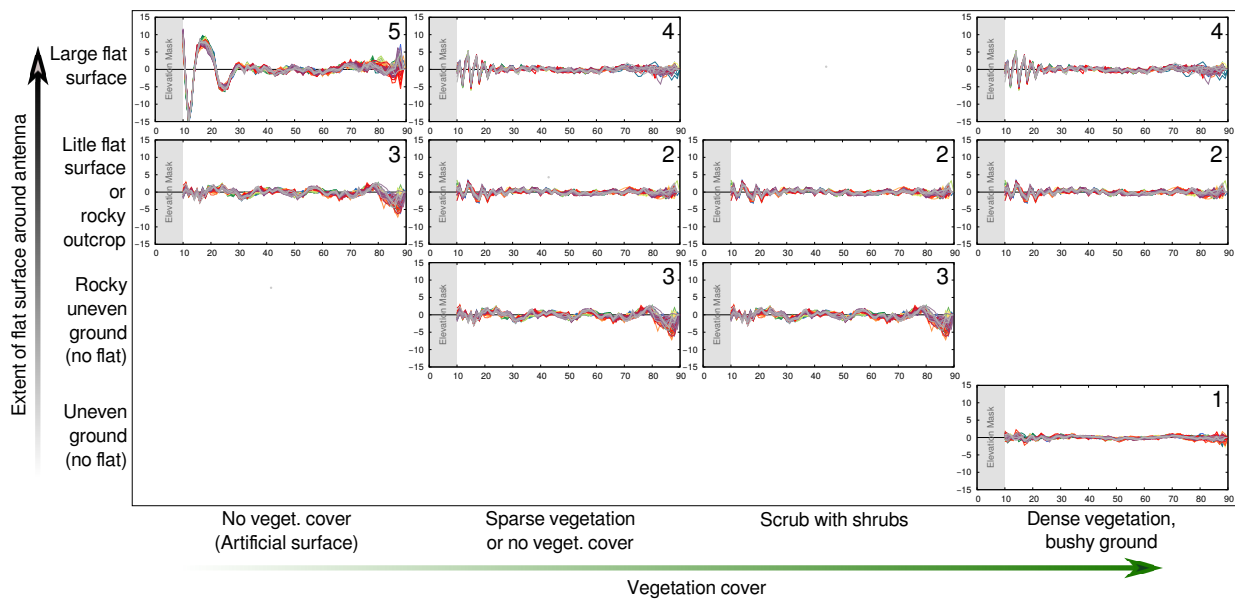


Fig. 4.4 Diagram of elmean phase residuals pattern types based on the antenna environment characteristics observed at the Topo-Iberia stations. The numbers correspond to the pattern type or station group established in this work

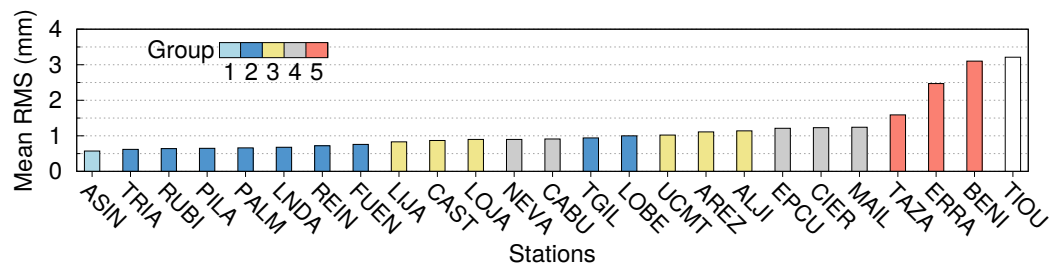


Fig. 4.5 Mean yearly RMS of the elmean phase residuals from each Topo-Iberia station. The stations are sorted by increasing RMS value and classified by color according to the group to which they belong

stations, but could be useful to select the optimal environment for a GNSS antenna.

Fig. 4.5 shows the mean yearly RMS of the elmean phase residuals corresponding to the whole period processed for each Topo-Iberia station. The values are generally low, with a median value of 0.9 mm. Although it is observed that the mean yearly RMS is variable within the same group in the central values (LIJA–ALJI) distributed in a range of 0.3 mm, the stations grouped based on the pattern type have very similar values. Therefore, it is possible to associate each group with a specific range of elmean phase residual RMS, or at least establish the pattern type with the lowest and highest RMS value, which corresponds to the best and worst antenna environment, respectively. The best group or pattern type with the lowest RMS value corresponds to group 1 composed only of the station ASIN, followed by group 2 with the exception of the stations TGIL and LOBE. In groups 3 and 4 there is not so much homogeneity, but as a whole it can be seen that group 3 presents a lower RMS value than group 4. And finally, the entire group 5 (antenna on building roof) stands out for presenting the highest RMS values.

The station TIOU has presented high elmean phase residuals since the beginning of its activity (Suppl. Fig. S5), as well as its data quality has worsened and shown sudden changes due to unknown causes (Fig. 3.15). It has not been possible to analyze its pattern properly due to lack of information on the site. Therefore, the station TIOU has not been considered representative of any group, nor its pattern characteristic of any antenna environment, nor has it been classified by color in Fig. 4.5.

4.3.1.1 Relationship between the antenna environment's effects and the GPS data quality

The high elmean phase residuals obtained at the stations of group 5, presumably related to the multipath effect, may lead us to think that the quality of their data is poor, but in reality these stations meet the quality threshold REC relative to the multipath (Fig. 3.7). On the contrary, these stations with antenna on building roof also have in common that they do not meet the threshold for the quality indicator CSR, and that the number of cycle slips has been very variable throughout their activity periods (García-Armenteros 2023b, Suppl. Figs. S7, S12, and S24). This antenna behavior is associated with an environment of high signal-interference and poor

signal reception such as urban areas, in which the cycle slips can be caused, among others, by buildings, multipath, or low satellite elevation (Hofmann-Wellenhof et al. 1993).

Other correlations with the published qc results have also been found; all the stations that meet the guidelines to become an IGS station according to the qc (FUEN, PALM, PILA, and TRIA) are also among those that have shown the lowest RMS of elmean phase residuals, and belong to group 2 (Fig. 4.5). The station ASIN, whose type of phase residuals pattern presents the lowest RMS value, is also the station with the lowest RMS of *postfit* phase residuals in the GPS processing (Figs. 3.8–3.9). This station is not among those that meet the guidelines to become an IGS station due only to that the percentage of its data meeting the indicator integrity is 92% and not 95%.

On the other hand, it can be seen with the naked eye in Figs. 4.14–4.18 (Appendix) some phase residual patterns wider and poorly defined than others, such as those of the stations ALJI,

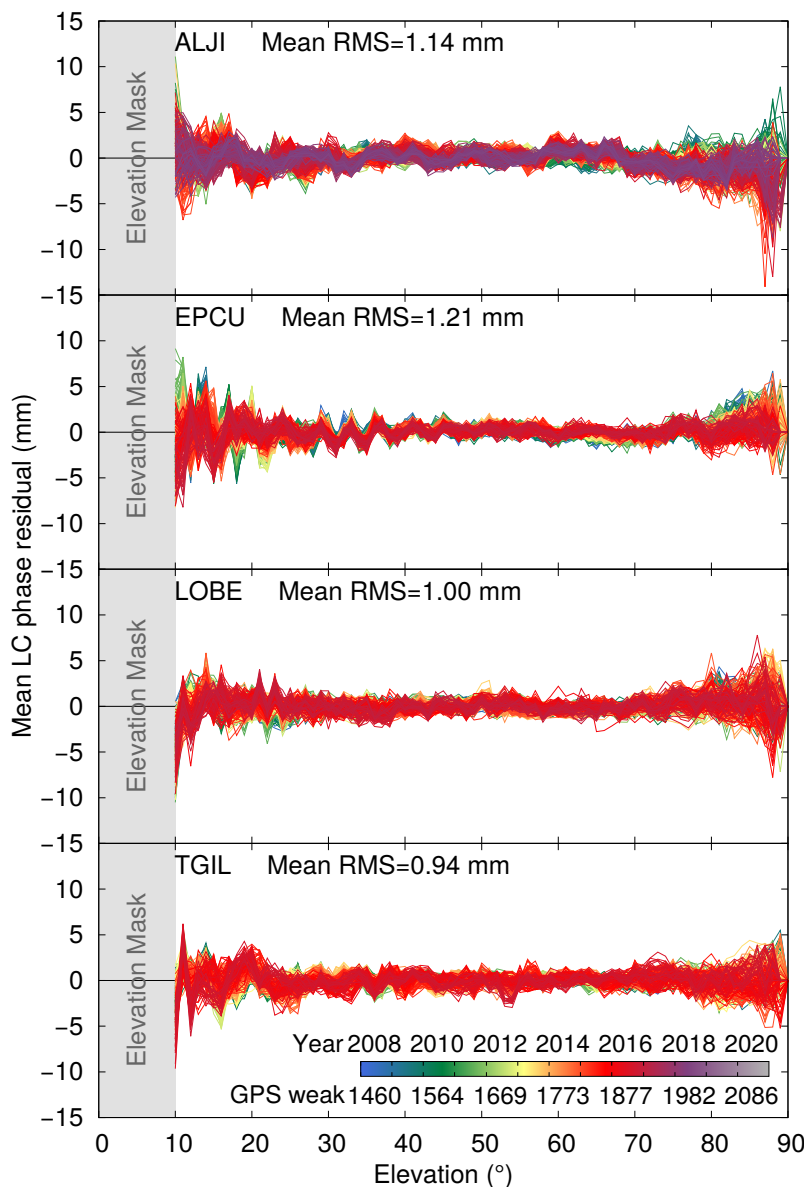


Fig. 4.6 Mean LC phase residuals for all satellites, averaged over each week of all the processed years in 1° elevation angle bins above the horizon, from some Topo-Iberia stations that have shown a wider and poorly defined pattern

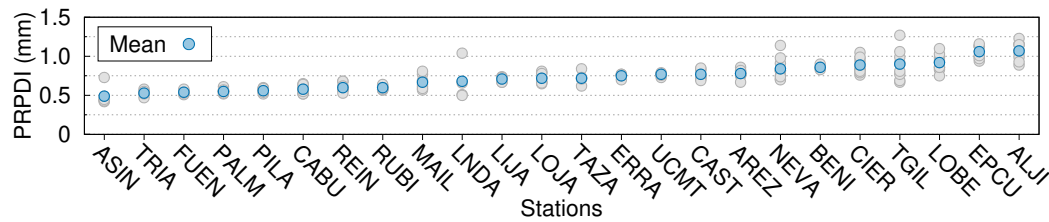


Fig. 4.7 Phase residuals pattern difference indices of the Topo-Iberia stations sorted by increasing mean value. The TIOU station PRPDI values are not depicted, but are provided along with the remaining stations in Supplement Table S1

EPCU, LOBE, and TGIL (Fig. 4.6). It is due to that a slightly different pattern is generated each year, and therefore, there is not a large overlap in the combination of all of them. Moreover, general increase is observed in the RMS of the elmean phase residuals. To accurately determine the level of overlap or similarity between consecutive yearly patterns, the difference index of phase residuals patterns is calculated according to Eq. (4.1). All the yearly patterns of the Topo-Iberia stations corresponding to the complete processed period have been matched, and their PRPDI calculated. The results are shown in Fig. 4.7 and Supplement Table S1. The TIOU station PRPDI values are not depicted in this Figure to perceive in greater detail the small variations that occur in the remaining stations. The mean PRPDI value for the stations whose patterns have shown the highest and lowest similarity level is ~ 0.5 and ~ 1 mm, respectively. A value close to 1 mm corresponds to notable changes in the graphs. The results clearly confirm that the highest PRPDI values correspond to the stations showing wider patterns in the graphs (ALJI, CIER, EPCU, LOBE, and TGIL). These stations have in common that showed remarkable changes or progressive increases in the multipath and cycle slips parameters (García-Armenteros 2023b, Suppl. Figs. S4, S11, S16, and S25). Moreover, these stations are among the poorest quality stations and among those with the highest postfit RMS of phase residuals (Fig. 4.8). All of them, except the station ALJI, showed changes in the occlusion horizon, i.e., they showed an increase in elevation of the horizon line, presumably due to variations in the vegetation cover (growth

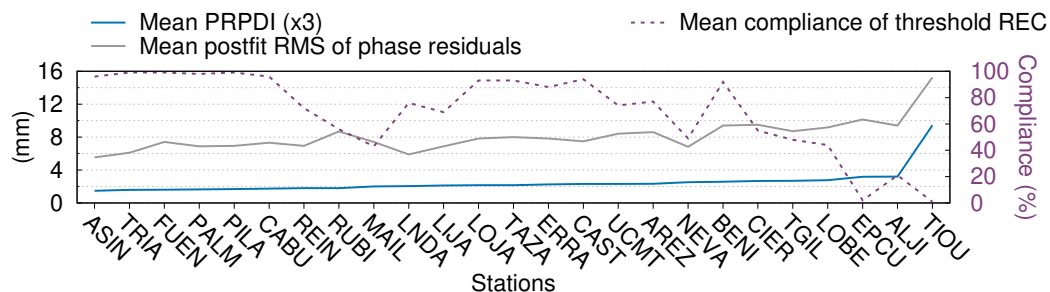


Fig. 4.8 Values obtained at each Topo-Iberia station for the mean PRPDI, mean postfit RMS of phase residuals from the GAMIT processing (García-Armenteros 2023a), and mean compliance percentage with the quality threshold REC considering all the quality indicators together (García-Armenteros 2023b, Table 3). Note that a factor of 3 has been applied to the PRPDI value to facilitate visual comparison. The stations are sorted by increasing PRPDI value

of nearby trees, increased leafiness, etc.). The PRPDI value is independent of the pattern type and the RMS of elmean phase residuals, depending solely on the antenna environment changes over the years which, in turn, cause changes in the data quality mainly related to the multipath effect and cycle slips. The progressive worsening of the data quality is the cause of these stations appearing separated from their group in Fig. 4.5 and with higher mean RMS values, although their values were similar to those of their group stations in the first activity years. It should be noted in Fig. 4.7 that the high PRPDI values of these stations are also variable, i.e., the differences between consecutive yearly patterns vary notably over time. This doubly confirms the presumed changes in the antenna environment at these stations.

The NEVA station PRPDI value in Fig. 4.7 also presents variations caused by the different effects of the snow periods on the yearly patterns, as previously shown in Fig. 4.3. A low PRPDI value should not be interpreted as an indicator of a good antenna environment, but rather as an indicator of a stable environment, and that the instability at these evaluated stations has led to a poor data quality. An exception is the station ASIN, where the noticeable variation of the PRPDI value corresponds to an antenna change in the year 2009 that generated a new pattern of elmean phase residuals (Suppl. Fig. S1). On the other hand, the highest PRPDI value of the station LNDA, corresponding to the years 2011–2012, coincides with the notable worsening of the data quality in almost all their parameters evaluated (García-Armenteros 2023b, Suppl. Fig. S15).

The stations with the lowest PRPDI values are also among those with the lowest postfit RMS of phase residuals (Fig. 4.8), and even among those with the lowest RMS of elmean phase residuals (Fig. 4.5). While there is a partial correspondence between the PRPDI and the RMS of elmean phase residuals, the correspondence between the PRPDI and the postfit RMS of phase residuals is greater, with a similar increasing trend as shown in Fig. 4.8. The results obtained in the present study show that the PRPDI is a good tool to identify changes in the antenna environment, as well as the stations with the best and worst data quality.

4.3.2 Geodetic monument noise and associated scattering

The different monument types used at the Topo-Iberia stations are shown in Table 4.1. The Fig. 4.9 shows the noise and basic statistics from the Topo-Iberia stations depending on the monument type. The weighted root-mean-square (WRMS) values are estimated from the scatter of position time series residuals. The equivalent horizontal random walk (HRW) values, representing the time correlated noise, are estimates of the random-walk process noise values in the horizontal component. The values obtained for each station are provided in Supplement Table S2.

The instability of the geodetic monuments due to different anchoring media (e.g., bedrock, buildings) is considered an important source of noise, thought to follow a random-walk process (Johnson and Agnew 1995). There are many sources of noise in the position time series, so it is

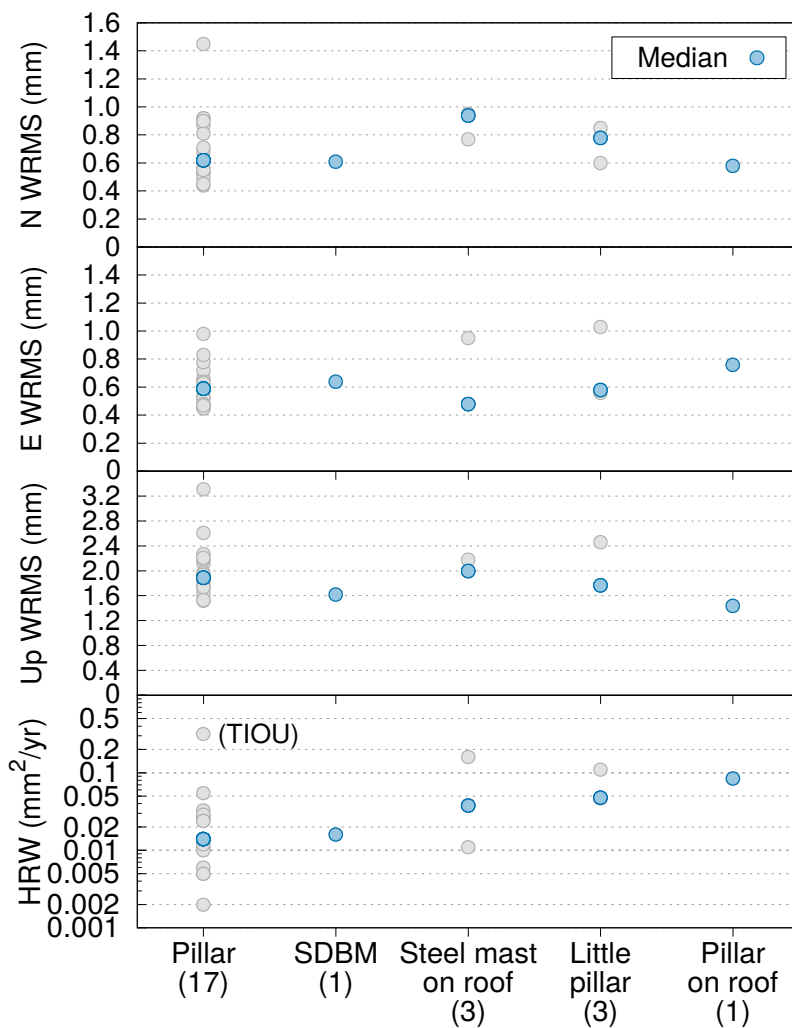


Fig. 4.9 Distribution of the WRMS values in the north, east and up components, and HRW values depending on the monument type sorted by increasing noise value. The HRW values are depicted with a logarithmic scale. The numbers in parentheses following the monument types are the total stations in that category

difficult to establish a clear relationship between the monument stability and the results shown. Considering the median value, it is observed that the stations with pillars on bedrock (standard height or greater) have better results than stations with little pillars (ALJI, LIJA, and LOJA). These three stations have in common that they belong to the group 3 previously established based on the pattern of their elmean phase residuals, in which there are also stations with other monument types and better results. Therefore, their high values in noise and scattering are not related to the antenna environment, but to the monument type. It would be necessary to have this monument type with different antenna environments to verify if the cause of the noise is a combination of both or not. These little pillars, together with the monuments on buildings present the highest HRW values, showing the steel mast on roof the highest total WRMS scatter. In contrast, the HRW value from the shallow-drilled braced monument is very close to that of the standard pillar, and its WRMS scatter is among the lowest. It could be interpreted as this monument type is more stable than others, but the sample is too small to confirm it since there is only one case for this category. Nonetheless, and although the Topo-Iberia network is a small data set, the results presented in relation to the categories with less noise value agree with those

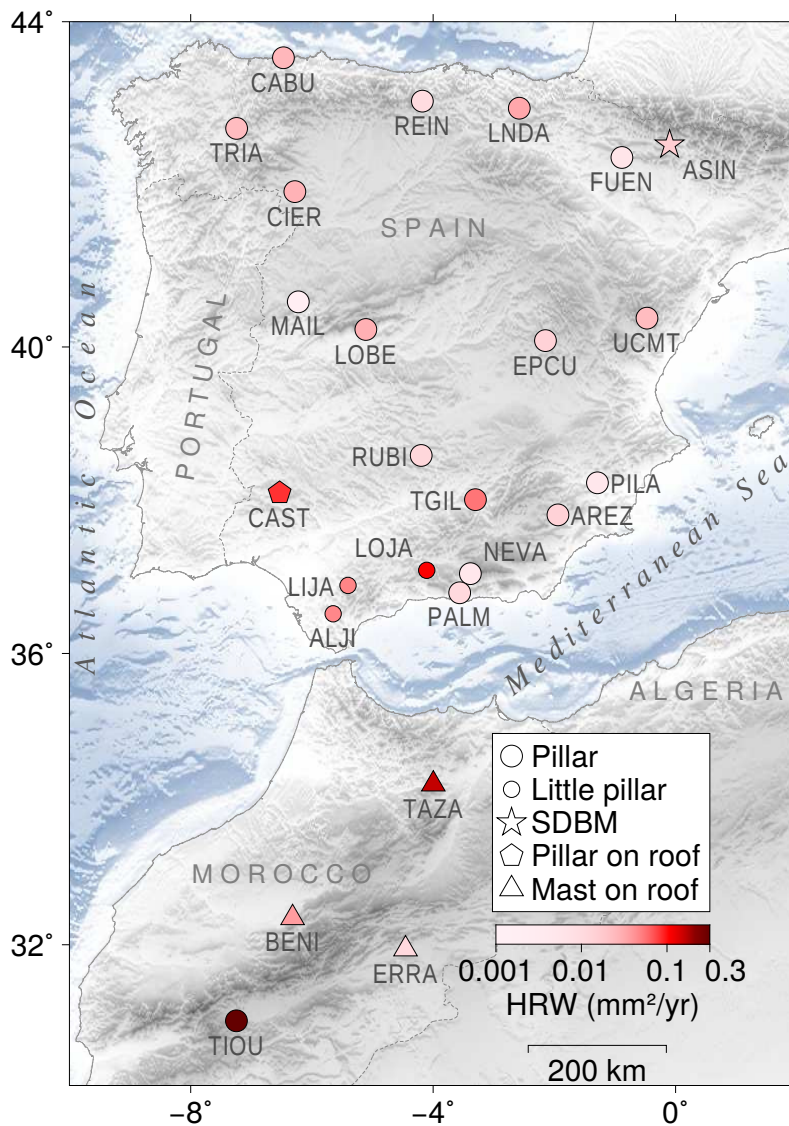


Fig. 4.10 Geographical distribution of the equivalent horizontal random walk values and monument types from the Topo-Iberia stations. The HRW noise is depicted with a logarithmic color scale

of Herring et al. (2016) on a larger data set, and other previous studies such as Williams et al. (2004) and Beavan (2005). The Topo-Iberia stations, except TIOU, present an HRW value below $0.162 \text{ mm}^2/\text{yr}$ with a median of $0.024 \text{ mm}^2/\text{yr}$, therefore it can be established that the RW noise level of the Topo-Iberia monuments is adequate for a geodetic monument.

Considering the elmean phase residuals, it could be said that all Topo-Iberia stations located in more southern latitudes (Morocco) present the highest residuals (Fig. 4.5), but as explained above, they have in common the monument type (steel mast on roof), except the station TIOU. Actually, the cause of these high residuals is the antenna environment associated with this monument type. Therefore, the geographical location of these stations is pure coincidence in relationship to the elmean phase residuals. No relationship was found between the HRW values and the geographical location of the sites either (Fig. 4.10). The relationship between the monument type and the HRW noise is not as evident as between the steel mast on roof and the elmean phase residuals, but the highest HRW values are also found at stations with monuments on buildings (0.085

and $0.161 \text{ mm}^2/\text{yr}$ at CAST and TAZA, respectively), and with little pillar ($0.110 \text{ mm}^2/\text{yr}$ at LOJA). The station TIOU with a pillar on bedrock shows the largest HRW value ($0.317 \text{ mm}^2/\text{yr}$) presumably due to anomalies of unknown origin.

4.3.2.1 Seasonal noise

A comparison has been made between the estimated random-walk (RW) noise considering and without considering the annual and semi-annual terms (seasonal signals) in the position time series from the GAMIT/GLOBK processing, and the results obtained are shown in absolute value in Fig. 4.11. These values represent the part of the noise associated with periodic signals, the seasonal noise. Possible sources of this noise include local fluctuations in groundwater or soil moisture in different seasons of the year producing instability, or periodic movement of the monument. Other sources are related to the antenna environment, such as the previously mentioned periodic vegetation or foliage growth that increases the elevation of the occlusion horizon, multipath, and cycle slips.

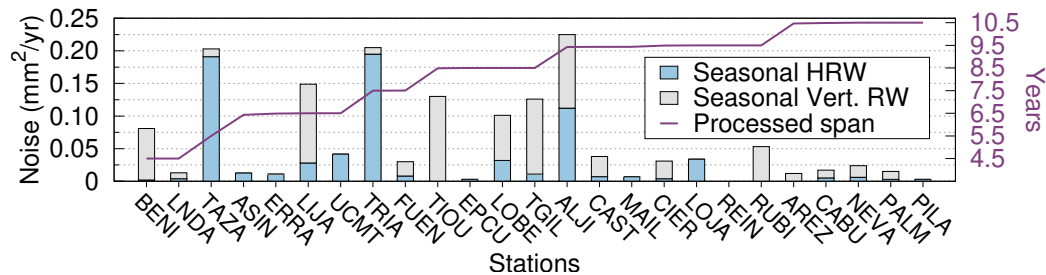


Fig. 4.11 Stacked equivalent horizontal and vertical components of the seasonal RW noise at the Topo-Iberia stations sorted by increasing processed span

The median value of the seasonal HRW noise for the Topo-Iberia stations is $0.007 \text{ mm}^2/\text{yr}$, and the median of the seasonal vertical RW noise is $0.012 \text{ mm}^2/\text{yr}$, fairly small quantities. The three stations with the greatest affection in the seasonal HRW noise are ALJI, TRIA, and TAZA. Ignoring the periodic signal estimation results in a final velocity error of 0.44 mm/yr in the east component for the station ALJI, and 0.24 mm/yr in the north component for the station TRIA. When the data were selected for processing, the effect of these signals on the velocity estimation (Blewitt and Lavallée 2002) was taken into account selecting data spans of integer-plus-half years and longer than 4.5 years, so that the affection was the least possible (García-Armenteros 2023a). The results indicate that, even so, the periodic signals should be estimated.

No relationship has been observed between the seasonal noise and the geographical location of the sites (Fig. 4.12). The highest seasonal HRW values are located at sites covering almost the entire latitude range of the network. Other studies carried out on networks of hundreds of sites occupying a large part of a continent, such as Herring et al. (2016) and Langbein and Svarc

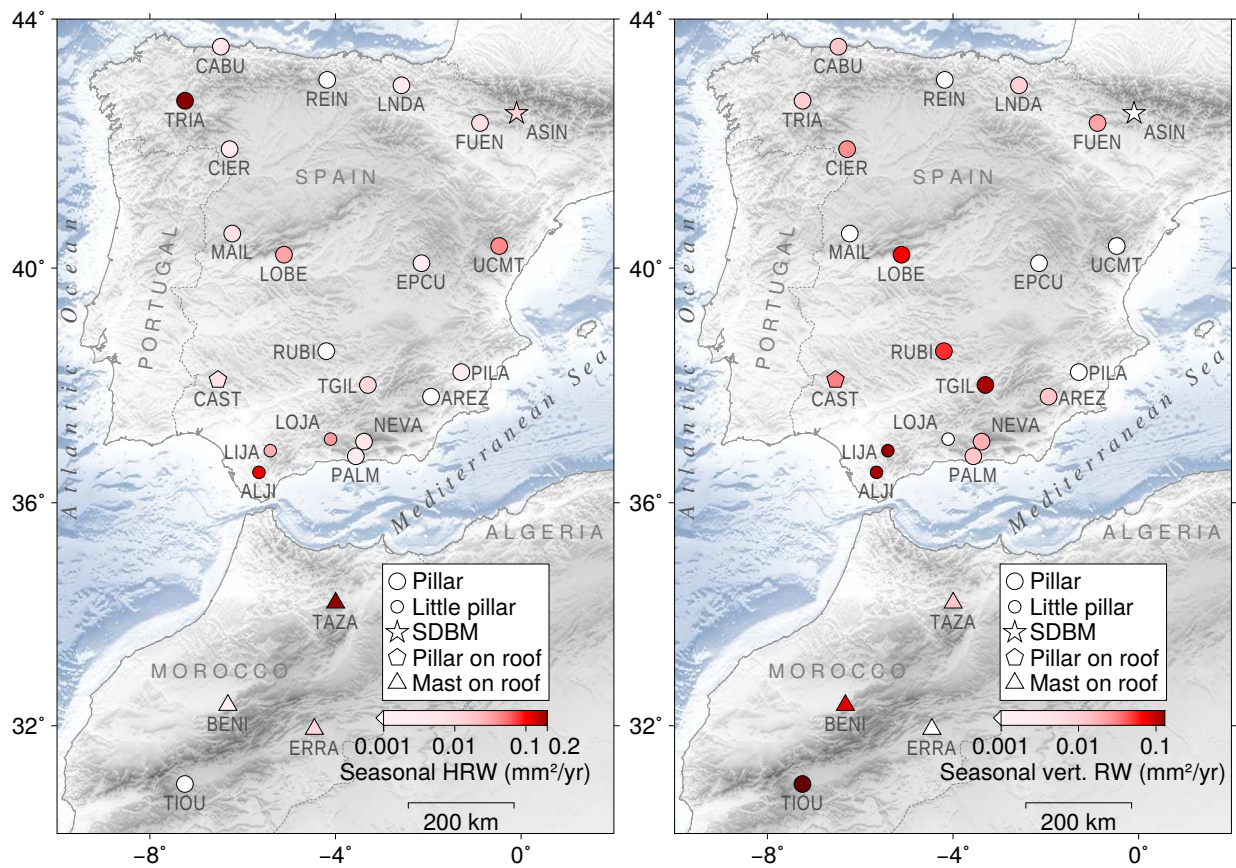


Fig. 4.12 Geographical distribution of the seasonal equivalent horizontal random walk (left) and the seasonal vertical RW noise (right), in combination with the monument types at the Topo-Iberia stations. The noise value is depicted with a logarithmic color scale. A white symbol indicates that the seasonal noise value is zero on the color scale

(2019), have identified correlation between the noise and geographic areas with more or less humidity and vegetation. The Topo-Iberia network is not dense, and there are no notable climatological differences in the area covered, except that corresponding to Morocco, but possibly the small number of stations installed in this region, and the monument type used, do not allow to identify the aforementioned correlation, if any.

The relationship between the seasonal noise and the monument type is also not clear, since stations with similar monument type present very different seasonal noise values. Despite this, considering the seasonal noise as a whole, some stations using monuments on building roofs and little concrete pillars show the highest values, especially in the vertical component. It should be noted that the expansion of buildings due to seasonal temperature variations can be considerable in regions with high thermal oscillations such as Morocco. On the other hand, the stations LOBE and TGIL also stand out with a high seasonal noise, but in this case using the standard concrete pillar. In the published quality assessment, an increase was observed in some of their quality parameters, presumably due to variations in the antenna environment, which has resulted in a poorly defined pattern of elmean phase residuals (Fig. 4.6). For all these reasons, it seems that

the seasonal noise detected in both stations could be more related to the antenna environment than to the monument type used. Moreover, it has been found that most of the stations that present seasonal vertical RW noise also present a clear periodicity in their quality parameters, especially in the multipath effect and cycle slips, such as the stations ALJI, BENI, CAST, LOBE, RUBI, and TGIL (García-Armenteros 2023b, Suppl. Figs. S4, S7, S9, S16, S23, and S25). A sample of them is shown in Fig. 4.13.

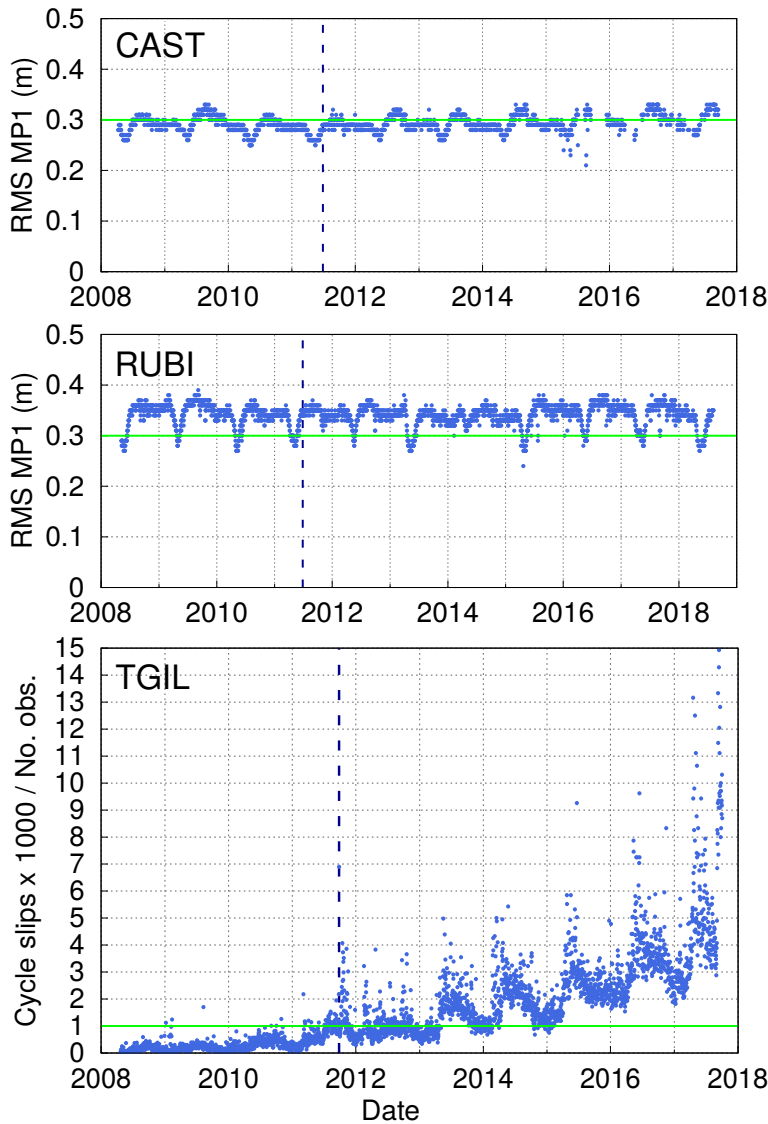


Fig. 4.13 Evolution of the quality parameters CSR and MP1 from Topo-Iberia stations which have presented seasonal vertical RW noise. The green horizontal line corresponds to the IGS quality threshold REC, and the blue vertical dashed line corresponds to receiver change. The graphs are modified from García-Armenteros (2023b, Suppl. Figs. S9, S23, and S25)

4.4 Conclusions

In the present work, the relationship between the antenna environment and elevation angle dependent ionosphere-free phase residuals, as well as with the data quality from the Topo-Iberia CGPS stations, has been determined for the first time.

The plot of these elmean phase residuals forms a certain pattern that has been correlated with

the antenna environment characteristics, and five pattern types have been established. The results have revealed that the smallest elmean phase residuals are produced by antenna environments with uneven ground and vegetation cover (mean RMS of 0.6 mm at ASIN station), and the highest residuals occur on flat roof of buildings (mean RMS of 3.1 mm at BENI station). Moreover, a pattern type diagram has also been created for the first time, which, although based on the antenna environment characteristics observed at the Topo-Iberia stations, could be useful to select the optimal GNSS antenna environment.

Regarding the correlations with results on data quality from previous publications, all the stations that meet the guidelines to become an IGS station also show low RMS of elmean phase residuals. Moreover, all the stations analyzed whose antennas are located on flat building roofs meet these guidelines in relation to the multipath effect despite their high residuals, but no in relation to the cycle slips. Therefore, this type of antenna location is not recommended if meeting such IGS requirements is intended.

A new metric has been proposed to accurately measure the differences between two yearly patterns, the phase residuals pattern difference index (PRPDI). The results reveal that the highest PRPDI values correspond to stations that show wider and poorly defined patterns in the graphs. Moreover, these stations have in common that they are among those with the worst quality and with the highest postfit RMS of phase residuals, and most of them have shown changes in the occlusion horizon. Conversely, the stations with the lowest PRPDI values are among those with the lowest postfit RMS of phase residuals, and with the lowest RMS of elmean phase residuals. The PRPDI value is independent of the pattern type and the RMS of elmean phase residuals, depending only on the antenna environment changes which, in turn, cause changes in the data quality. Therefore, this index is a good tool to identify these changes, as well as the best and worst quality stations.

The relationship between the geodetic monument type used at the Topo-Iberia stations and the associated noise has also been determined for the first time in the present work. The results indicate that the stations with standard pillars on bedrock present less noise than those with little pillars. The highest values of equivalent horizontal random walk are found at stations with little pillars and with monuments on buildings, presenting the steel mast on roof the highest total WRMS scatter. In contrast, the HRW value from the shallow-drilled braced monument is very close to that from the standard pillar, and its WRMS scatter is among the lowest. Although the number of cases for some monument types is very small, the results regarding the least noisy monument types agree with those of previous publications on a larger data set. The RW noise level of the Topo-Iberia monuments, with a median HRW value of 0.024 mm²/yr, is adequate for a geodetic monument. No relationship between the HRW value and geographical location of the sites has been observed.

Finally, the noise associated with the periodic signals has also been determined. In general, the seasonal noise is low at the Topo-Iberia stations (median seasonal HRW value and median

vertical RW noise of 0.007 and 0.012 mm²/yr, respectively), however, the results indicate that the periodic signals should be estimated. No relationship between seasonal noise and geographical location has been observed, although possibly the small number of sites and the covered area do not allow this correlation to be determined, if any. No relationship between seasonal noise and the monument type has been found either, but between seasonal noise and the antenna environment that has shown annual variations. Moreover, it has been found that most of the stations that present seasonal vertical RW noise also present a clear periodicity in their quality parameters.

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Data availability Derived data from the GAMIT/GLOBK processing (phase residuals and RW summary files) supporting the findings of this study are available from the corresponding author upon reasonable request. Maps were created using GMT software version 5.4.5 (Wessel et al. 2013), graphs were created using Gnuplot version 5.2 (<http://www.gnuplot.info>), and figures were edited using Inkscape version 0.92.4 (<https://inkscape.org>). Additional data and resources used in this work are indicated in the main body.

Supplementary information This article contains supplementary material.

Appendix: Topo-Iberia elmean LC phase residuals

Figs. 4.14–4.18 show graphs of the GAMIT-derived LC phase residuals from the Topo-Iberia GPS data processing by García-Armenteros (2023a). These graphs correspond to the complete processed period for each station. A compilation of all yearly graphs is provided in Supplement (Figs. S1–S5).

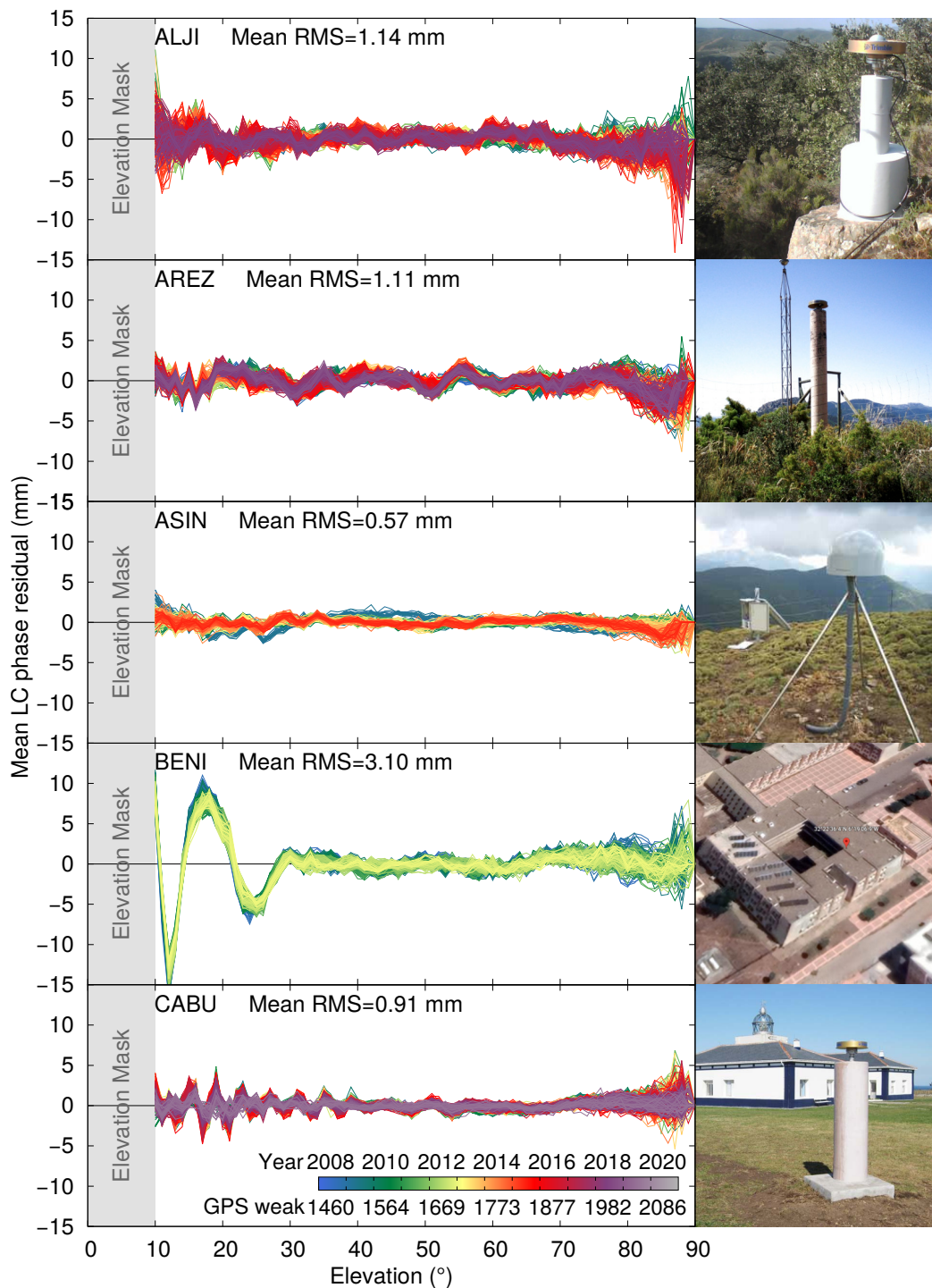


Fig. 4.14 Mean LC phase residuals for all satellites, averaged over each week of the processed span in 1° elevation angle bins above the horizon (left), and antenna/site photograph (right) of the Topo-Iberia stations ALJI, AREZ, ASIN, BENI, and CABU. The mean RMS of phase residuals corresponds to the complete processed span. Photographs: the ALJI photo is modified from Gallastegui et al. (2008), the ASIN photo is modified from Asensio et al. (2010), the BENI photo is from Google Earth (<https://earth.google.com/web/search/32.37679,-6.31859>), and the CABU photo is modified from <http://geol100.geol.uniovi.es/Investigacion/Consolider/GPS/GPS-BUSTO.htm>

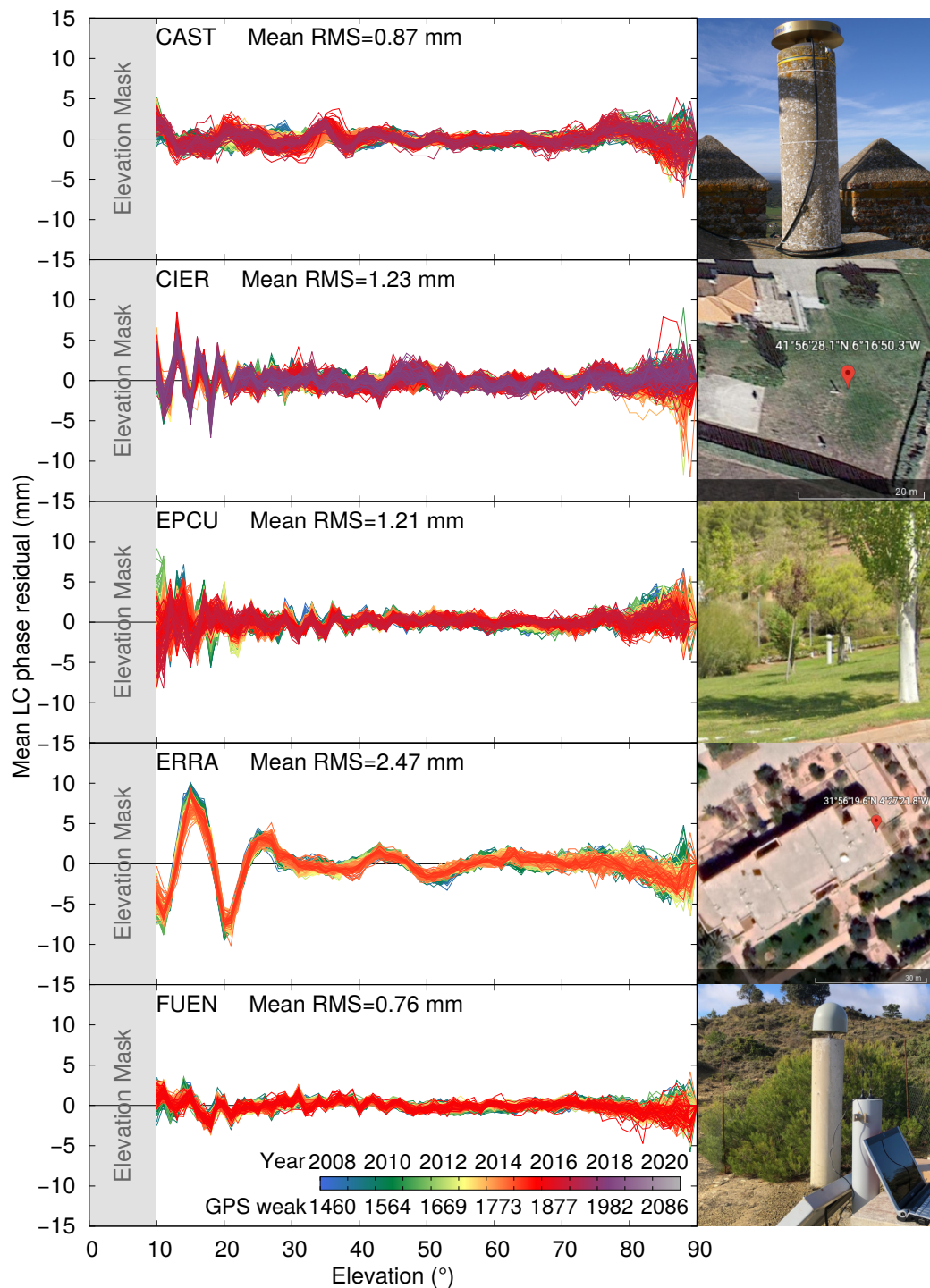


Fig. 4.15 Mean LC phase residuals for all satellites, averaged over each week of the processed span in 1° elevation angle bins above the horizon (left), and antenna/site photograph (right) of the Topo-Iberia stations CAST, CIER, EPCU, ERRA, and FUEN. The mean RMS of phase residuals corresponds to the complete processed span. Photographs: the CAST photo is courtesy of Jorge Gárate Pasquín (ROA), the CIER and ERRA photos are from Google Earth (<https://earth.google.com/web/search/41.94113,-6.28065> and <https://earth.google.com/web/search/31.93879,-4.45606>, respectively), the EPCU photo is from Google Street View (<https://earth.google.com/web/search/40.07955,-2.14646>), and the FUEN photo is courtesy of Giorgi Khazaradze (UB. Project NSOURCES PID2020-119772RB-I00)

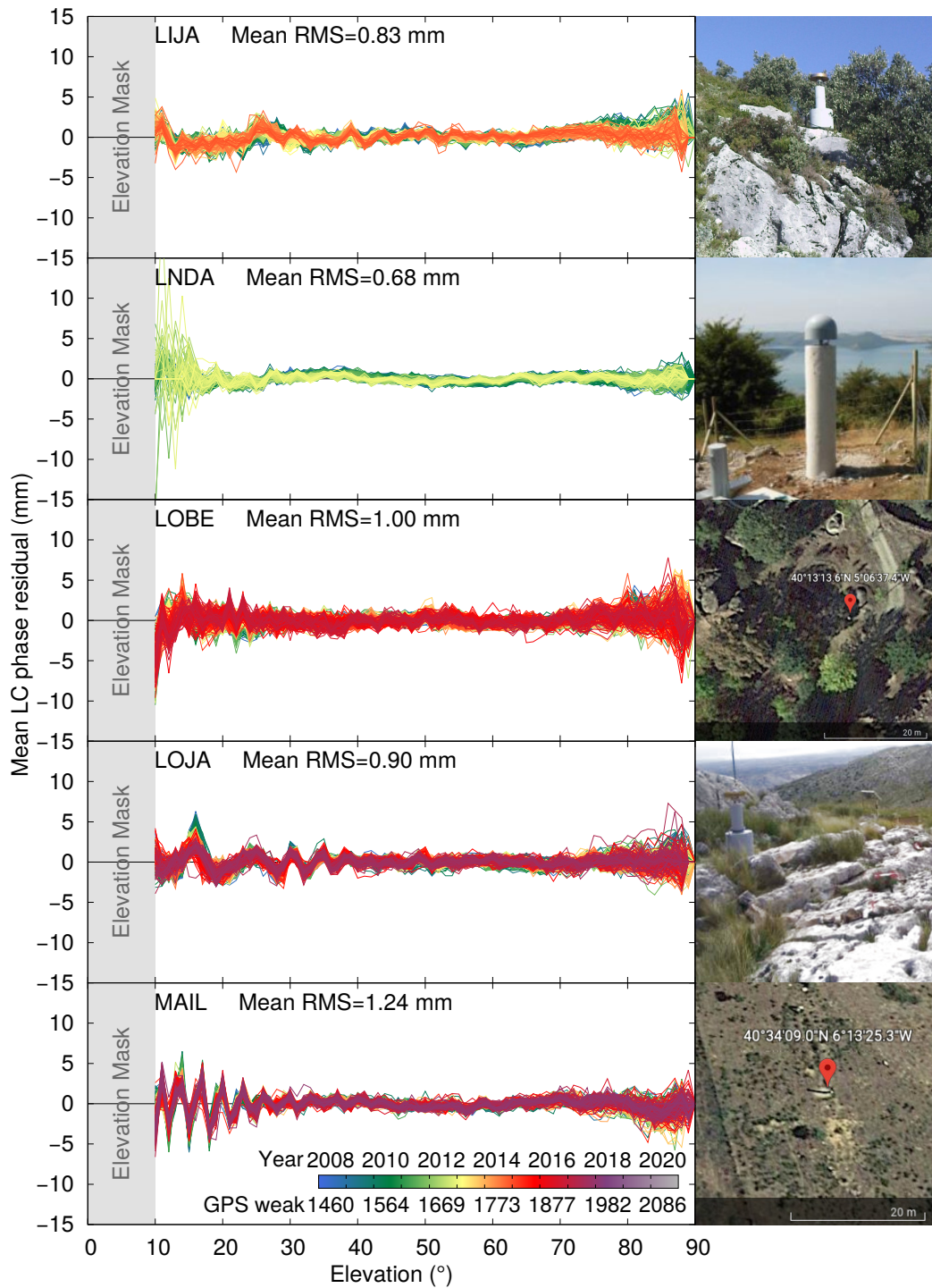


Fig. 4.16 Mean LC phase residuals for all satellites, averaged over each week of the processed span in 1° elevation angle bins above the horizon (left), and antenna/site photograph (right) of the Topo-Iberia stations LIJA, LNDA, LOBE, LOJA, and MAIL. The mean RMS of phase residuals corresponds to the complete processed span. Photographs: the LIJA photo is courtesy of Manuel Catalán-Morollón (ROA), the LNDA and LOJA photos are modified from Asensio et al. (2010), the LOBE and MAIL photos are from Google Earth (<https://earth.google.com/web/search/40.22045,-5.11040> and <https://earth.google.com/web/search/40.56916,-6.22369>, respectively)

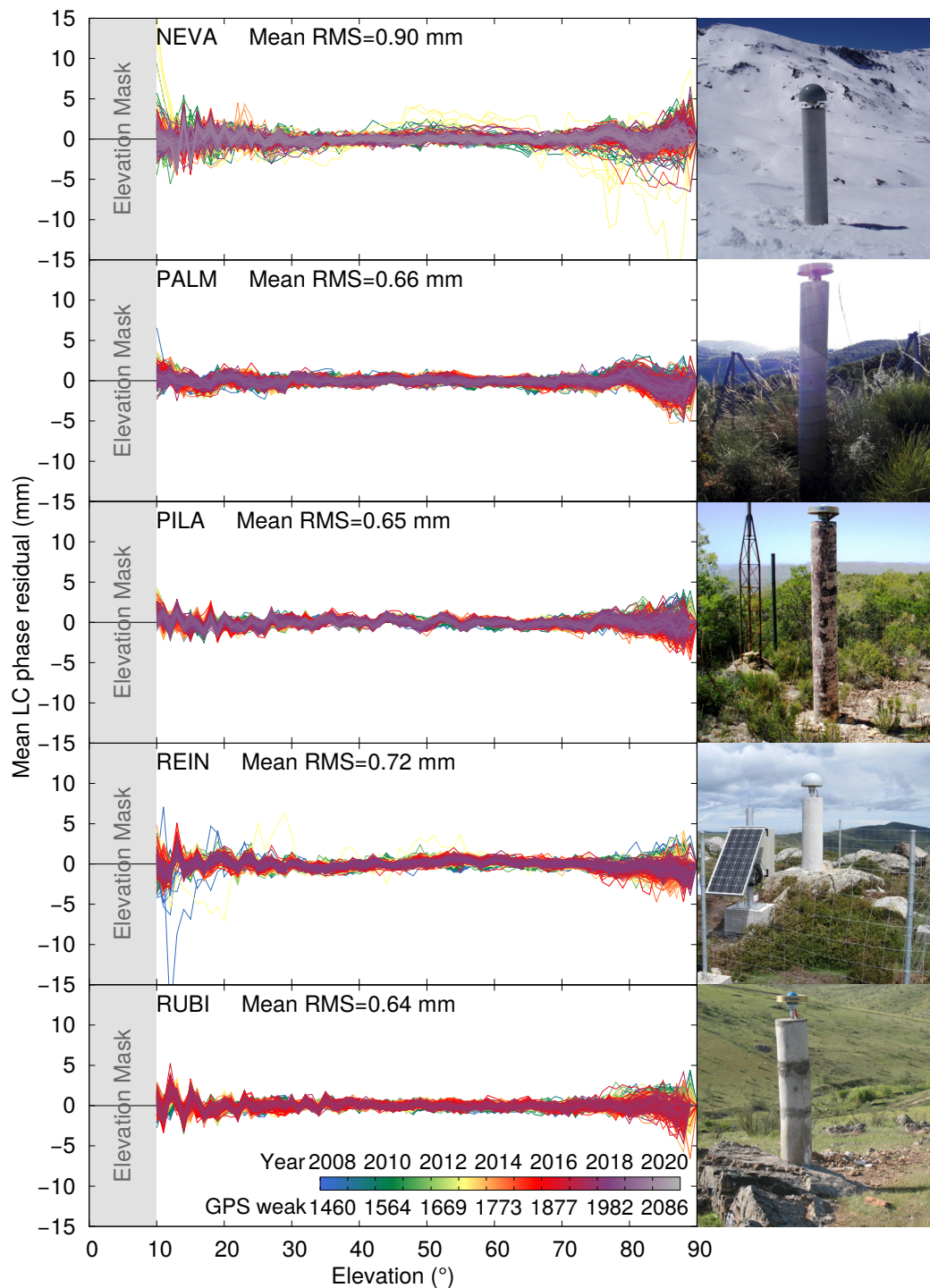


Fig. 4.17 Mean LC phase residuals for all satellites, averaged over each week of the processed span in 1° elevation angle bins above the horizon (left), and antenna/site photograph (right) of the Topo-Iberia stations NEVA, PALM, PILA, REIN, and RUBI. The mean RMS of phase residuals corresponds to the complete processed span. Photographs: the PALM photo is courtesy of Antonio M. Ruiz-Armenteros (UJA) and taken in 2017, the REIN photo is modified from <http://geol00.geol.uniovi.es/Investigacion/Consolider/GPS/GPS-REIN.htm>, the RUBI photo is courtesy of Juliana M. Martín León (IGME), and taken by José M. Llorente Delgado (IGME) and Agustín González Durán (IGME)

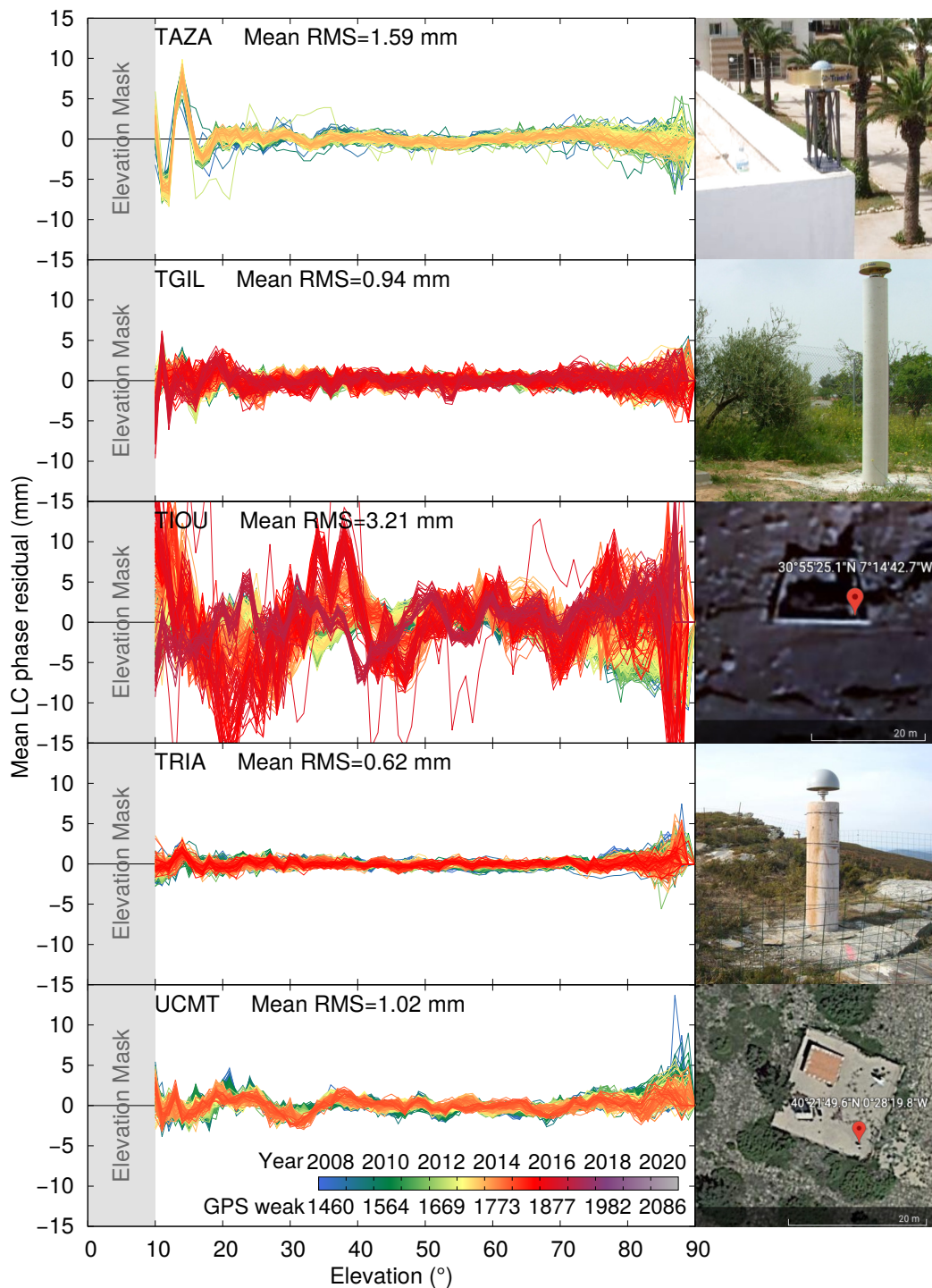


Fig. 4.18 Mean LC phase residuals for all satellites, averaged over each week of the processed span in 1° elevation angle bins above the horizon (left), and antenna/site photograph (right) of the Topo-Iberia stations TAZA, TGIL, TIOU, TRIA, and UCMT. The mean RMS of phase residuals corresponds to the complete processed span. Photographs: the TAZA photo is modified from Asensio et al. (2010), the TGIL photo is modified from Lacy et al. (2014), the TIOU and UCMT photos are from Google Earth (<https://earth.google.com/web/search/30.92363,-7.24520> and <https://earth.google.com/web/search/40.36378,-0.47217>, respectively), and the TRIA photo is modified from <http://geol00.geol.uniovi.es/Investigacion/Consolider/GPS/GPS-TRIA.htm>

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5

Resultados generales y discusión

Los resultados se exponen en dos grandes bloques. El primero corresponde a los resultados de la primera publicación (capítulo 2) que engloba los relacionados con el procesamiento GPS y la geodinámica. El segundo bloque corresponde a los resultados de la segunda y tercera publicación (capítulos 3 y 4) relacionados con la evaluación de la calidad de las estaciones y datos GPS, los efectos de la calidad y del entorno de antena en el procesado, además del ruido asociado al monumento geodésico usado, y la identificación de posibles causas de pérdida de calidad a tener en cuenta en la gestión y mantenimiento de redes GNSS permanentes, como es el caso de la red Topo-Iberia.

5.1 Procesamiento GPS y geodinámica

Estrategia de procesado

Se han procesado todos los datos GPS disponibles de la red Topo-Iberia (2008–2019), teniendo el 50 % de las estaciones más de 9.5 años de datos. Se han usado los programas GAMIT (doble diferenciación) y GipsyX (PPP) con la intención de tener análisis diferentes para comparar y evitar posibles errores introducidos durante el procesamiento manteniendo la premisa de utilizar diferentes técnicas de procesamiento GNSS. Las soluciones velocidad finales de los diferentes programas no se han combinado ni promediado, sino que las dos soluciones independientes libremente constreñidas de GAMIT y GipsyX son combinadas mediante un filtro kalman (GLOBK) siguiendo la estrategia de Herring et al. (2016), obteniendo una solución final común.

Se han introducido dos cambios o modificaciones que simplifican dicha estrategia. Para que las soluciones individuales sean comparables se reescalan sus matrices covarianza de modo que las soluciones estén igualmente ponderadas. El factor de escala se determina de forma que el

valor medio de χ^2/f , donde f es el número de grados de libertad, del ajuste de las diferencias de coordenadas de las estaciones de referencia sea cercano a la unidad. Teniendo en cuenta el modo de procesamiento de GAMIT y su esquema de reponderación por defecto, el valor medio cuadrático normalizado (NRMS) obtenido en las series temporales está en el rango $\sim 0.6\text{--}0.8$. Ya que el problema de que las soluciones individuales sean comparables se reduce a un problema de peso relativo de una solución respecto de la otra, en vez de reescalar las dos soluciones, se reescala solamente la solución de GipsyX. Con esta modificación, ya no es necesario que el factor de escala haga que χ^2/f de cada solución sea cercano a la unidad, sino que el valor de escala apropiado se determina a partir de la relación entre los sigmas de las series temporales de ambas soluciones. Además, para aplicar esta estrategia es necesario que la solución de GipsyX sea leída por GLOBK, es decir, es necesario convertir los archivos *gdcov* de GipsyX a archivos SINEX, y un nuevo programa llamado *gdcov2sinex* se ha creado específicamente para ello, ya que el programa del JPL que realiza la conversión no funciona para un usuario ajeno a esta institución. Gracias al programa creado, cualquier usuario podrá aplicar la estrategia seguida.

Cabe destacar que durante el diseño de la estrategia de procesado más adecuada para esta tesis, se detectó un error en GipsyX que fue puesto en conocimiento del Jet Propulsion Laboratory de la NASA. Este error es del orden de mm, principalmente en la vertical, y afecta a los RINEX2 de estaciones que, además del sistema GPS, registran el ruso GLONASS (Global'naya Navigatsionnaya Sputnikovaya Sistema). El 17 de junio de 2021 el JPL anunció oficialmente la identificación de este error, y que sobre un procesamiento PPP de 679 estaciones permitió corregir 201 de ellas con un cambio promedio de 2.3 mm en sus posiciones 3D.

En la estrategia de procesado se ha usado un enfoque en tres pasos usual en el procesamiento con GAMIT/GLOBK: en el primer paso se obtienen estimaciones libremente constreñidas de coordenadas de estaciones y covarianzas; en el segundo paso se generan series temporales en un marco consistente con las estaciones CORS; y en el tercer paso todos los datos son combinados en una solución individual aplicando constreñimientos generalizados en posición y velocidad para definir un marco de referencia uniforme a la vez que estima los parámetros Helmert a la red en conjunto. Este procedimiento general se ha llevado a cabo con GAMIT, GipsyX y su combinación (excepto el primer paso), resultando tres estrategias y correspondiendo la solución velocidad final a la Combinada.

En la estrategia GAMIT se han procesado simultáneamente 25 estaciones Topo-Iberia y 15 CORS mediante la técnica de doble diferenciación. La resolución de ambigüedades ha sido satisfactoriamente resuelta (fijada) con una media del 96.1 % para wide-lane (WL) y 92.8 % para narrow-lane (NL), y un NRMS medio de 0.18, lo cual es un indicador de la calidad de las soluciones. En la estrategia de GipsyX se han procesado separadamente cada una de las 40 estaciones mediante la técnica PPP. En este caso la resolución de ambigüedades fue del 99.8 % para todos los RINEX. Las dos estrategias han tenido en común algunos modelos y parámetros de procesamiento.

Con el fin de obtener un campo de velocidad lo más preciso posible, sobre todo teniendo en cuenta la componente vertical, se realizaron algunos cambios en la configuración por defecto del software de procesamiento dentro de las posibles opciones que permite, entre otros: se aplicaron correcciones ionosféricas de segundo y tercer orden de los archivos IONEX (Ionosphere Map Exchange); se usó el modelo VMF1 (Vienna Mapping Function) que proporciona una reconstrucción más precisa del modelo meteorológico numérico (NWM) para modelar y estimar el retardo atmosférico; se usó también el grid VMF1 que era la fuente disponible más precisa para el retraso hidrostático cenital (ZHD) a priori; se estimaron los retrasos cenitales cada 2 horas a pesar del gran incremento del tiempo de computación y de la pequeña mejora en la precisión de la altura de las estaciones; y respecto al modelo de carga oceánica se eligió el modelo FES2014b incluyendo correcciones para el movimiento del centro de masas, en concreto se optó por un listado de coeficientes de desplazamiento de carga oceánica específicos para cada estación y no un grid.

Las soluciones libremente constreñidas previamente obtenidas con GAMIT y GipsyX se han procesado individualmente en GLOBK para generar las series temporales brutas de posiciones GPS de cada estación en el marco de referencia IGB14 (No-Net-Rotation). Estas series temporales se han analizado para estimar y eliminar valores atípicos, señales periódicas (anual y semianual) y discontinuidades en un proceso iterativo. Se elimina cualquier posición estimada cuya incertidumbre sea mayor de 2, 2 y 3 cm en las componentes este, norte y vertical, respectivamente, así como los puntos que excedan el valor 2-sigma después de eliminar la tendencia. El análisis se ha realizado con el programa de GLOBK *tsfit*, una herramienta de línea de comandos para ajustar series temporales y generar estadísticas, y el programa interactivo *tsview* basado en MATLAB (Herring 2003). Los archivos generados con *tsfit/tsview* que contienen valores atípicos, discontinuidades y señales periódicas se introducen nuevamente en GLOBK para obtener una solución combinada y extraer posiciones y velocidades más refinadas. Finalmente, se ha asumido que el ruido en la serie temporal es una combinación de ruido blanco más ruido de paseo aleatorio (RW), que se ha tenido en cuenta aplicando en el procesamiento final el algoritmo *realistic-sigma* (Herring et al. 2015; Floyd y Herring 2020).

Análisis de resultados e interpretación geodinámica

Aunque el objetivo fundamental es determinar con precisión las velocidades actuales de las estaciones Topo-Iberia, la estrategia de procesamiento ha tenido un papel relevante y, por consiguiente, también el análisis de los resultados obtenidos con las diferentes estrategias (GAMIT, GipsyX y Combinada). Atendiendo a las series temporales de posiciones obtenidas con las tres estrategias, el valor medio cuadrático ponderado (WRMS) se encuentra en un rango de 0.6–0.7 mm en las componentes norte y este, y de 2.0–2.1 mm en la componente vertical, indicando buena repetibilidad. Atendiendo a las soluciones de velocidad final obtenidas con cada estrategia, su

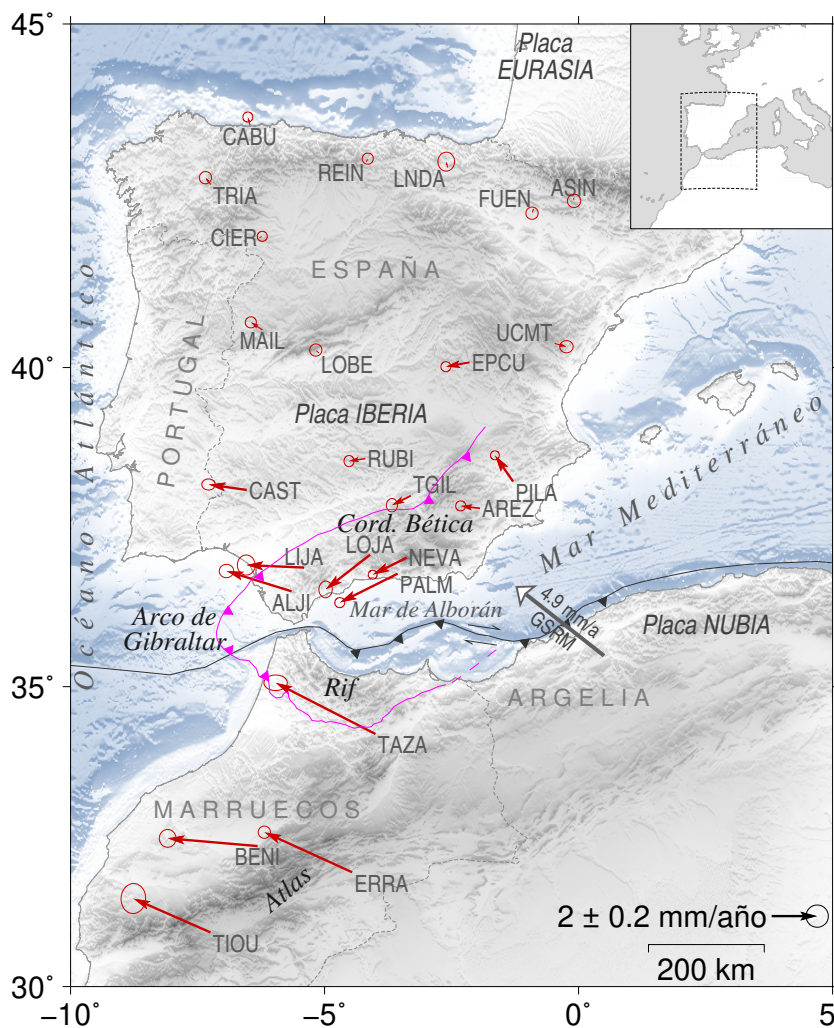


Fig. 5.1 Mapa de nuevas velocidades horizontales (intervalo de confianza del 95 %) de la red CGPS Topo-Iberia en un marco de referencia con Eurasia fijada. Las líneas magenta y negra representan respectivamente la zona de deformación Bético-Rifeña y el hipotético límite de placas Eurasia-Nubia. El vector gris representa la dirección de convergencia y velocidad entre las placas según el modelo GSRM v2.1

concordancia en general también es muy buena, siendo el RMS de sus diferencias <0.2 mm/año en la componente horizontal y <0.3 mm/año en la componente vertical. No obstante, comparando las estimaciones de velocidad de las estrategias GAMIT y Combinada, el RMS decrece a <0.1 mm/año en las componentes horizontal y vertical. La incertidumbre promedio de la velocidad horizontal es de 0.1 mm/año para las tres estrategias. La solución velocidad horizontal Combinada se presenta como el nuevo campo de velocidad horizontal GPS de la red Topo-Iberia basado en 11 años (2008–2019) (Figs. 5.1–5.2). Las velocidades verticales son bajas en general para las tres estrategias con un valor absoluto medio de 0.5 mm/año e incertidumbre media de 0.2 mm/año. También se ha observado en las tres estrategias una tendencia decreciente de la incertidumbre conforme aumenta el intervalo de datos procesado. La solución velocidad vertical Combinada se presenta como el primer campo de velocidad vertical GPS de la red Topo-Iberia (Fig. 5.3).

Para evaluar el grado de coincidencia entre las soluciones de GAMIT y GipsyX se hizo una comparación entre ambas estimando y sin estimar translación en GLOBK. Estimándose, que es lo usual, se observan discrepancias en la dirección de los vectores velocidad que podrían interpre-

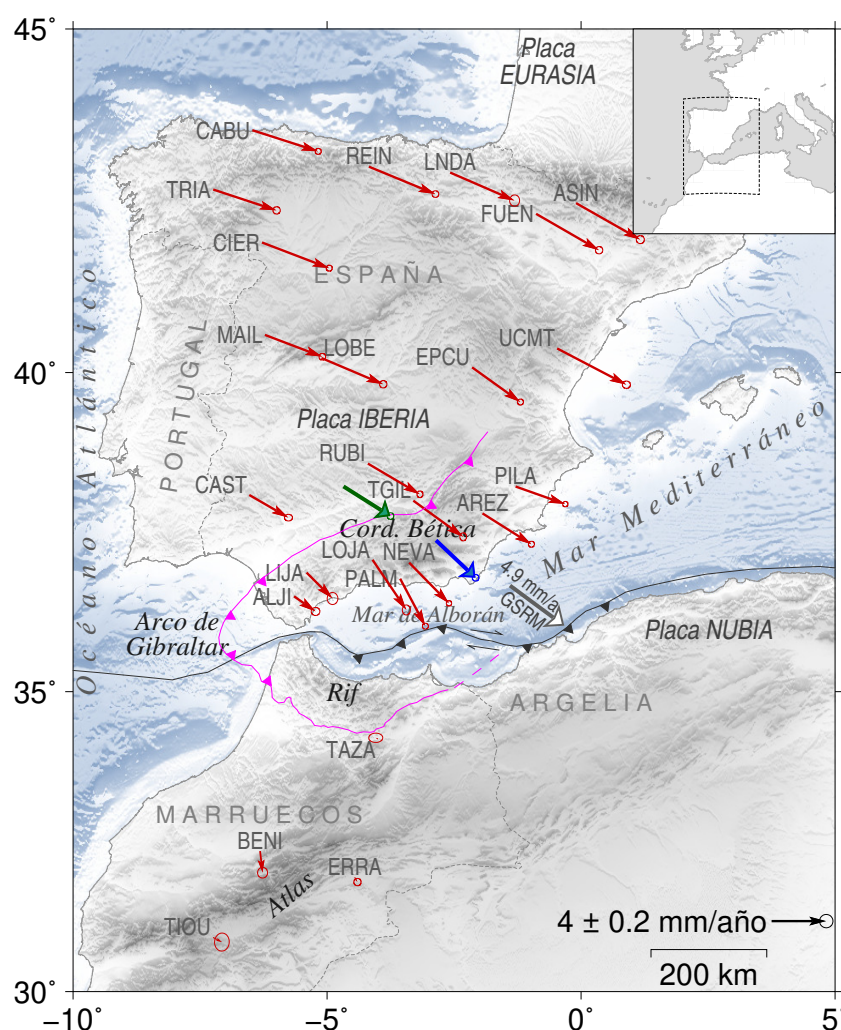


Fig. 5.2 Mapa de nuevas velocidades horizontales (intervalo de confianza del 95 %) de la red CGPS Topo-Iberia en un marco de referencia con Nubia fijada. Las líneas magenta y negra representan respectivamente la zona de deformación Bético-Rifeña y el hipotético límite de placas Eurasia-Nubia. El vector gris representa la dirección de convergencia y velocidad entre las placas según el modelo GSRM v2.1. Los vectores azul y verde representan respectivamente la dirección de convergencia y velocidad media en los sectores central y oriental de las Béticas, y en el antepaís próximo a partir de las nuevas velocidades

tarse como una ligera rotación de una solución con respecto a la otra. En el caso de no estimarla (*sólo con propósito de comparación*), el solape de ambas soluciones velocidad es notable siendo el RMS de sus diferencias 0.08 y 0.07 mm/año en las componentes norte y este, respectivamente. Las discrepancias encontradas podrían estar relacionadas con los diferentes efectos que se producen en ambas soluciones velocidad al estimar la translación, ya que los archivos SINEX de GipsyX creados no contienen información sobre parámetros de orientación terrestre (EOP) y, por tanto, no les afecta dicha estimación a menos que sean combinados con la solución de GAMIT que sí contiene EOP válidos.

Las nuevas velocidades horizontales realizadas en el marco IGB14 concuerdan en general con las velocidades publicadas por Garate et al. (2015). Los menores desplazamientos residuales respecto a Eurasia se observan en el norte de la placa Iberia en el rango de 0.1–1.1 mm/año. Las estaciones con los mayores desplazamientos son las desplegadas en Marruecos y ubicadas en la placa Nubia, mostrando desplazamientos generales hacia el noroeste en el rango de 3.7–4.9 mm/año. Las principales diferencias se hallan en la Cordillera Bética, concretamente en las estaciones ALJI, LIJA, LOJA y NEVA, situadas en la zona de deformación Bético-Rifeña. Las

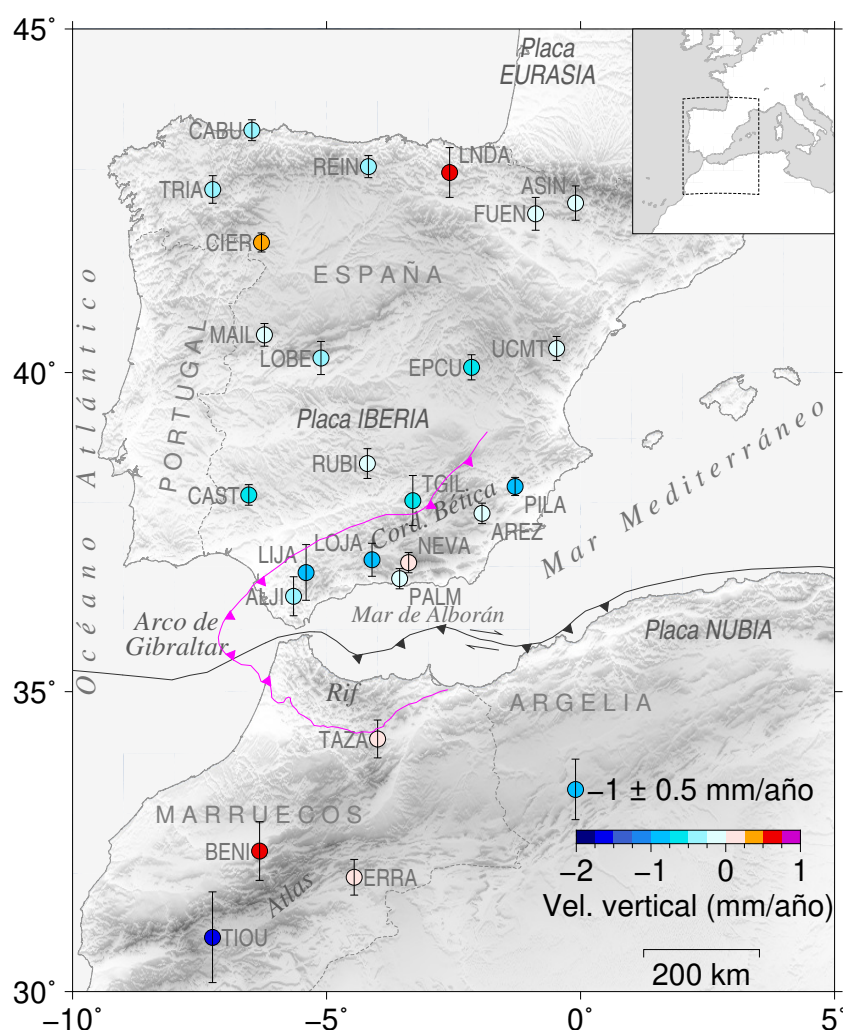


Fig. 5.3 Mapa de nuevas velocidades verticales de la red CGPS Topo-Iberia. Los valores positivos y negativos corresponden respectivamente a levantamiento y subsidencia. Las incertidumbres 1σ están representadas por barras de error verticales. Las líneas magenta y negra representan respectivamente la zona de deformación Bético-Rifeña y el hipotético límite de placas Eurasia-Nubia

estaciones NEVA y LOJA muestran una mayor componente hacia el suroeste en lugar del movimiento puramente hacia el oeste mostrado en Garate et al. (2015), y junto con PALM se integran perfectamente con otras estaciones de su alrededor pertenecientes al campo de velocidad de Koulali et al. (2011). Los desplazamientos en la Cordillera Bética occidental también muestran movimientos hacia el oeste como en anteriores publicaciones (Garate et al. 2015; Gonzalez-Castillo et al. 2015), pero en este caso la estación ALJI muestra un movimiento hacia el oeste-noroeste. Este nuevo desplazamiento comparado con el campo de velocidades de Koulali et al. (2011) está en armonía con otras estaciones de su alrededor, siendo aún más evidente con respecto a Nubia. Los nuevos resultados permitirían corroborar hipótesis tectónicas previamente publicadas (Balaný et al. 2007; Gonzalez-Castillo et al. 2015), en las que la deformación en la parte externa del arco de Gibraltar tiene una tendencia radial y en el interior existe una compleja relación entre extensión y la influencia de un hipotético *indenter* tectónico (Galindo-Zaldívar et al. 2022). Se ha determinado la dirección de convergencia y velocidad media con respecto a Nubia a partir de las velocidades de las estaciones Topo-Iberia de la mitad sur de la península ibérica. Considerando la complejidad tectónica presente en esta zona, se ha determinado una tasa de convergencia

noroeste-sureste de 4 mm/año para los sectores central y oriental de las Béticas (vector azul en Fig. 5.2), y de 4.1 mm/año para el antepaís próximo, franja más estable de esta región de la placa Eurasia (vector verde).

Con respecto al campo de velocidad vertical, además de las mayores incertidumbres asociadas a esta componente, la densidad de la red utilizada en este trabajo, aunque cubre el área de estudio, no permite establecer tasas de subsidencia o levantamiento con confianza para toda la península ibérica y Marruecos. Coincidiendo con previas publicaciones, se observa una subsidencia generalizada en la península ibérica (valor medio de 0.5 ± 0.1 mm/año) excepto en algunas estaciones aisladas que presentan levantamiento, como BENI y LNDA. En el sur de la península ibérica se localiza una velocidad media de subsidencia de 0.6 ± 0.1 mm/año, aproximándose a cero cerca del sur de los Pirineos coincidiendo con Serpelloni et al. (2013). Aunque la estación NEVA presenta un levantamiento absoluto de 0.2 ± 0.2 mm/año, su movimiento relativo será considerablemente mayor al encontrarse situada dentro de esta zona de subsidencia. Los índices de velocidad cercanos a cero en los Pirineos también coinciden con los presentados por Nguyen et al. (2016), donde existen cuatro estaciones en común y la velocidad estimada coincide en dos de ellas (LNDA y FUEN), lo que podría confirmar el levantamiento en la estación LNDA (0.6 ± 0.4 mm/año).

5.2 Evaluación de la calidad

Calidad de las estaciones y datos GPS

La calidad de todos los datos GPS Topo-Iberia que estaban disponibles el 11 de febrero de 2020, un total de 77506 archivos RINEX (Receiver Independent Exchange), se ha evaluado con el programa TEQC (Estey y Meertens 1999). La presencia de obstáculos que pudieran impedir la recepción de la señal GPS en las estaciones se ha evaluado usando el programa QC2Sky (Roggero 2010). Con este programa se han creado gráficos del cielo en función de la elevación y azimut del satélite en el momento de la observación para cada una de las estaciones. Según los resultados, el horizonte de oclusión está por debajo de 10° no existiendo obstáculos importantes excepto en el caso de las estaciones ALJI, LIJA, NEVA, PALM y TIOU. Aun así, estas cinco estaciones tienen un horizonte lo suficientemente amplio como para registrar las observaciones necesarias.

El indicador de la intensidad de señal GNSS establecido en los archivos RINEX como umbral para un buen seguimiento de la señal es 5, correspondiendo a una relación ruido-señal (SNR) de 30–35 dBHz (Romero 2020). Todas las estaciones Topo-Iberia, excepto EPCU y UCMT, han mostrado una intensidad de señal media en L1 (SNR1) en el rango de 44–47 dBHz (indicador 7), es decir, está por encima del umbral de una buena SNR. La SNR1 media en las estaciones EPCU y UCMT es ~ 6 dBHz, aunque aumentó en la estación EPCU manteniéndose estable desde

2015. Un valor SNR alto indica una señal fuerte, pero un valor SNR bajo indica una señal débil o cercana al nivel de ruido y puede ser difícil de rastrear para el receptor (Bilich 2006). El bajo valor SNR en la estación UCMT se debe presumiblemente a que la antena está instalada a pocos metros de una antena parabólica VSAT (terminal de apertura muy pequeña) que aumenta el nivel de ruido. En cambio, la antena de la estación EPCU está instalada en un campus universitario, un entorno que podría estar afectado temporalmente de la misma manera. En general el horizonte de oclusión se ha mantenido estable a lo largo del tiempo excepto en las estaciones CIER, EPCU, LOBE y TGIL, siendo más notable en las dos últimas. Estos cambios se han relacionado con alteraciones en los parámetros de la calidad analizados a continuación.

La información resultante del control de calidad de los datos GPS se ha utilizado en diferentes etapas de la tesis. Cuando se seleccionaron los datos para su procesamiento se tuvo en cuenta el efecto de las señales periódicas en la estimación de velocidades establecido por Blewitt y Lavallée (2002), seleccionando tramos de años enteros más medio año y mayores de 4.5 años, de modo que la afectación fuese la menor posible. Los tramos de datos disponibles se acortaron eliminando prioritariamente los periodos con archivos incompletos o de pobre calidad que gracias al control de calidad son fácilmente identificables. Esta información se ha ofrecido mediante gráficas históricas (periodo completo de actividad) de la calidad de los datos para todas las estaciones Topo-Iberia, que debido a su elevado número se proporcionaron como material suplementario del trabajo publicado. También se han generado todas las gráficas anuales (253) que han sido alojadas en la plataforma Zenodo (García-Armenteros 2023), pero pueden consultarse en https://blogs.ujaen.es/jgarmen/topo-iberia_data_quality. Las gráficas contienen los parámetros o indicadores de la calidad obtenidos con TEQC en los cuales se basa el control de calidad (OBS, INT, CSR, MP1 y MP2).

Para analizar la calidad de los datos también se han calculado estadísticos básicos de los indicadores de calidad con los que se han realizado tres análisis:

- *Análisis basado en la mediana.* En relación al indicador INT, spepeólo las estaciones EPCU y TIOU no cumplen con el valor recomendado por el IGS (95 %), aunque con valores muy cercanos, 94 % y 93 % respectivamente. En cuanto a los saltos de ciclo, 6 estaciones no cumplen el valor recomendado (1 CSR), incluyendo nuevamente a EPCU y TIOU. El peor resultado corresponde a la estación ALJI que presenta valores elevados durante casi la mitad de su periodo de actividad por causas desconocidas. En cuanto al indicador MP1, 8 estaciones no cumplen con el valor recomendado (0.3 m) y nuevamente ALJI es la estación con la mediana más alta. La estación NEVA tampoco lo cumple, mostrando, sin embargo, buenos resultados en el resto de indicadores a lo largo de su periodo de actividad con incrementos en los periodos invernales que se han relacionado con la cubierta de nieve (García-Armenteros 2020).
- *Análisis basado en el porcentaje de cumplimiento.* Considerando el nivel de porcentaje de

cumplimiento de cada indicador respecto de los umbrales de calidad para cada estación. Si se consideraran todos los indicadores en conjunto para una estación, el porcentaje medio de cumplimiento nos proporciona una medida de su calidad total. De este modo, las dos peores estaciones son TIOU y EPCU con menos del 2 % de cumplimiento seguidas de ALJI con el 21 %.

- *Análisis basado en un criterio discreto de cumplimiento.* Habiendo sólo dos valores posibles, 1 (cumple el umbral de calidad) y 0 (no lo cumple), y considerando además que una estación cumple el umbral de calidad para un indicador si el porcentaje de cumplimiento de todos sus datos es $>95\%$, los resultados indican que 4 estaciones (FUEN, PALM, PILA y TRIA) cumplen las recomendaciones para ser una estación del IGS relativo a los parámetros considerados en este trabajo (INT, CSR, MP1 y MP2), y 5 estaciones (ALJI, EPCU, LOBE, TGIL y TIOU) no lo cumplen en ningún parámetro.

Entre las estaciones que no cumplen ningún indicador de calidad en el umbral REC, destacan EPCU y LOBE por cumplir todos los indicadores en los demás umbrales de calidad. La estación LOBE, situada en el Parque Regional de la Sierra de Gredos, inició su periodo de actividad con todos los parámetros de calidad dentro del umbral REC, excepto el parámetro MP2, empeorando progresivamente de forma similar a la estación TGIL. En otras estaciones ubicadas en entornos naturales o con árboles cercanos, como el caso de TGIL, este aumento progresivo y constante de los saltos de ciclo y del efecto multitrayectoria se ha relacionado con cambios en el entorno de la antena, como el crecimiento de la vegetación (Pirti 2008; Uzodinma y Nwafor 2018; García-Armenteros 2020). Además, si este crecimiento también se produce junto al panel solar, podría crear sombra sobre él. La estación LOBE está rodeada de árboles e inicialmente mostró un horizonte de oclusión por debajo de 10° , pero se ha comprobado que su línea del horizonte aumentó en elevación en algunas zonas. El aumento de la frondosidad de los árboles no tiene que ser necesariamente causa de una nueva línea del horizonte por oclusión total de la señal GPS, sino que es más factible el aumento del número de saltos de ciclo en elevaciones cada vez más altas, como ha podido observarse. También se ha observado una progresiva reducción en el número de observaciones registradas y en el valor de la integridad con descensos notables en periodos invernales. Este comportamiento fue asociado en otras estaciones, como PALM, con problemas de bajo rendimiento de batería. La adición del aumento de horas de sombra sobre el panel solar, y las pocas horas de sol disponibles en estos periodos invernales para recargar las baterías, provocaría una reducción del tiempo de funcionamiento del receptor, y en ocasiones fallos de funcionamiento, como presumiblemente ocurrió en la estación TGIL. La estación EPCU también está situada entre árboles mostrando un comportamiento similar a la estación LOBE, aunque sin empeorar en periodos invernales.

Efectos de la calidad

Para evaluar los efectos de la calidad de los datos GPS en los residuales de fase, se ha analizado en particular el RMS post-ajuste de los residuales de fase LC de cada solución diaria de GAMIT para las dos mejores y dos peores estaciones Topo-Iberia, es decir, las dos estaciones con el más bajo y alto valor RMS, respectivamente, obteniendo los siguientes resultados:

- Comparando los resultados con los obtenidos en el *análisis basado en la mediana*, las peores estaciones en las soluciones de GAMIT (RMS post-ajuste más alto) (TGIL, LOBE, ALJI, CIER, EPCU y TIOU) se encuentran entre las estaciones que presentan peor calidad. Del mismo modo, las mejores estaciones (RMS post-ajuste más bajo) también se encuentran entre las que mejor calidad presentan. Comparando con los resultados del *análisis basado en porcentaje de cumplimiento*, el grupo de peores estaciones también corresponde casi en su totalidad a las estaciones que muestran bajos porcentajes de cumplimiento del umbral de calidad recomendando. Y finalmente, comparando con los resultados del *análisis basado en el criterio discreto de cumplimiento*, este grupo de peores estaciones, excepto CIER, coincide exactamente con las 5 estaciones que no alcanzan el umbral recomendado en ningún indicador de calidad. Además, 3 estaciones (PALM, PILA y TRIA), que cumplen los requisitos para convertirse en una estación IGS respecto a los indicadores de calidad considerados, se encuentran entre las mejores estaciones en las soluciones diarias de GAMIT. Los resultados revelan una relación inversamente proporcional entre la calidad de los datos GPS y los residuales de fase LC post-ajuste. Una baja calidad de los datos, es decir, valores bajos en integridad y valores altos en saltos de ciclo y efecto multitrayectoria, corresponde a un alto RMS post-ajuste de los residuales de fase LC en las soluciones GAMIT. Los resultados obtenidos usando GipsyX confirman esta relación.
- Por otro lado, dentro del grupo de las peores estaciones se encuentran las 4 estaciones (CIER, EPCU, LOBE y TGIL) que mostraron cambios en el horizonte de oclusión, es decir, un aumento en la elevación de la línea del horizonte. Se ha observado que la variación en el tiempo de sus residuales de fase es muy similar en las cuatro estaciones, mostrando en general un incremento progresivo. Comparando la evolución de los parámetros de calidad MP1 y CSR con la de los residuales de fase se observa un cierto sincronismo, más evidente en el caso de los saltos de ciclo. En este trabajo los cambios en el horizonte de oclusión no se han definido expresamente como un indicador de calidad, pero presumiblemente los cambios en el entorno de la antena, como el crecimiento de los árboles cercanos, el aumento de la frondosidad y otros obstáculos físicos, provocan la degradación del seguimiento de la señal en bajas elevaciones que implica la elevación de la línea del horizonte y el aumento de los saltos de ciclo, efecto multitrayectoria y la dispersión o ruido.

Caracterización de la calidad

De los tres análisis realizados, el basado en el estadístico mediana tiene el inconveniente de que proporciona información de la calidad sólo del 50 % de los datos, y los restantes podrían presentar un grave deterioro, lo que daría una falsa sensación de calidad. En cambio, las estaciones con problemas son evidentes utilizando el análisis basado en el porcentaje de cumplimiento, y aún más considerando en conjunto todos los indicadores proporcionando una visión general de su calidad. El análisis basado en el criterio discreto de cumplimiento, además de mostrar la calidad de los datos, determina qué estaciones cumplen los requisitos de calidad para convertirse en una estación IGS. Las estaciones que presentan mala calidad o cambios en el entorno de la antena también son fácilmente identificables debido al carácter restrictivo de este análisis, y se ha encontrado que la mayoría de estas estaciones no cumplen ningún indicador de calidad en el umbral de calidad recomendado.

Según los resultados obtenidos de la red CGPS Topo-Iberia, las estaciones que tienen un porcentaje medio total de cumplimiento ≥ 98 % cumplen los requisitos de calidad para ser una estación IGS. Las estaciones cuyo porcentaje de cumplimiento está por encima del 50 % tienen una calidad aceptable, aumentando proporcionalmente con el porcentaje. Por debajo de este nivel o porcentaje de cumplimiento se puede considerar que las estaciones son problemáticas o presentan datos de mala calidad, correspondiendo a un alto RMS post-ajuste de los residuales de fase. El límite establecido en 50 % se debe de tomar como orientativo, por lo que valores próximos indican que, aún pudiendo ser su calidad aceptable, los datos deberían de analizarse más detalladamente para evaluar su uso e identificar las posibles causas de su nivel de calidad.

Considerando todo lo anterior, un método adecuado para caracterizar la calidad de los datos sería la combinación de estos dos últimos análisis. Mediante el análisis basado en el porcentaje de cumplimiento se puede establecer la calidad total de los datos, así como las estaciones cuyos resultados pueden no ser confiables y requerirían especial atención en el posterior análisis de series temporales. Utilizando el análisis basado en el criterio discreto de cumplimiento, se identifican fácilmente las estaciones con problemas y las estaciones que cumplen con los requisitos para convertirse en una estación IGS. En este sentido sería útil que el IGS estableciera también los porcentajes de cumplimiento adecuados, y no sólo el valor umbral individual de calidad. Actualmente EUREF, además de las gráficas de calidad de las estaciones de la red EPN, también proporciona el porcentaje de la calidad de los datos calculados en base al número de observaciones registradas con respecto a las esperadas (INT), pero no proporciona el porcentaje de la calidad total considerando los parámetros en conjunto. Esta información sería útil a los usuarios ayudando a seleccionar las estaciones por su calidad más rápido que en base a la consulta de sus gráficas de calidad.

Efectos del entorno de antena

Se han representado los residuales de fase LC promediados dependientes del ángulo de elevación (elmean) obtenidos en el procesamiento GPS con GAMIT, y en función del patrón o forma de la onda resultante se han establecido cinco tipos de patrón en los cuales son agrupadas las estaciones Topo-Iberia:

- *Grupo 1* (ASIN). El trazo del patrón resultante es estrecho y no hay áreas que destaquen por presentar residuales notables. La antena está instalada en terreno irregular con densa cubierta vegetal (pequeños matorrales tupidos) resultando un buen entorno dispersivo. La estación ASIN presenta los residuos de fase elmean más bajos (RMS medio de 0.57 mm).
- *Grupo 2* (FUEN, LNDA, LOBE, PALM, PILA, REIN, RUBI, TGIL y TRIA). Los residuales de fase elmean son bajos y el patrón es estrecho también, pero en este caso los residuales más altos ocurren en ángulos de elevación bajos $\sim (0^\circ-20^\circ)$ con un patrón bien definido coincidiendo con la presencia de una pequeña superficie, más o menos plana, o con un afloramiento rocoso alrededor de la antena que favorece el efecto multitrayectoria. La antena está instalada en terreno irregular con diferentes tipos de cubierta vegetal.
- *Grupo 3* (ALJI, AREZ, CAST, LIJA, LOJA y UCMT). Los residuales de fase son mayores y se distribuyen a lo largo de todo el rango de ángulos de elevación. Es destacable la presencia de terrenos rocosos combinados con diferentes tipos de cubierta vegetal.
- *Grupo 4* (CABU, CIER, EPCU, MAIL y NEVA). En el patrón se distinguen claramente dos áreas. La zona de bajos ángulos de elevación $\sim (0^\circ-20^\circ)$ destaca por presentar los mayores residuales de fase en un patrón bien definido. Considerando en esta zona el trazo como una onda, se puede decir que tiene mayor frecuencia y amplitud que el grupo 2. El área restante muestra valores bajos en los residuales de fase similares a los vistos en los grupos 1 y 2. Las estaciones tienen en común que la antena está ubicada en grandes superficies planas y uniformes, con gran parte del área alrededor de la antena libre de obstáculos. El efecto multitrayectoria asociado con este entorno específico es probablemente la causa de la mayor frecuencia y amplitud mencionadas. El suelo herbáceo uniforme, escasa vegetación o sin cubierta vegetal, según el caso, hace que el patrón restante presente residuales de fase bajos. Un caso particular en este grupo es la estación NEVA que muestra un patrón variable en el tiempo en función de si el suelo está cubierto o no de nieve, así como por los diferentes espesores de nieve.
- *Grupo 5* (BENI, ERRA y TAZA). El patrón muestra los residuos de fase elmean más altos, siendo en algunos casos superiores a 10 mm. Considerando la forma de onda, y comparándola con la del grupo 4, la frecuencia es menor pero la amplitud aumenta considerablemente en la zona de ángulos de elevación $\sim (0^\circ-30^\circ)$. Las estaciones tienen en común que

la antena está instalada en tejados planos de edificios, un entorno muy poco dispersivo. La estación BENI destaca por presentar los residuos de fase elmean más altos (RMS medio de 3.1 mm).

En general, el RMS medio anual de los residuales de fase elmean para cada una de las estaciones ha resultado bajo (mediana de 0.9 mm). Se ha observado que las estaciones agrupadas según el tipo de patrón tienen valores RMS muy similares, aunque el RMS es variable dentro de un mismo grupo en los valores intermedios. Por consiguiente, es posible asociar cada grupo con un rango específico de RMS medio de residual de fase elmean o, al menos, establecer el tipo de patrón con el valor RMS más bajo y más alto que corresponde respectivamente al mejor y peor entorno de la antena. El mejor grupo o tipo de patrón con menor valor RMS corresponde al grupo 1 (ASIN), seguido del grupo 2 a excepción de las estaciones TGIL y LOBE. En los grupos 3 y 4 no hay tanta homogeneidad, pero en conjunto el grupo 3 presenta un valor RMS inferior al grupo 4. Y por último, el grupo 5 (antena en tejado plano de edificio) destaca por presentar los valores RMS más altos. La estación TIOU no se ha considerado representativa de ningún grupo, ni su patrón característico de ningún entorno de la antena debido a que no ha sido posible analizarla adecuadamente por la mala calidad de sus datos y la falta de información.

Se ha creado un diagrama de tipos de patrón de residuales de fase elmean en función del tipo de cubierta vegetal y de la extensión de superficie plana alrededor de la antena, en combinación con la presencia de suelo rocoso. Este diagrama está basado en las características del entorno de la antena observadas en las estaciones Topo-Iberia, pero podría ser útil para seleccionar el entorno óptimo para una antena GNSS.

Los efectos del entorno de antena sobre los residuales de fase elmean se han analizado conjuntamente con la calidad de los datos, y se han encontrado las siguientes correlaciones:

- Todas las estaciones que cumplen con los requisitos para ser una estación IGS (FUEN, PALM, PILA y TRIA) se encuentran entre las que han mostrado el RMS de residuales de fase elmean más bajo y pertenecen al grupo 2. La estación ASIN, cuyo tipo de patrón presenta el RMS de los residuales de fase elmean más bajo, es también la estación con el RMS post-ajuste más bajo.
- Los altos residuales de fase elmean del grupo 5 (antena en tejado plano de edificio), presumiblemente relacionados con el efecto multitrayectoria, pueden hacernos pensar que la calidad de sus datos es mala en relación a este parámetro, pero en realidad cumplen con el umbral del IGS. Por el contrario, no cumplen el umbral para los saltos de ciclo. Este comportamiento de la antena está asociado con un entorno de alta interferencia y mala recepción de señal, como son las áreas urbanas, en las cuales los saltos de ciclo pueden ser causados por edificios, efecto multitrayectoria o satélites a baja elevación, entre otros (Hofmann-Wellenhof et al. [1993](#)).

- Por otro lado, se ha observado que los patrones de algunas estaciones son más anchos y peor definidos que en otras. Esto se debe a que cada año se ha generado un patrón ligeramente diferente y, por consiguiente, no existe una gran superposición en la combinación de todos ellos. Además, se observa en estos patrones un incremento general del RMS. Para determinar con precisión el nivel de superposición, o de similitud, entre patrones anuales consecutivos se ha usado una nueva métrica propuesta en esta tesis, el índice de diferencia de patrones de residuales de fase (PRPDI). El PRPDI medio de las estaciones cuyos patrones han mostrado el nivel de similitud más alto y más bajo es ~ 0.5 y ~ 1 mm, respectivamente. Un valor cercano a 1 mm corresponde a cambios notables en el patrón. Los resultados confirman claramente que los valores más altos de PRPDI corresponden a las estaciones que muestran patrones más anchos o peor definidos (ALJI, CIER, EPCU, LOBE y TGIL). Estas estaciones tienen en común que mostraron cambios notables o incrementos progresivos en los saltos de ciclo y efecto multitrayectoria, se encuentran entre las estaciones de peor calidad y con el RMS post-ajuste de residuales de fase más alto. Todas ellas, excepto ALJI, mostraron cambios en el horizonte de oclusión, es decir, mostraron un aumento en la elevación de la línea del horizonte, presumiblemente debido a variaciones en la cubierta vegetal (crecimiento de árboles cercanos, aumento de frondosidad, etc.). El índice PRPDI es independiente del tipo de patrón y del RMS de los residuales de fase elmean, dependiendo únicamente de los cambios en el entorno de la antena a lo largo de los años que, a su vez, provocan cambios en la calidad relacionados principalmente con el efecto multitrayectoria y los saltos de ciclo. El índice PRPDI también es sensible a los cambios del entorno producidos por los periodos nivales, como en el caso de la estación NEVA. Un valor bajo de PRPDI no debe interpretarse como indicador de buen entorno de la antena, sino más bien como indicador de entorno estable, y que la inestabilidad de las estaciones evaluadas ha provocado mala calidad de los datos.
- Las estaciones con el índice PRPDI más bajo también se encuentran entre aquellas con los RMS de los residuales de fase post-ajuste y elmean más bajos. Si bien existe una correspondencia parcial entre el PRPDI y el RMS de los residuales de fase elmean, la correspondencia entre el PRPDI y el RMS post-ajuste es mayor y directamente proporcional. Los resultados obtenidos muestran que el índice PRPDI es una buena herramienta para identificar cambios en el entorno de la antena, así como las estaciones con mejor y peor calidad de datos.

Ruido del monumento geodésico

La inestabilidad de los monumentos geodésicos debido a los diferentes medios de anclaje se considera una importante fuente de ruido y se piensa que sigue un proceso de camino aleatorio (RW) (Johnson y Agnew 1995). Se ha analizado el ruido y el valor medio cuadrático ponderado

(WRMS) de las series temporales de posiciones GPS de cada estación Topo-Iberia junto con el tipo de monumento usado. El ruido correlacionado con el tiempo se ha representado con valores HRW que son estimaciones de valores de ruido de proceso camino aleatorio en la componente horizontal equivalente, y se han encontrado las siguientes relaciones:

- Atendiendo al valor de la mediana de HRW y WRMS, las estaciones con pilares sobre lecho rocoso (altura estándar o mayor) tienen mejores resultados que las estaciones con pilares pequeños (ALJI, LIJA y LOJA). Estas tres estaciones tienen en común que pertenecen al grupo 3 previamente establecido en función del patrón de sus residuales de fase elmean, en cuyo grupo también hay estaciones con otros tipos de monumentos y mejores resultados. Por consiguiente, sus altos valores de ruido y dispersión no están relacionados con el entorno de la antena, sino con el tipo de monumento. Sería necesario disponer de este tipo de monumento con diferentes entornos de antena para verificar si la causa del ruido es una combinación de ambos o no. Estos pequeños pilares, junto con los monumentos en edificios, presentan los valores HRW más altos, siendo el mástil de acero en el tejado el que muestra la mayor dispersión WRMS. Por el contrario, el valor HRW del monumento SDBM es muy próximo al del pilar estándar y su dispersión WRMS se encuentra entre las más bajas. Se podría interpretar que este tipo de monumento es más estable que otros, pero la muestra es demasiado pequeña para confirmarlo ya que sólo existe un caso en esta categoría. No obstante, y aunque la red Topo-Iberia es un conjunto de datos pequeño, los resultados en relación a los tipos de monumentos con menor ruido coinciden con los de Herring et al. (2016), realizado sobre un conjunto de datos más amplio, y con trabajos previos como Williams et al. (2004) y Beavan (2005). Las estaciones Topo-Iberia, excepto TIOU, presentan un valor HRW inferior a $0.162 \text{ mm}^2/\text{año}$ con una mediana de $0.024 \text{ mm}^2/\text{año}$, por lo que se puede establecer que sus niveles de ruido RW son adecuados para un monumento geodésico.
- Considerando los residuales de fase elmean, se podría decir que todas las estaciones Topo-Iberia situadas en latitudes más meridionales (Marruecos) presentan los valores más elevados, pero como se ha explicado anteriormente, tienen en común el tipo de monumento (mástil de acero en tejado) a excepción de la estación TIOU. En realidad, la causa de estos altos residuales es el entorno de la antena asociado a este tipo de monumento. Por tanto, la ubicación geográfica de estas estaciones es pura coincidencia en relación con los residuales de fase elmean. Tampoco se ha encontrado relación entre la ubicación geográfica y los valores de HRW.
- La relación entre el tipo de monumento y el ruido HRW no es tan evidente como entre el tipo de monumento (mástil de acero en tejado) y los residuales de fase elmean, pero los valores HRW más altos también lo presentan estaciones con monumentos en edificios

(0.085 y 0.161 mm²/año en CAST y TAZA, respectivamente), y con pilar pequeño (0.110 mm²/año en LOJA). La estación TIOU con pilar sobre lecho rocoso muestra el mayor valor HRW (0.317 mm²/año) presumiblemente debido a anomalías de origen desconocido.

Para determinar la parte del ruido asociado a señales periódicas, el ruido estacional, se ha realizado una comparación entre las estimaciones del ruido RW considerando y sin considerar las señales estacionales (términos anual y semianual) en las series temporales de posiciones GPS, obteniendo los siguientes resultados:

- La mediana del ruido HRW estacional en las estaciones Topo-Iberia es de 0.007 mm²/año, y la mediana del ruido RW vertical estacional es de 0.012 mm²/año. Las tres estaciones con mayor afectación estacional son ALJI, TRIA y TAZA. Ignorar la estimación periódica causa un error en la velocidad final de 0.44 mm/año en la componente este de la estación ALJI y 0.24 mm/año en la componente norte de TRIA, lo cual indica que debería estimarse.
- No se ha observado relación entre el ruido estacional y la ubicación geográfica de las estaciones. Otros trabajos realizados sobre redes de cientos de estaciones que ocupan gran parte de un continente, como Herring et al. (2016) y Langbein y Svarc (2019), han identificado correlación entre el ruido y zonas geográficas con mayor o menor humedad y vegetación. La red Topo-Iberia no es densa y no existen diferencias climatológicas destacables en la zona que abarca, salvo la correspondiente a Marruecos, pero posiblemente el reducido número de estaciones instaladas en esta región y el tipo de monumento utilizado no permita identificar dicha correlación, si la hubiera.
- La relación entre el ruido estacional y el tipo de monumento tampoco está clara ya que estaciones con monumentos similares presentan valores de ruido estacional muy diferentes. A pesar de ello, considerando el ruido estacional en conjunto, algunos monumentos en tejado de edificio y pequeños pilares de hormigón muestran los valores más altos, especialmente en la componente vertical. Cabe señalar que la expansión de las edificaciones debido a variaciones de temperatura estacionales puede ser considerable en regiones con altas oscilaciones térmicas como Marruecos.
- Por otro lado, también destacan las estaciones LOBE y TGIL con un elevado ruido estacional, pero en este caso usando el pilar estándar de hormigón. En la evaluación de la calidad realizada se observó un incremento en algunos de sus parámetros de calidad, presumiblemente debido a variaciones en el entorno de la antena, lo cual resultó en un patrón de residuales de fase elmean poco definido. Por todo ello, el ruido estacional detectado en ambas estaciones podría estar más relacionado con el entorno de la antena que con el tipo de monumento utilizado. Además, se ha encontrado que la mayoría de las estaciones que presentan ruido RW vertical estacional, también presentan una clara periodicidad en sus

parámetros de calidad, especialmente en el efecto multitrayectoria y saltos de ciclo, como las estaciones ALJI, BENI, CAST, LOBE, RUBI y TGIL.

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6

Conclusiones

Se presenta una estrategia de procesamiento y combinación GPS basada en la de Herring y colaboradores, usando los programas GAMIT (doble diferenciación) y GipsyX (PPP), que se ha simplificado mediante dos modificaciones: se reescala solamente la solución de GipsyX y no la de GAMIT; y el factor de escala se determina a partir de la relación entre los sigmas de las series temporales de ambas soluciones. Mediante un filtro kalman (GLOBK) se han combinado las soluciones independientes libremente constreñidas de ambos programas, y no las soluciones velocidad individuales finales, reduciendo así la posibilidad de que datos corruptos contaminen la solución velocidad final combinada y perder precisión. Además, se presenta un nuevo programa de conversión de archivos gdcov de GipsyX a SINEX, llamado gdcov2sinex, necesario para aplicar dicha estrategia.

La solución combinada obtenida se presenta como el nuevo campo de velocidad horizontal GPS de la red Topo-Iberia basado en 11 años con una incertidumbre media (1σ) de 0.1 mm/año. Los resultados en el marco de referencia IGB14 (Eurasia fijada) coinciden en general con los obtenidos en anteriores investigaciones, excepto por algunas discrepancias en estaciones concretas de la Cordillera Bética. Las estaciones del sector central Bético presentan una mayor componente hacia el suroeste en lugar de un movimiento puramente hacia el oeste. La principal discrepancia en la Cordillera Bética occidental se observa en la estación ALJI que muestra en esta investigación un movimiento hacia el oeste-noroeste en lugar de hacia el oeste. A partir de las nuevas velocidades en los sectores central y oriental de las Béticas se ha determinado una tasa media de convergencia noroeste-sureste de 4 mm/año con respecto a Nubia en esta zona. Los nuevos resultados permiten aquilatar hipótesis tectónicas previamente publicadas, en las que la deformación en la parte externa del arco de Gibraltar tiene una tendencia radial y en el interior existe una compleja relación entre extensión y la influencia de un hipotético *indenter* tectónico. A pesar de que la red Topo-Iberia complementa las redes GNSS existentes en la región Ibérica-

Marroquí, se requeriría una mayor densificación para resolver la complejidad que presenta el orógeno Bético-Rifeño y las discrepancias en los diferentes modelos tectónicos, además de un análisis con precisiones como las propuestas en esta investigación.

También se presenta el primer campo de velocidad vertical GPS de la red Topo-Iberia que complementa los pocos trabajos que han estimado la velocidad vertical en la península ibérica y Marruecos. Se observa una baja subsidencia generalizada en la península ibérica, excepto en alguna estación aislada, como LNDA, que presenta levantamiento. En el sur de la península ibérica se localiza una velocidad media de subsidencia de 0.6 ± 0.1 mm/año, aproximándose a cero cerca de los Pirineos en concordancia con trabajos previos.

El control de calidad de los datos GPS Topo-Iberia (2008–2020) ha facilitado la selección de los tramos de datos óptimos para el procesamiento. La información obtenida sobre las 26 estaciones de la red se ofrece mediante gráficas de calidad históricas conteniendo, entre otros, los indicadores de la calidad contemplados en las directrices del IGS para las estaciones GNSS, como son los relativos a la integridad (INT), efecto multitrayectoria (MP1 y MP2) y saltos de ciclo (CSR); y tomando como principal referencia su valor umbral recomendado (REC). El análisis conjunto de la evaluación de la calidad y de los resultados del procesamiento GPS ha permitido establecer relaciones entre ellos y detectar cualidades y anomalías en las estaciones. Las conclusiones derivadas se exponen a continuación.

Las estaciones presentan un horizonte de oclusión adecuado y libre de obstáculos importantes, excepto algunas estaciones, pero su horizonte es suficiente para registrar las observaciones necesarias. La intensidad de señal media mostrada por casi la totalidad de las estaciones durante su periodo de actividad está por encima del umbral de una buena relación ruido-señal, por lo que se concluye que en general no presentan problemas en sus ubicaciones.

Tres estaciones destacan por resultar las peores en los análisis realizados sobre la calidad (Tabla 6.1). Por el contrario, cuatro estaciones cumplen los requisitos de calidad para ser una estación IGS.

Se ha determinado una relación inversamente proporcional entre la calidad de los datos GPS y los residuales de fase LC post-ajuste derivados de su procesamiento. A datos con baja calidad le corresponden altos residuales de fase post-ajuste (Tabla 6.1), lo que evidencia la importancia de la calidad para obtener resultados más precisos.

Las estaciones que muestran cambios en el horizonte de oclusión (Tabla 6.1) también presentan un aumento en los saltos de ciclo y efecto multitrayectoria, y están en el grupo de las estaciones de peor calidad y más alta dispersión RMS post-ajuste de los residuales de fase. Además, estas estaciones presentan una variación en el tiempo de los residuales de fase muy similar, sincronizada con el incremento de los saltos de ciclo y efecto multitrayectoria, todo ello producido presumiblemente por un cambio progresivo en el entorno de la antena (crecimiento de vegetación, árboles cercanos, aumento de frondosidad, etc.).

En estaciones alimentadas con batería recargada mediante panel solar se ha observado la

Tabla 6.1 Características de las estaciones Topo-Iberia que han destacado por la mala o buena calidad de sus datos en relación a las principales conclusiones de la investigación. Las estaciones están ordenadas por su porcentaje de calidad total

	TIOU	EPCU	ALJI	LOBE	TGIL	CIER	PALM	FUEN	PILA	TRIA
Cumplen REC IGS ¹							x	x	x	x
Cumplen cero REC IGS ²	x	x	x	x	x					
Peores estaciones ³	x	x	x							
Cambios en Horz. Ocl. ⁴		x		x	x	x				
Incr. de CSR y MP ⁵		x		x	x	x				
RMS post-ajuste ⁶ (mm)	15.3	10.2	9.4	9.2	8.7	9.5	6.8	7.4	6.9	6.1
RMS elmean ⁷ (mm)	3.2	1.2	1.1	1.0	0.9	1.2	0.7	0.8	0.7	0.6
PRPDI ⁸ (mm)	3.2	1.1	1.1	0.9	0.9	0.9	0.6	0.5	0.6	0.5
% de calidad total REC ⁹	1	2	21	44	48	55	98	99	99	99

¹Cumplen los requisitos de calidad recomendados para ser una estación IGS, es decir, los indicadores (INT, MP1, MP2 y CSR) cumplen el umbral REC (criterio discreto de cumplimiento)

²Ningún indicador de la calidad cumple el umbral REC

³Peores estaciones en los análisis de calidad realizados

⁴Presentan cambios en el horizonte de oclusión, aumento en la elevación de la línea del horizonte

⁵Presentan incremento en los saltos de ciclo y efecto multitrayectoria a lo largo del tiempo

⁶RMS medio post-ajuste de los residuales de fase obtenidos en el procesamiento con GAMIT

⁷RMS medio de los residuales de fase elmean obtenidos en el procesamiento con GAMIT

⁸Índice PRPDI medio. Valores ~ 0.5 y ~ 1 indican respectivamente ausencia de cambios (entorno estable) y presencia de cambios en el entorno de antena

⁹Porcentaje medio de cumplimiento considerando en conjunto los indicadores (INT, MP1, MP2 y CSR) en el umbral REC

pérdida de calidad durante períodos invernales, lo cual se ha asociado a problemas de batería y recarga que podrían agravarse si coinciden con los cambios relativos a la vegetación mencionados, pero en este caso alrededor del panel solar. Estos síntomas son muy identificables en las gráficas de calidad proporcionadas. La pérdida de datos en la estación LOBE probablemente se deba a una o ambas de estas causas.

Se propone como método para caracterizar la calidad de los datos GNSS la combinación de un análisis basado en el porcentaje de cumplimiento y de otro basado en un criterio discreto de cumplimiento. De este modo se proporciona el porcentaje de la calidad total de cada estación y se identifican fácilmente las estaciones problemáticas (porcentaje total cercano o menor de 50 %) y las que tienen la calidad para ser una estación IGS (≥ 98 %) (Tabla 6.1). Actualmente, algunos servicios GNSS proporcionan el porcentaje de calidad basado en un solo indicador, pero no en conjunto. Ofrecer el porcentaje de la calidad total ayudaría en la selección de las estaciones frente a la tradicional visualización de gráficas. Para ello sería necesario que el IGS estableciera los porcentajes adecuados de cumplimiento, y no sólo los valores umbral individuales.

Se confirma que los residuales de fase LC dependientes del ángulo de elevación (elmean) son útiles para determinar el efecto multitrayectoria asociado al entorno de antena. El patrón resultante de la traza de estos residuales se ha relacionado con las características del entorno

y se han establecido cinco tipos. Los residuales más pequeños se producen en entornos con terreno irregular y cubierta vegetal, y los más altos en tejados planos de edificios. Se presenta un diagrama de tipos de patrón que, aunque basado en las características del entorno de las estaciones Topo-Iberia, podría ser útil para seleccionar el entorno óptimo para una antena GNSS.

Las estaciones que presentan la mejor calidad también muestran bajos RMS de los residuales de fase elmean y post-ajuste (Tabla 6.1). Además, todas las estaciones con antenas situadas en tejados planos de edificios cumplen los requisitos del IGS relativos al efecto multitrayectoria a pesar de sus altos residuales de fase elmean, pero no en relación a los saltos de ciclo. Por consiguiente, se recomienda no usar este tipo de ubicación si se pretende cumplir los requisitos de calidad del IGS.

Se propone una nueva métrica para medir con precisión las diferencias entre dos patrones anuales, el índice de diferencia de patrones de residuales de fase (PRPDI). Los valores más altos de PRPDI corresponden a estaciones con patrones anchos y poco definidos, se encuentran entre las de peor calidad, con mayor RMS de los residuales de fase post-ajuste, y la mayoría muestran cambios en el horizonte de oclusión (Tabla 6.1). Por el contrario, los valores de PRPDI más bajos corresponden a estaciones con los RMS post-ajuste y elmean más bajos. El índice PRPDI es independiente del tipo de patrón y de los residuales de fase elmean, dependiendo únicamente de los cambios en el entorno de antena que, a su vez, podrían provocar cambios en la calidad de los datos. En consecuencia, este índice resulta una buena herramienta para identificar cambios en el entorno de antena, así como a las estaciones de mejor y peor calidad. Además, esta información se obtiene sin necesidad de realizar ningún control de calidad tradicional, sino a partir de los residuales de fase elmean derivados del procesamiento GNSS.

En base al ruido de proceso camino aleatorio en la componente horizontal equivalente (HRW) presente en la series temporales, se determina que el ruido de los monumentos de la red Topo-Iberia, con una mediana de $0.024 \text{ mm}^2/\text{año}$, es adecuado para un monumento geodésico. Las estaciones con pilar estándar presentan menos ruido que aquellas con pilar pequeño. Los valores más altos de ruido HRW se producen en estaciones con pilar pequeño y con monumentos en edificios, siendo el mástil sobre tejado plano el que presenta la mayor dispersión total WRMS en las series temporales. Por el contrario, el monumento reforzado de perforación corta sobre lecho rocoso (SDBM) presenta un valor HRW muy próximo al del pilar estándar, y su dispersión WRMS se encuentra entre las más bajas. Las conclusiones respecto a los tipos de monumentos menos ruidosos coinciden con las de publicaciones previas sobre un conjunto de datos más amplio. No se ha observado relación entre el ruido HRW y la ubicación geográfica de las estaciones.

Finalmente, se ha determinado que el ruido asociado a las señales periódicas, el ruido estacional, en las estaciones Topo-Iberia es en general bajo (mediana del ruido estacional HRW y RW vertical de 0.007 y $0.012 \text{ mm}^2/\text{año}$, respectivamente). Aún así, los resultados indican que las señales periódicas se deberían considerar en la estimación de velocidades. No se ha observado que el ruido estacional esté relacionado con la localización geográfica, ni con el tipo de monumento,

pero sí con el entorno de antena que presenta variaciones anuales. Además, se ha comprobado que la mayoría de las estaciones que presentan ruido RW vertical estacional también presentan una clara periodicidad en sus parámetros de calidad.

Esta investigación ofrece una cinemática 3D lo más precisa posible de la península ibérica y Marruecos a partir de la red Topo-Iberia (2008–2019) mediante una cuidadosa estrategia de procesado y combinación GPS y un control de calidad de los datos. En la estrategia se han configurado y elegido los modelos geofísicos disponibles más precisos con el fin de mejorar la estimación de la componente vertical. La evaluación de la calidad ha servido de apoyo en el procesamiento, pero a su vez los resultados del procesamiento han servido para ampliar dicha evaluación, en un proceso retroalimentado, y así comprender el comportamiento de algunas estaciones en relación a la calidad de sus datos. Este comportamiento y diversas correlaciones encontradas relativas a la calidad han permitido crear herramientas o métodos que podrían ayudar en la gestión y mantenimiento de redes GNSS. La evaluación de la calidad realizada muestra que las estaciones Topo-Iberia y sus emplazamientos son óptimos para formar una red con fines geodésicos, aunque sería necesaria su monitorización permanente para poder detectar cualquier cambio en los indicadores de la calidad o en el horizonte de oclusión, y aplicar medidas correctoras oportunas, de modo que se minimice la pérdida de datos. Además, la información generada en esta tesis sobre la calidad de las estaciones y datos Topo-Iberia complementaría la información y datos custodiados por el IGME, mejorando su usabilidad en investigaciones futuras.

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Índice de abreviaturas y acrónimos

En la mayoría se emplea la abreviatura o acrónimo anglosajón debido a su empleo más generalizado. El desarrollo está expresado en español o en *inglés* según el uso que ha tenido en la memoria.

ASCII *American standard code for information interchange*

CEACTEMA Centro de Estudios Avanzados en Ciencias de la Tierra, Energía y Medio Ambiente – *Center for Advanced Studies in Earth Sciences, Energy and Environment*

CGPS Estación GPS en funcionamiento continuo – *Continuously operating GPS station*

CNEAI Comisión Nacional Evaluadora de la Actividad Investigadora

CORS Estación de referencia de operación continua – *Continuously operating reference station*

CPL Pilar pequeño de hormigón sobre lecho rocoso – *Little concrete pillar on bedrock*

CP Pilar de hormigón sobre lecho rocoso – *Concrete pillar on bedrock*

CPR Pilar de hormigón sobre tejado de edificio – *Concrete pillar on building roof*

CSIC *Spanish National Research Council*

CSR Número de saltos de ciclo por cada 1000 observaciones – *Number of cycle slips per 1000 observations*

DD *Number of double differences*

DOY Día del año – *Day of year*

EE. UU. Estados Unidos

elmean Promedio dependiente del ángulo de elevación – *Elevation angle dependent mean*

EOP Parámetros de orientación terrestre – *Earth Orientation Parameter*

EPN *EUREF permanent GNSS network*

ES *Spain*. (Código ISO 3166-1 alfa-2)

ETRS89 *European Terrestrial Reference System 1989*

FOGMEX *First-Order Gauss–Markov Extrapolation*

GAGE *Geodetic Facility for the Advancement of Geoscience*

GLONASS *Global'naya Navigatsionnaya Sputnikovaya Sistema*

GMF *Global mapping function*

GMT *Generic Mapping Tools*

GNSS Sistema Global de Navegación por Satélite – *Global Navigation Satellite System*

GPRS *General packet radio service*

GPS Sistema de Posicionamiento Global – *Global Positioning System*

GSRM Modelo de tasa de deformación global – *Global Strain Rate Model*

HRW Ruido de proceso camino aleatorio en la componente horizontal equivalente – *Equivalent horizontal random walk noise*

IAA Instituto de Astrofísica de Andalucía

- IERS** *International Earth Rotation and Reference Systems Service*
- IGME** Instituto Geológico y Minero de España – *Spanish Geological Survey*
- IGS** Servicio Internacional GNSS – *International GNSS Service*
- INT** Integridad – *Integrity*
- IONEX** *IONosphere-map EXchange*
- ITRF** *International Terrestrial Reference Frame*
- JIF** Factor de impacto – *Journal Impact Factor*
- JPL** *Jet Propulsion Laboratory*
- LC** Combinación lineal libre de ionosfera – *Ionosphere-free linear-combination*
- MA** *Morocco*. (Código ISO 3166-1 alfa-2)
- MINECO** Ministerio de Economía, Industria y Competitividad – *Spanish Ministry of Economy, Industry and Competitiveness*
- MIT** Instituto Tecnológico de Massachusetts – *Massachusetts Institute of Technology*
- MP1** Efecto multitrayectoria en L1 – *Multipath effect on L1*
- MP2** Efecto multitrayectoria en L2 – *Multipath effect on L2*
- NL** *Narrow-lane*
- NNR** *No-net-rotation*
- NRMS** Valor medio cuadrático normalizado – *Normalized root-mean-square*
- NWM** *Numerical weather model*
- OBS** Número máximo de observaciones registradas – *Maximum number of observations recorded*
- PBO** *Plate Boundary Observatory*
- PPP** Posicionamiento de Punto Preciso – *Precise Point Positioning*
- PRPDI** Índice de diferencia de patrones de residuales de fase – *Phase residuals pattern difference index*
- qc** *Quality check*
- REC** Umbral de calidad recomendado – *Recommended quality threshold*
- RF1** *Quality threshold at more than half of the IGS stations*
- RF2** *Quality threshold at 2/3 of the IGS stations*
- RINEX** *Receiver Independent Exchange*
- RMS** Valor medio cuadrático - *Root-Mean-Square*
- ROA** Real Observatorio de la Armada – *Spanish Navy Observatory*
- RW** Camino o paseo aleatorio – *Random-Walk*
- SDBM** Monumento reforzado de perforación corta sobre lecho rocoso – *Shallow-drilled braced monument on bedrock*
- SI** *Supplementary Information*
- SINEX** *Solution Independent Exchange*
- SiTopo** Sistema de información de Topo-Iberia – *Topo-Iberia Information System*
- SMR** Mástil de acero sobre tejado de edificio – *Steel mast on building roof*
- SNR1** Relación ruido-señal en L1 – *Signal-to-noise ratio in L1*
- SNR** Relación ruido-señal – *Signal-to-noise ratio*
- SRTM** Misión Topográfica Shuttle Radar – *Shuttle Radar Topography Mission*
- Suppl.** *Supplement*

UB Universidad de Barcelona – *University of Barcelona*

UCM Universidad Complutense de Madrid – *Complutense University of Madrid*

UJA Universidad de Jaén – *University of Jaén*

UNAVCO *University Navistar Consortium*

UO Universidad de Oviedo – *University of Oviedo*

USAL Universidad de Salamanca – *University of Salamanca*

VMF *Vienna Mapping Function*

VSAT Terminal de apertura muy pequeña – *Very small-aperture terminal*

WL *Wide-lane*

WLPB *Wide-Lane Phase Bias*

WRMS Valor medio cuadrático ponderado – *Weighted root-mean-square*

ZHD *Zenith hydrostatic delay*

*Research is alive when you have new ideas
or see where others do not see*

Doctoral studies in Earth and Environmental Sciences

Thesis

3D kinematics of the Iberian Peninsula and Morocco from time series of the Topo-Iberia CGPS stations (2008–2019): quality assessment, and processing strategy



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