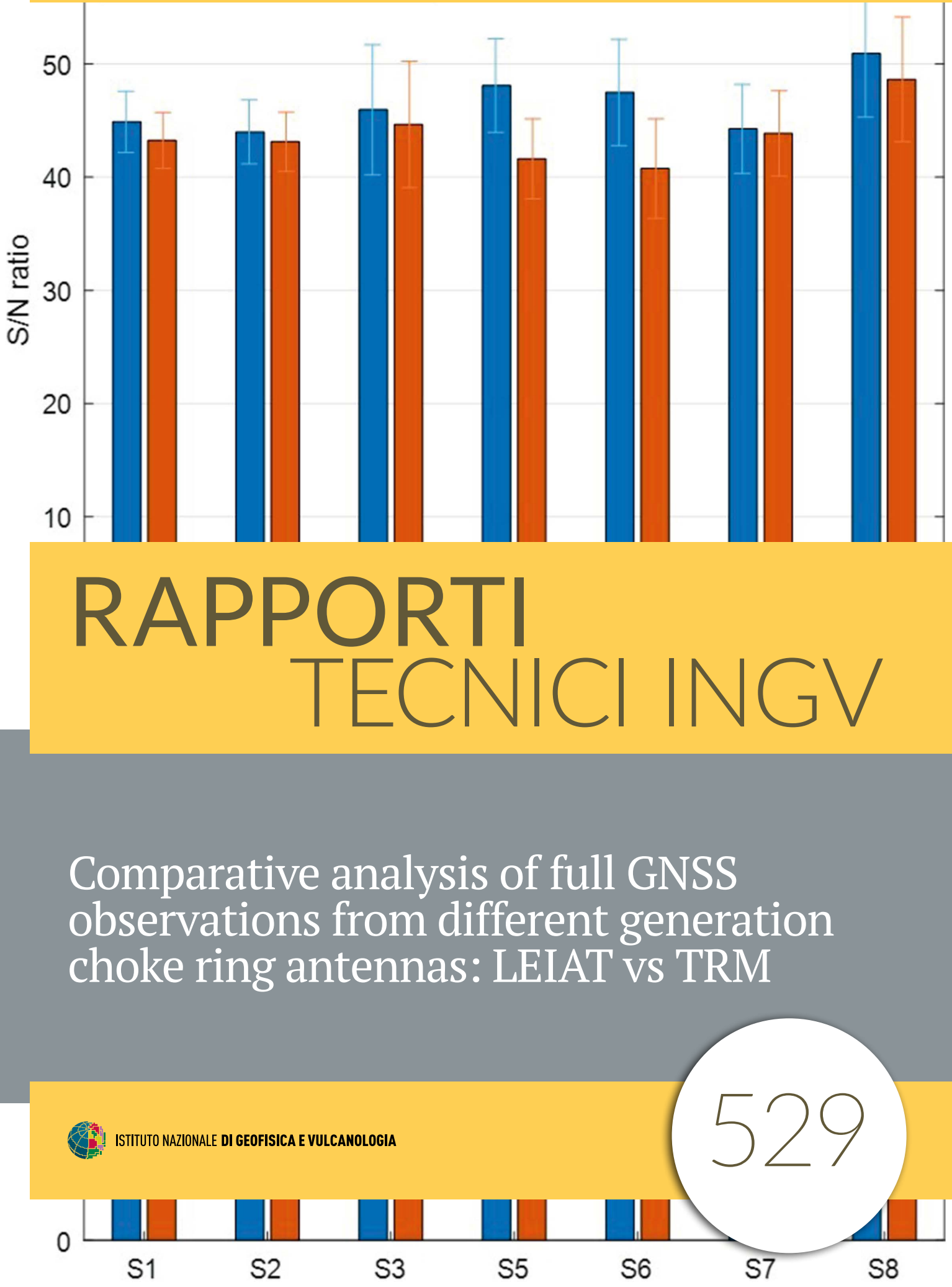
ISSN 2039-7941
anno 2026 numero 529



RAPPORTI TECNICI INGV

Comparative analysis of full GNSS observations from different generation choke ring antennas: LEIAT vs TRM

529

ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA



Direttore Responsabile
Daniela VERSACE

Editor in Chief
Milena MORETTI

Editorial Board
Laura ALFONSI
Sofia BARANELLO
Carla BARNABA
Christian BIGNAMI
Simona CARANNANTE
Maria Grazia CIACCIO
Luca COCCHI
Luigi CUCCI
Lorenzo CUGLIARI
Elisabetta D'ANASTASIO
Alessia DI CAPRIO
Roberto DI MARTINO
Domenico DI MAURO
Domenico DORONZO
Filippo GRECO
Alessandro IAROCCI
Mario MATTIA
Daniele MELINI
Anna NARDI
Lucia NARDONE
Marco OLIVIERI
Arianna PESCI
Stefano PINTORE
Pierangelo ROMANO
Paola SBARRA
Davide SCAFIDI
Maurizio SOLDANI
Sara STOPPONI
Umberto TAMMARO
David ZULIANI

REGISTRAZIONE AL TRIBUNALE DI ROMA N.173 | 2014, 23 LUGLIO
© INGV Istituto Nazionale di Geofisica e Vulcanologia
Rappresentante legale: Presidente INGV
Sede: Via di Vigna Murata, 605 | Roma
Tutti i diritti riservati

www.ingv.it

ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

ISSN 2039-7941
anno **2026** numero **529**

RAPPORTI
TECNICI INGV

Comparative analysis of full GNSS observations from different generation choke ring antennas: LEIAT vs TRM

Mirko Iannarelli*, Roberto Devoti, Grazia Pietrantonio

INGV | Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Nazionale Terremoti

Corresponding author

Accepted 25 August 2026 | *Accettato 25 agosto 2026*

How to cite | *Come citare* Iannarelli, M., Devoti, R., & Pietrantonio, G. (2026). Comparative analysis of full GNSS observations from different generation choke ring antennas: LEIAT vs TRM. *Rapporti Tecnici INGV*, *529*, 1-18. https://doi.org/10.13127/rpt/529

Cover First test week, antennas TRM and LEIAT504 | *In copertina Prima settimana di test, antenna TRM e LEIAT504*

529

INDEX

Abstract	**7**
Introduction	**7**
1. Experimental setup	**7**
2. Analized observations	**8**
3. Results	**9**
4. Summary	**14**
Acknowledgements	**14**
References	**14**
Web References	**14**

Abstract

The national RING infrastructure (Rete Integrata Nazionale GNSS) historically equipped with Dorne-Margolin choke ring antennas, is currently undergoing a significant upgrade of the GNSS equipment, primarily aimed at supporting full multi-constellation GNSS capabilities. Therefore, it is interesting to screen the working, almost 20-year-old, technology with the most up-to-date electronic devices in order to establish the pros and cons of those upgrades. We tested two LEIAT choke ring antennae (LEIAT504 and LEIAT504GG), designed originally for tracking only GPS and GPS/GLONASS satellites, by scoring the acquired observations from the full-GNSS constellation. We perform a complete quality check comparing the observations of the LEIAT antennae with those of an up-to-date TRM choke ring antenna used as reference. The test sessions are carried out using the same receiver type (Trimble Alloy). Both LEIAT antennas do acquire full-GNSS observations, although the LEIAT504GG only partially, at a few percent lower rate with respect to the TRM antenna. The LEIAT504GG antenna seems unable to track the L5 band observations of both GPS and GALILEO satellites.

Keywords Choke ring; GNSS antenna; GNSS observables; Time series

Introduction

The National Integrated GNSS Network (RING - Rete Integrata Nazionale GNSS [Avallone et al., 2010; INGV RING Working Group, 2016; [1]), managed by the Istituto Nazionale di Geofisica e Vulcanologia (INGV), represents a fundamental infrastructure for monitoring tectonic deformation, volcanic dynamics, and seismic hazards across Italy. Historically equipped with high-precision Dorne-Margolin style choke ring antennas, the network is currently undergoing a comprehensive technological upgrade aimed at achieving full multi-constellation and multi-frequency GNSS capabilities (GPS, GLONASS, Galileo, and BeiDou).

While upgrading receivers is essential to track multi-constellation signals, replacing legacy antennas is a far more critical decision. Installing a new antenna alters phase center variations (PCVs), local multipath, and geometric offsets, inducing artificial discontinuities in long-term geodetic time series. It is therefore crucial to assess whether legacy models (such as LEIAT504 and LEIAT504GG), originally designed for GPS/GLONASS, are limited in tracking newer frequencies (Galileo, BeiDou, L5).

In this work, we present a comparative performance analysis of two Leica choke ring antenna models (LEIAT504 and LEIAT504GG) against a state-of-the-art reference choke ring antenna (Trimble TRM159900.00-SCIS). All antennas were collocated under controlled field conditions and connected to identical multi-constellation Trimble Alloy receivers. By analyzing one week of 30s rate observations per setup, we systematically assess key quality parameters, including raw data acquisition rates, code multipath, signal-to-noise ratio (SNR), frequency-specific response (with emphasis on the L5 band), and high-precision hourly positioning repeatability.

1. Experimental setup

The main goal of this work is to test the performances of two types of GNSS antennae (LEIAT504 and LEIAT504GG) that, in principle, are not designed to observe the GALILEO and BEIDOU

constellation frequencies. After accumulating one week of observations, we evaluate the number of epochs and quality parameters of GNSS observables recorded at both the LEIAT antenna, collocated with a brand new TRM choke ring antenna (TRM159900.00-SCIS) used as a reference. Each antenna was connected to the same type of receiver (Trimble Alloy). During the first week (Oct. 7-14, 2022) the LEIAT504-LEIS choke ring antenna was tested against TRM159900.00-SCIS, during the second week (Oct. 14-20, 2022) the LEIAT504GG-LEIS choke ring model GG was tested against the same TRM159900.00-SCIS. All three antennae were equipped with radome enclosing (radome codes: LEIS and SCIS respectively) and placed on the backyard floor of INGV institute in Rome. Figure 1 depicts the experimental setup used during the first week. The two GNSS antennae mounted on aluminum easel stand tripods are visible in the foreground, each antenna is placed at approximately 120 centimeters height. The structural details and dimensions of the two choke ring antennas are presented in Figure 2. Although geometrically identical, the antennas differ in their internal amplifier electronics. The antenna cables connecting the antenna to the receiver were two identical 10 meters long coaxial TNC cables. The power box unit is visible in the background, hosting the solar panels, the two receivers and battery units. The receivers were configured as to acquire hourly files at 1 Hz sampling rate for all satellites setting a 10° elevation cut off. The original data were later converted to RINEX 3 format using Trimble conversion software. More details on observation types are given in next paragraph.



Figure 1 Setup of the twin stations: the TRM159900.00SCIS antenna is on the left and the LEIAT504LEIS on the right, with the power box in the background hosting solar panels, receivers, and batteries.

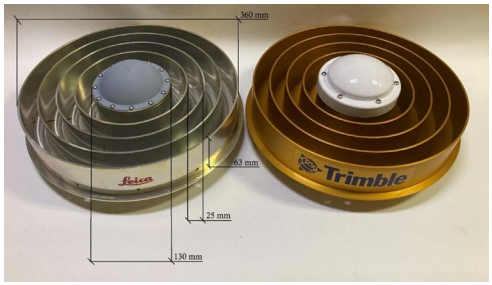


Figure 2 LEIAT504 (left) and TRM159900.00 (right) antennas. The 2 choke rings are geometrically identical and LEIAT504GG look the same, while the electronics of the receiving units differ for each antenna.

2. Analized observations

The full set of pseudorange and phase observations considered in this work is listed in Table 1, the full range of allowed observations for the four major constellations were chosen (GPS, GLONASS, GALILEO and BEIDOU).

Following the RINEX3 convention [2], the code and phase observations are identified by a 3-character code (i.e. the observation code): the first character identify the observation type (C = pseudorange, L = carrier phase, D = doppler, S = signal strength), the second character identify the frequency band (1, 2, ..., 9), and the third indicates the tracking mode or channel

(e.g. I, Q, X, ...). We downloaded the observations formatted as RINEX 3.05 files, consistently, we indicate therein the frequency bands with the "L" character (L1, L2, L3, etc). The actual transmitted frequencies for the major GNSS constellation are detailed in Table 2.

Sats	No.	Observation codes
G	15	C1C, L1C, S1C, C1X, L1X, S1X, C2W, L2W, S2W, C2X, L2X, S2X, C5X, L5X, S5X
R	15	C1C, L1C, S1C, C1P, L1P, S1P, C2C, L2C, S2C, C2P, L2P, S2P, C3X, L3X, S3X
E	15	C1X, L1X, S1X, C5X, L5X, S5X, C6X, L6X, S6X, C7X, L7X, S7X, C8X, L8X, S8X
C	9	C2I, L2I, S2I, C7I, L7I, S7I, C6I, L6I, S6I

Table 1 List of observation types considered in this work for the GNSS constellations (G=GPS; R=GLONASS; E=GALILEO and C=BEIDOU).

GNSS frequency bands (MHz)	L1	L2	L3	L5	L6	L7	L8
GPS	1575.42	1227.60	-	1176.45	-	-	-
GALILEO	1575.42	-	-	1176.45	1278.75	1207.14	1191.795
GLONASS	1602+k*9/16 K=-7...+12	1246+k*7/16 k=-7...+12	1202.025	-	1248.06	-	-
BEIDOU	-	1561.098	-	-	1268.52	1207.14	-

Table 2 Actual frequency of the frequency bands considered in this work. The frequency bands are defined as in observation codes of the RNX3 conventions, the frequency unit is MHz.

We evaluate the performance of each antenna by computing the following parameters: 1) the code multipath on L1, L2, L5, L6, L7 and L8 bands, averaged over all satellites of a given constellation; 2) the daily total number of observed epochs; 3) the total number of observed epochs and the signal-to-noise ratio, grouped over each frequency band and finally 4) the total observed epochs grouped by satellite constellation.
All these parameters are computed using G-Nut/Anubis (ver. 2.3) software [2] analyzing the daily Rinex files decimated at 30s sampling rate. This sampling rate provides an evaluation resolution on the order of 0.03%, which is more than adequate for a reliable quantitative assessment.

3. Results

Multipath. Micro waves emitted by GNSS satellites reach usually the antenna directly in the line of sight direction, but the environment may cause multiple reflections that reach the receiver antenna by two or more paths. This phenomenon is called multipath noise, it affects either the pseudorange and the phase observables and may bias the position estimation in an unpredictible way (see e.g. [Fuhrmann et al., 2021]). Choke ring antennae are specially designed GNSS receiving antennae that reduce the recording of indirect radiation from below the horizon. A choke ring antenna consists of a central antenna receiver, which is surrounded by concentric conductive rings of equal depth. The rings are usually a quarter wavelength deep, in order to establish a high impedance

surface that prevents generation of surface waves near the antenna and excitation of undesired modes. Further mitigation of multipath is achieved by electronic filtering devices that reject the left hand circular polarization (LHCP) component, mostly originated by odd order reflections (e.g. single reflections). The choke rings of the TRM and LEIAT antennas are geometrically identical, a picture of both antennae and their physical dimensions are reported in Figure 2.
Multipath distorts both pseudorange (code) and carrier phase measurements. Code multipath errors can reach several meters, whereas phase multipath errors are typically at the millimeter to centimeter level. The Anubis software computes the code multipath MP_i using a linear combination of two carrier phase frequencies, i and j [2]:

$$MP_i = P_i - L_i - \frac{2f_j^2}{f_i^2 - f_j^2}(L_i - L_j)$$

where P_i, L_i and f_i are respectively the pseudorange, phase (converted in units of distance) and frequency of the observables.
Table 3 shows the root mean squared (RMS) of the code multipath (MP) averaged over the entire period of data acquisition for the three considered antennas. The multipath on all frequency bands shows higher values for the old LEIAT antennas, whereas the new TRM antenna perform generally up to 10% better, except for the L5 band where both LEIAT display a 50% worsening. Since the external choke ring geometry is identical, the L5 worsening should be imputed to the internal amplifier and filtering units.

	TRM159900.00-SCIS	LEIAT504-LEIS	LEIAT504GG-LEIS
MP1	mp1- Code multipath average RMS on L1 (cm)		
GPS	18.8	21.0	21.2
GLONASS	25.5	28.5	26.1
GALILEO	20.4	22.1	24.6
MP2	mp2- Code multipath average RMS on L2 (cm)		
GPS	25.4	27.2	27.8
GLONASS	26.3	29.7	29.1
BEIDOU	19.5	20.7	20.7
MP5	mp5- Code multipath average RMS on L5 (cm)		
GPS	20.9	31.7	30.9
GALILEO	21.5	33.7	N/A
MP6	mp6- Code multipath average RMS on L6 (cm)		
GALILEO	33.4	36.4	43.4
BEIDOU	23.4	27.6	27.0
MP7	mp7- Code multipath average RMS on L7 (cm)		
GALILEO	24.8	25.2	27.1
BEIDOU	27.4	27.9	28.7
MP8	mp8- Code multipath average RMS on L8 (cm)		
GALILEO	8.5	9.35	23.7

Table 3 Code multipath (MP) averaged for all satellites over the entire time span, each MP is given for each GNSS constellation individually. Note that MP5 values for Galileo satellites are unavailable, as Anubis likely omits this calculation due to observation counts systematically falling below the 0.5% threshold. In contrast, GPS observation counts on this band are 3 to 4 times higher.

Number of observations vs time. Figure 3 shows the total number of observations per day in percentage with respect to the expected observations above 10° elevation for all satellites. Due to a failure in data transfer during doy 282 and 283, the recorded observations for the TRM antenna are incomplete. As a result, both days were omitted from subsequent evaluations regarding frequency tracking percentages and signal-to-noise ratios. Doy 287 and 293 contain partial data due to changes in the experimental setup. On a daily basis, the LEIAT504 antenna records systematically a few percent (2-3%) less observations than the TRM antenna, whereas the LEIAT504GG acquires the same amount of observations.

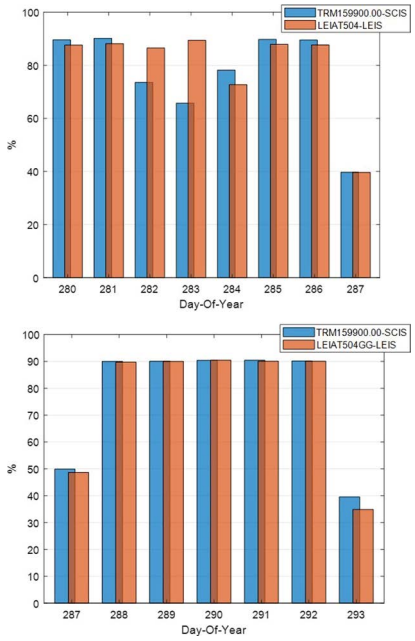


Figure 3 Ratio of existing to expected observations above 10° elevation mask. Top panel: TRM vs LEIAT504 during the first week (doy 280–287); bottom panel: TRM vs LEIAT504GG in the second week (doy 287–293).

This behavior is confirmed in Figure 4, where the percentage of usable observations are subdivided by constellation type. The criterium of usable observation is: observing at least 4 satellites at epoch with dual frequency. Here the LEIAT504 antenna leaks 5% of GLONASS observations and about 1% of GALILEO observations with respect to TRM, LEIAT504GG instead, leaks very few observations (<1%) on all constellations. This behavior indicates that the LEIAT504 antenna is less effective in tracking at least two frequencies for GLONASS and GALILEO satellites, whereas LEIAT504GG performs better. This conclusion is not true for any of the tracked frequencies, as we will discuss later on, e.g. LEIAT504GG is unable to track observations of L5 frequency band.

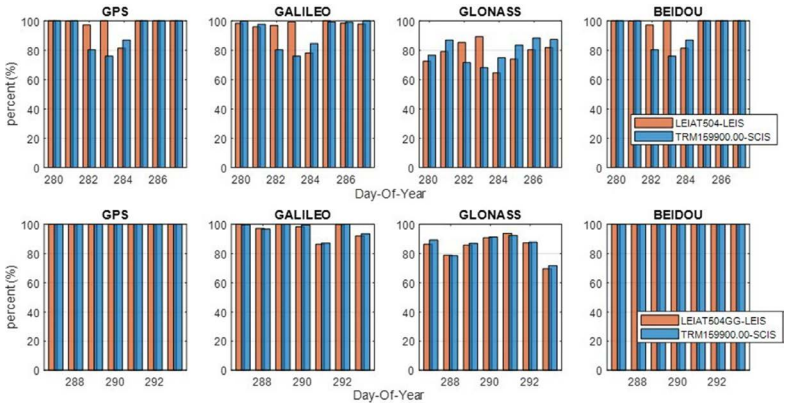


Figure 4 Percentage of usable observations within each constellation, as a function of time (existing/expected, the criterion is 4 satellites in the epoch with dual-frequency data for each GNSS constellation).

Observations vs frequency band. Figures 5 and 6 represent the number of observations summed over all satellites that transmit on a given frequency band, focused respectively on antenna LEIAT504 and LEIAT504GG. Inspection of Figure 5 reveals that LEIAT504 antenna loses a few percent of observations uniformly over all frequencies, confirming the analogous daily loss observed in Figure 3. The LEIAT504GG (Figure 6) records almost all observations but missed almost completely the L5 band observations (GPS third frequency and GALILEO second open frequency). Since all receiver configuration parameters are the same for the two antennae, and the choke rings are geometrically identical, we infere that LEIAT504GG suppress to some degree the low frequency L5 (1176.45 MHz), most likely in the electronic LNA (Low Noise Amplifier) or filtering unit.

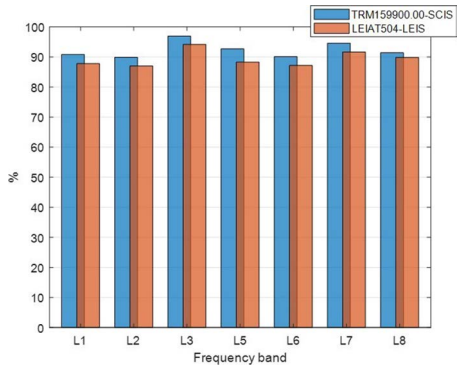


Figure 5 Number of observations averaged over all satellites as a function of selected frequency bands, test-bed week1, comparing TRM and LEIAT504 antennae.

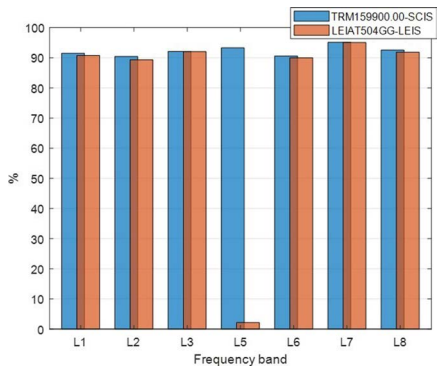


Figure 6 Number of observations averaged over all satellites as a function of selected frequency bands, test-bed week-2, comparing the TRM and LEIAT504GG antennae.

Signal to noise ratio. Figure 7 shows the signal to noise ratio (SNR) for the first week (antenna LEIAT504-LEIS) averaged over the entire period and all satellites of the given frequency band. The error bar indicates the standard deviation of the residuals, indicating the variability of the observed SNR in the frequency band. Figure 8 shows the same SNR parameters collected in the second week (antenna LEIAT504GG-LEIS). The comparison of the two antennae reveals a systematic lower SNR (on average 6%) for the LEIAT504 with respect to the reference TRM antenna. This is generally true also for the LEIAT504GG antenna (Figure 8), with the exception of the L5 band in which the SNR reduces to a modest value (30). Thus both the LEIAT antennae acquire a lower signal strength on average, that could be explained by an improved gain in the amplifier chain for the up-to-date TRM antenna, but the LEIAT504GG seems designed to reject the L5 frequency and is unable to acquire the GPS and GALILEO L5 observations.

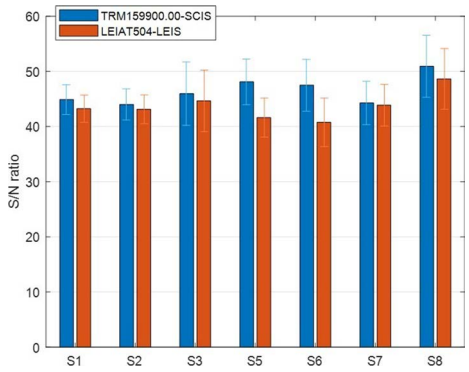


Figure 7 First test week, antennas TRM and LEIAT504. Signal to noise ratio, averaged over all satellites, for different frequency band. The error bars are the standard deviations computed on daily residuals.

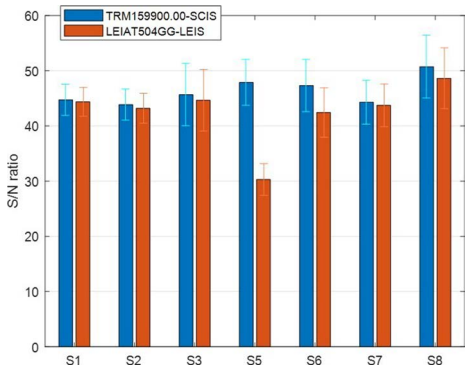


Figure 8 Second test week, antennas TRM and LEIAT504GG. Signal to noise ratio, averaged over all satellites, for different frequency band. The error bars are the standard deviations computed on daily residuals.

Time series. We estimated station positions at hourly steps using double differences of L1 and L2 phase observables, including GPS and GLONASS observations. To fix the reference frame we included 10 IGS14 stations that were constrained to the apriori IGS14 position [4] computed at any epoch, the solution was performed using Bernese software version 5.2 [5]. In Figure 9 we show the time series of the two test antennae versus the reference TRM antenna, the coordinates and the root mean squares (RMS) are given in a local reference frame (Up, East, North). We see a worsening of 1.2 mm (in 3D) of the LEIAT504 antenna with respect to the reference TRM, whereas the LEIAT504GG show only half of that worsening (0.7 mm). This result suggest that LEIAT504GG antenna is performing better than LEIAT504, which is not surprising since the GG antenna model represents an upgrade to the previous choke ring antenna. The cons is that model GG is band-limited and does not acquire L5 observations at all.

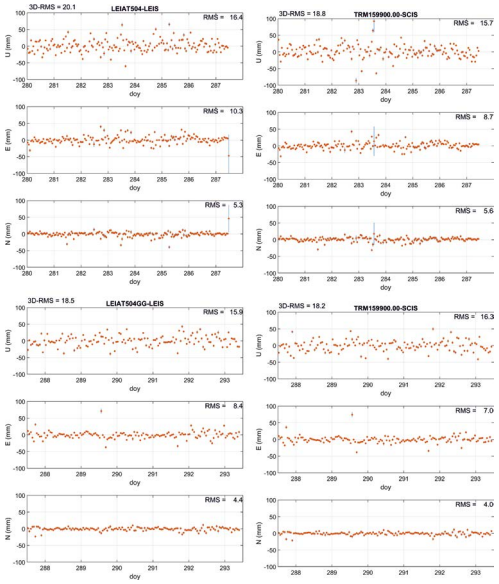


Figure 9 Hourly positions double-difference estimated from GPS and GLONASS observations. Upper panels: LEIAT504-LEIS vs TRM159900.00-SCIS, lower panels: LEIAT504GG-LEIS vs TRM159900.00-SCIS.

4. Summary

In this study, legacy Leica choke ring antennas (LEIAT504 and LEIAT504GG) were evaluated against a modern Trimble reference antenna to assess their suitability for the RING network upgrade. The analysis reveals that the older LEIAT504 model successfully captures signals across all multi-constellation frequency bands, including L5, despite exhibiting a minor daily data loss of 2–3% and slightly higher code multipath. Conversely, although most constellation frequencies are tracked by the LEIAT504GG, L5 frequency observations are entirely filtered out by its internal electronics. Both legacy antennas demonstrate excellent positioning stability with only sub-millimeter to millimeter RMS degradation in hourly solutions, but their older electronics result in a lower signal-to-noise ratio and higher multipath noise overall. Therefore, we recommend replacing the LEIAT504GG antennas as a priority, since their inability to track L5 frequencies compromises the multi-frequency objectives of the upgrade. Conversely, the LEIAT504 antennas can be conditionally retained alongside modern receivers in sites where preserving the uninterrupted continuity of long-term geodetic time series is paramount.

Acknowledgements

The authors would like to thank the Editor and the two anonymous reviewers for their constructive comments, which greatly improved the quality of the manuscript.

References

Avallone, A., Selvaggi, G., D'Anastasio, E., D'Agostino, N., Pietrantonio, G., Riguzzi, F., Serpelloni, E., Anzidei, M., Casula, G., Cecere, G., D'Ambrosio, C., De Martino, P., Devoti, R., Falco, L., Mattia, M., Rossi, M., Obrizzo, F., Tammaro, U., & Zarrilli, L. (2010). The RING Network: Improvement of a GPS Velocity Field in the Central Mediterranean. *Annals of Geophysics*, *53*(2), 39-54. https://doi.org/10.4401/ag-4549

Fuhrmann, T., Garthwaite, M. C., & McClusky, S. (2021). Investigating GNSS multipath effects induced by co-located Radar Corner Reflectors. *Journal of Applied Geodesy*, *15*(3), 207-224, doi:10.1515/jag-2020-0040

INGV RING Working Group. (2016). Rete Integrata Nazionale GPS (RING). https://doi.org/10.13127/RING

Sitography

[1] https://webring.gm.ingv.it/
[2] https://files.igs.org/pub/data/format/rinex305.pdf
[3] https://gnutsoftware.com/software/anubis
[4] https://www.aiub.unibe.ch/download/BSWUSER52/STA/IGS14_R.CRD
[5] https://www.bernese.unibe.ch/docs/DOCU52.pdf

QUADERNI di GEOFISICA

ISSN 1590-2595 https://collane-editoriali.ingv.it/index.php/qdg/it/index/

QUADERNI di GEOFISICA è una rivista scientifica che pubblica dati, misurazioni e osservazioni geofisiche (anche preliminari) in italiano e inglese. L'obiettivo è una diffusione rapida e gratuita per la comunità scientifica, garantita da un processo di peer-review e da un Editorial Board multidisciplinare. La rivista è inclusa in "Emerging Sources Citation Index" di Clarivate Analytics e "Open Access Journals" di Scopus, e adotta il modello Diamond Open Access, che non prevede costi né per gli autori né per i lettori.

QUADERNI di GEOFISICA is a scientific journal that publishes geophysical data, measurements and observations, including preliminary results, in Italian and English. Its aim is to ensure rapid and free dissemination to the research community, supported by a peer-review process and by a multidisciplinary Editorial Board. The journal is included in the Emerging Sources Citation Index of Clarivate Analytics and it's included in the Open Access journals of Scopus. It follows the Diamond Open Access model, with no charges for either authors or readers.

RAPPORTI TECNICI INGV

ISSN 2039-7941 https://collane-editoriali.ingv.it/index.php/rt/it/index

RAPPORTI TECNICI INGV è una rivista tecnico-scientifica che mette in mostra le numerose attività tecnologiche e di ricerca condotte dai ricercatori e tecnici INGV, e non solo. Pubblicata in italiano e inglese, RAPPORTI TECNICI INGV è ideata per valorizzare anche quei lavori che offrono un contributo significativo dal punto di vista tecnico, operativo o documentale fondamentale per lo sviluppo dell'Ente. La rivista adotta il modello Diamond Open Access, che non prevede costi né per gli autori né per i lettori.

RAPPORTI TECNICI INGV is a technical–scientific journal that showcases the wide range of technological and research activities carried out by INGV researchers and technical staff, as well as by external contributors. Published in Italian and English, RAPPORTI TECNICI INGV is designed to highlight works that provide a significant contribution from a technical, operational, or documentary perspective, and that are essential to INGV development. The journal follows the Diamond Open Access model, with no charges for either authors or readers.

MISCELLANEA INGV

ISSN 2039-6651 https://collane-editoriali.ingv.it/index.php/mi/it/index

MISCELLANEA INGV rappresenta una tipologia di editoria non tradizionalmente catalogabile nelle ordinarie riviste scientifiche di settore. Pubblicata in lingua italiana e inglese, MISCELLANEA INGV offre uno spazio per la pubblicazione di materiali eterogenei che, pur non rientrando nei formati più strutturati delle altre Collane editoriali INGV, rivestono un interesse scientifico, tecnico o divulgativo. La rivista adotta il modello Diamond Open Access, che non prevede costi né per gli autori né per i lettori.

MISCELLANEA INGV represents a form of publishing that cannot be classified within the standard scientific journals. Published in Italian and English, MISCELLANEA INGV provides a venue for the publication of heterogeneous materials that are of scientific, technical or outreach interest, even though they do not fall within the more structured formats of the other INGV editorial series. The journal follows the Diamond Open Access model, with no charges for either authors or readers.

Progetto grafico
Barbara ANGIONI
Istituto Nazionale di Geofisica e Vulcanologia

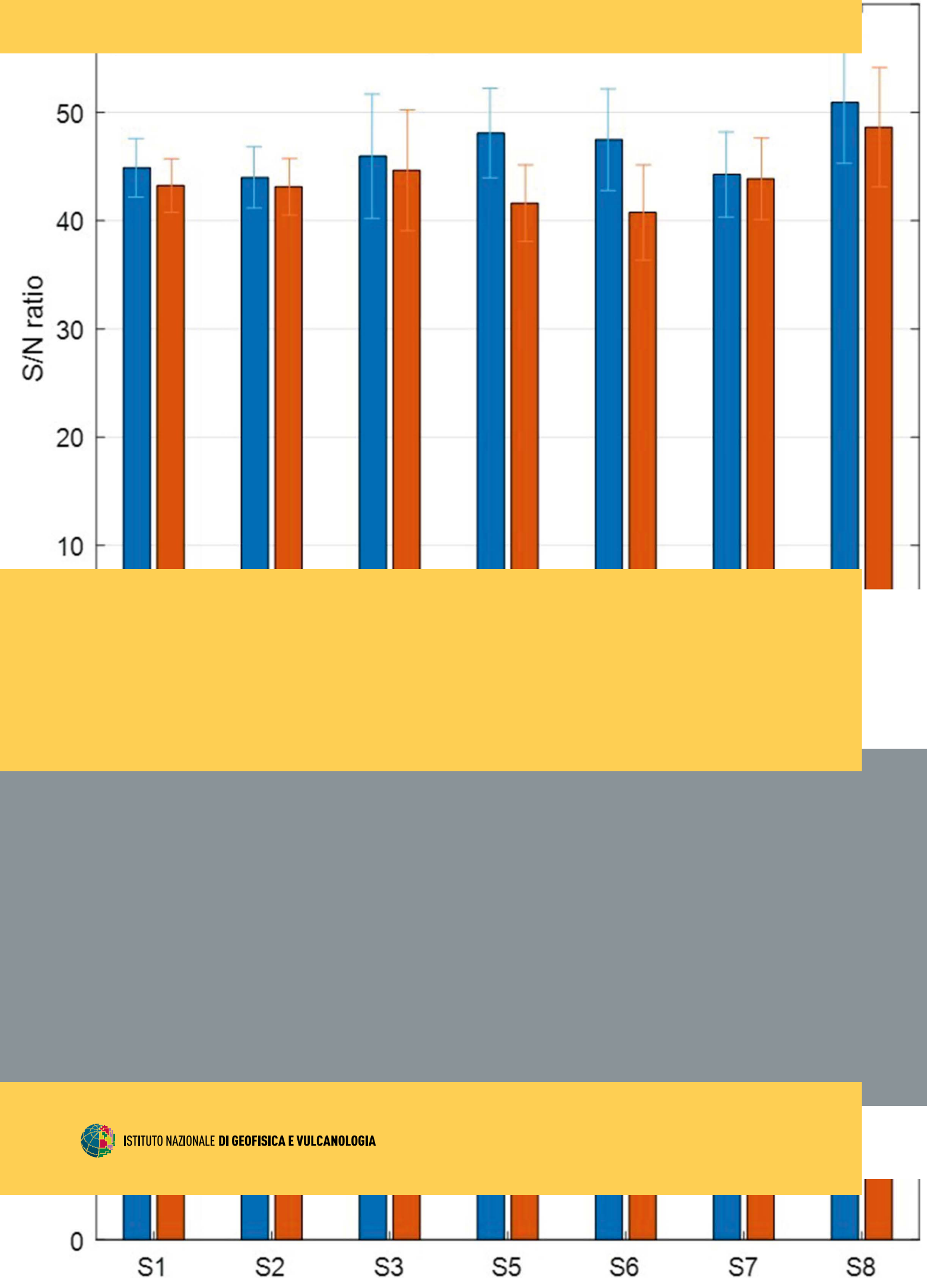
Ufficio Editoriale
Francesca DI STEFANO | Coordinatore

Segreteria di redazione
segreteria.collane-editoriali@ingv.it

Editing | Produzione | Grafica redazionale
Barbara ANGIONI
Massimiliano CASCONE
Francesca DI STEFANO
Patrizia PANTANI

© 2026 the Author(s). All rights reserved. Open Access

Creative Commons Attribution 4.0 International


S/N ratio
50
40
30
20
10
0
S1
S2
S3
S5
S6
S7
S8