Long-Term Analysis of SIRGAS ZTD Time Series for Early Anomaly Detection

M.F. CAMISAY[1], P. A. ROSELL[2,3], M. V. MACKERN[2,3,4] and M. L.MATEO[2,3]

[1]Instituto de Agrimensura, Facultad de Ingeniería, Universidad de la República, Uruguay.
[2]Facultad de Ingeniería, Universidad Nacional de Cuyo, Argentina.
[3]Facultad de Ingeniería y Enología, Universidad Juan Agustín Maza, Argentina.
[4]Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina.

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INTRODUCTION

The Geodetic Reference System for the Americas (SIRGAS) provides the essential geospatial infrastructure (+600 GNSS stations) for positioning and atmospheric research across the continent. Through the SIRGAS Analysis Centre for the Neutral Atmosphere (CIMA), Zenith Tropospheric Delay (ZTD) products are routinely generated with hourly resolution. Results from the analysis of long-term (+20 years) ZTD time series are presented, which could be used as a reference for climatological studies and the monitoring of extreme meteorological events.

OBJECTIVES

- Define an hourly and monthly mean ZTD parameters for each SIRGAS station with at least 10 years of data, to be used as a climatological reference.
- Develop a scalable framework capable of integrating additional stations as they reach 10-year of observation.
- Propose a near-real-time methodology for identifying ZTD anomalies by comparing rapid PPP-derived estimates with climatological statistical reference indicators.
- Validate the ZTD_{SIR} against the ZTD products from the IGS REPRO3 to assess its accuracy and long-term consistency.

METHODS

- ZTD_{SIR} final products were estimated (Mackern et al., 2025) over a 23-year period,2002–2025.
- Stations with more than 10 years of data were selected in this statistical analysis.
- Outliers were excluded based on a 3-σ threshold, relative to the monthly mean.
- To 387 SIRGAS stations (~53 % of the network), the hourly, monthly, annual, and total ZTD mean values were estimated.
- **Calculation and Analysis of ZTD Anomalies in a Case Study**:

-Near real-time ZTD_{PPP} was estimated using the Canadian Spatial Reference System PPP Service, employing IGS rapid ephemerides, for 23 stations located in central Argentina. Period: DoY 348 - 352, 2023.
-For each epoch, the difference $ZTD_{PPP}–ZTD_{SIR}$ was computed. Differences exceeding ±10 cm were identified as anomalies.

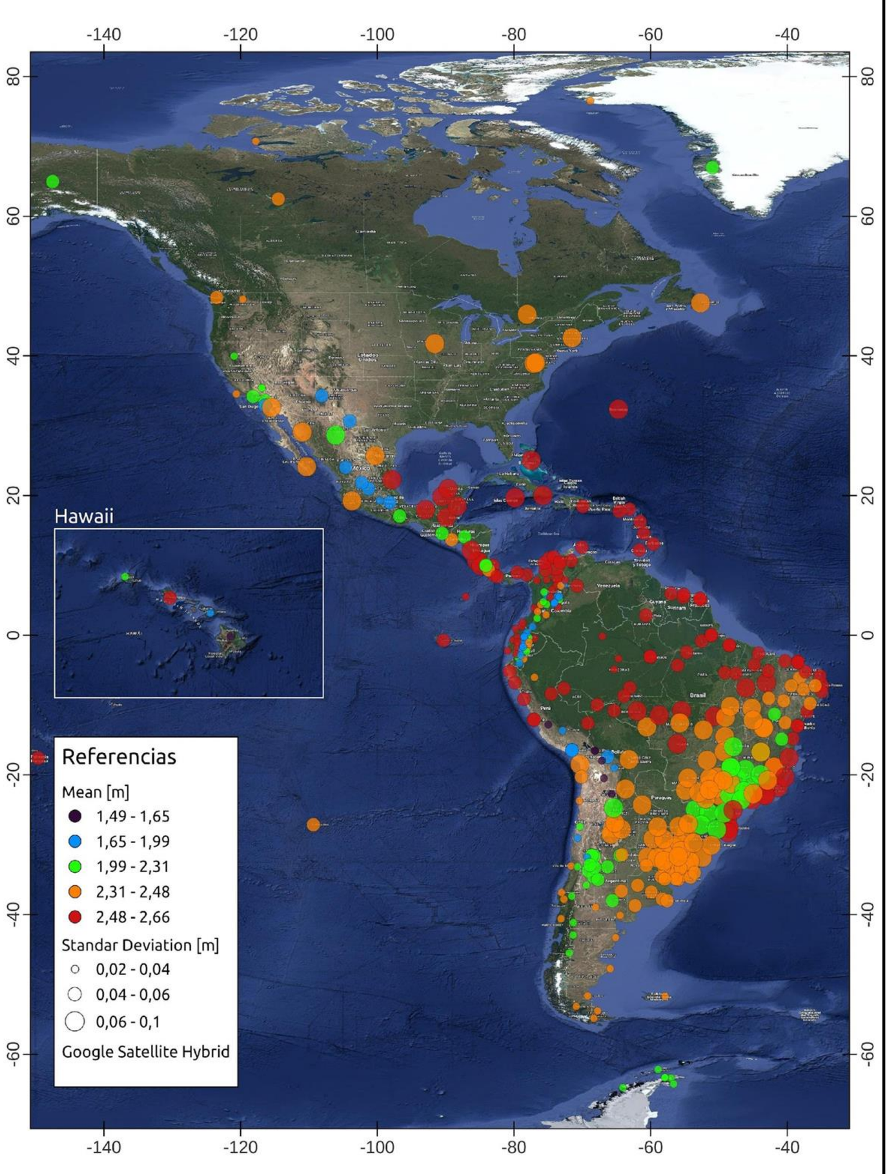


Figure 1: Spatial distribution of total ZTD mean values and Standard Deviation, at SIRGAS-CON stations with more than 10 years ZTD products. Period 2002–2025.

RESULT

ZTD time series: Diurnal ZTD cycle and Annual ZTD cycle

- Total ZTD Mean values and SD for 387 SIRGAS stations (Fig. 1), establishing a baseline threshold and alert limit for extreme weather events.
- A "Diurnal ZTD cycle" and "Annual ZTD cycle" were defined per station.

Fig. 2 displays a well-defined diurnal ZTD cycle for an equatorial station BOGT. High-altitude (2576 m) shifts ZTD values to a lower absolute range due to a thinner atmospheric column.
Fig. 3 (OHI2) shows the climatological mean for a polar, sea-level Antarctic site (32 m). Large error bars indicate that atmospheric behavior is driven by synoptic-scale polar weather systems rather than regular daily solar heating.

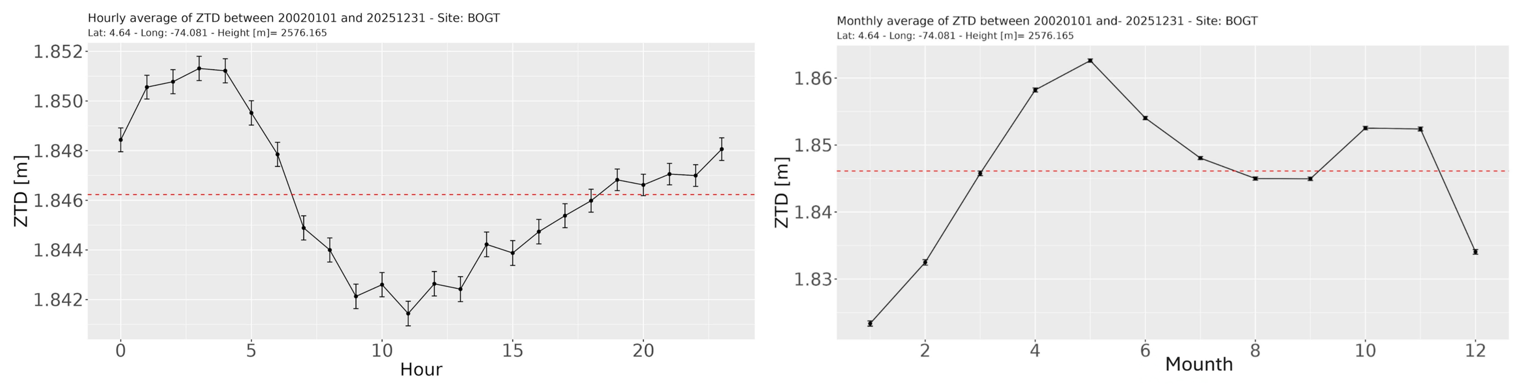


Fig. 2: Hourly mean ZTD for BOGT station (left), Monthly mean ZTD (right), period 2002-2025.

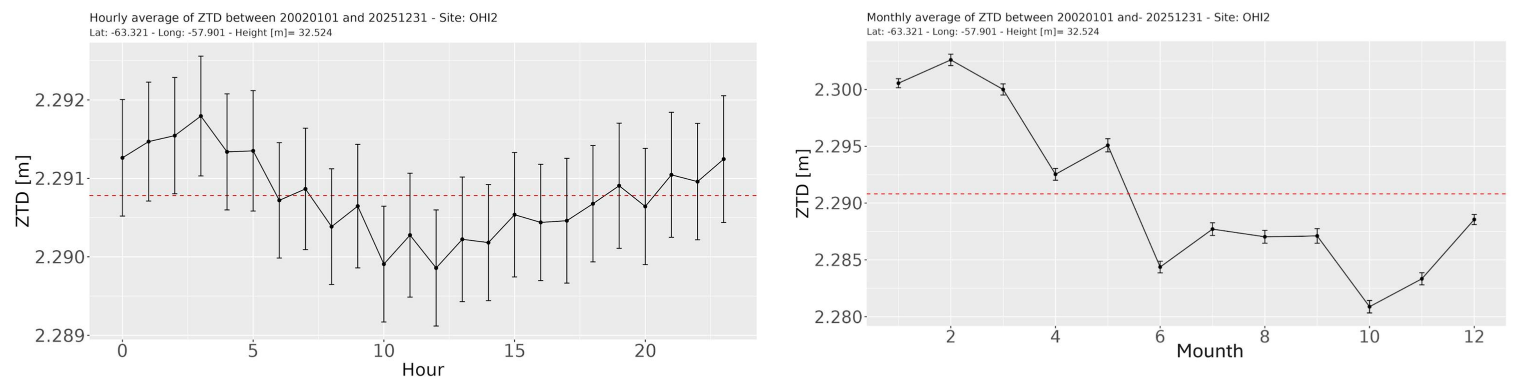


Fig. 3: Hourly mean ZTD for OHI2 station (left), Monthly mean ZTD (right), period 2002-2025.

ZTD Anomalies detected during extreme events

Case Study: Central Argentina, on December 16th, 2023 (DoY 350)

Fig. 4 shows the estimated ZTD series surrounding the events. The ZTD_{PPP} series (red) clearly deviates from the climatological hourly mean ZTD (black). The final post-processed SIRGAS ZTD_{SIR} series is plotted in blue.

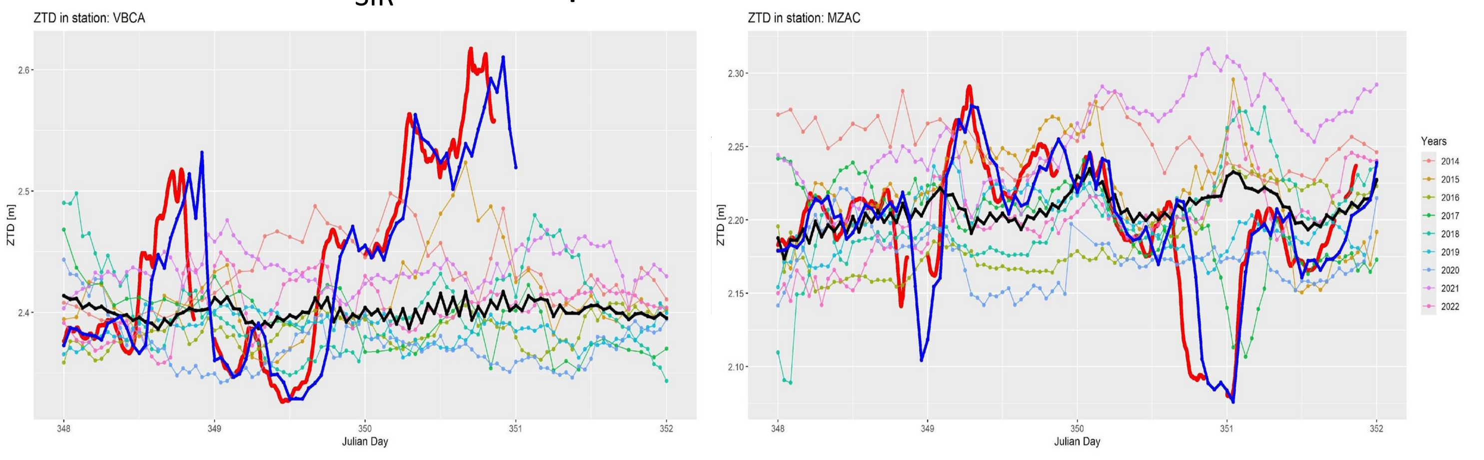


Fig. 4: ZTD_{PPP} (red), ZTD hourly means (black), ZTD_{SIR} (blue), at Bahía Blanca (VBCA) and Mendoza (MZAC).

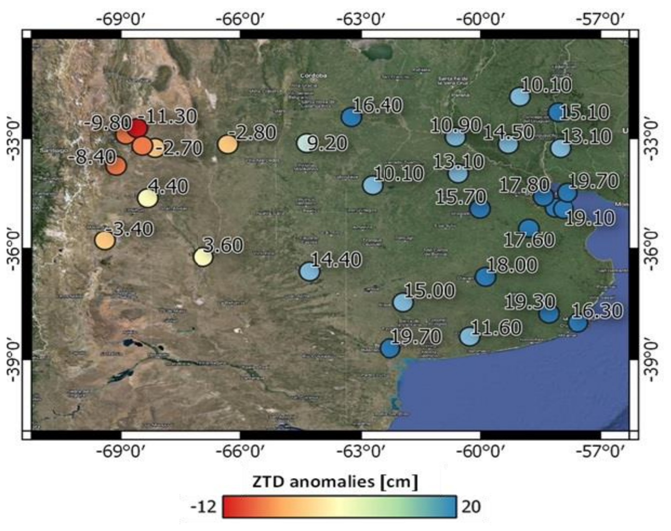


Figure 5: Mayors ZTD Anomalies computed at 20 hs UTC (DoY 350)

Hourly maps of ZTD anomalies show indirect changes in the distribution of atmospheric water vapor, temperature, and atmospheric pressure.

- **Central-East Argentina: Severe Storm**

-Pronounced increase anomalies (10 to 20 cm) were detected in 20 stations (Fig. 5, blue circles).

- **Central-West Argentina: Zonda Wind**

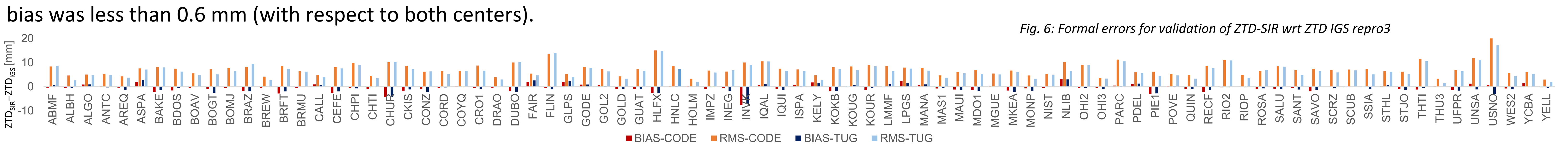
-An abrupt ZTD drop exceeding -10 cm was detected at 4 stations (Fig.5, orange and red circles) in the hours preceding the event.

Scan for the extended anomalies video

Validation of SIR ZTD against IGS Repro3 Products

The ZTD_{SIR} estimates were compared with the IGS ZTD repro3 from two Analysis Centers (ACs), CODE and TUG, because both use a network-processing strategy, with TUG offering the most stations in common and CODE using the same processing software as SIRGAS.
Mean bias and mean RMS values of the differences ($ZTD_{SIR}–ZTD_{IGS}$) were computed in 85 stations. The analysis focused on the 2013 time series, the last year of SIRGAS Repro2 (2002-2013), which includes the highest number of available IGS stations integrated into SIRGAS.
Mean bias and mean RMS values were consistent across both ACs (Fig. 6), with TUG exhibiting a lower mean RMS (6.41 mm) compared to CODE (7.52 mm). The mean bias was less than 0.6 mm (with respect to both centers).

Fig. 6: Formal errors for validation of ZTD-SIR wrt ZTD IGS repro3



CONCLUSIONS

- Climatological Value: Long-term ZTD hourly mean and monthly mean provide a robust baseline reference for atmospheric and climate studies.
- Extreme Events: The SIRGAS ZTD products can successfully be used to identifies significant tropospheric anomalies previously (6 hours before) and during severe weather events.
- Real-Time Potential: Integrating these climatological means with near-real-time PPP processing enables immediate atmospheric anomaly monitoring.
- Assessment of SIR ZTD Using IGS Repro3 Products : Comparison yielded highly satisfactory results, showing a near-zero bias and an RMS below 0.3% of the total ZTD value.

References

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