Meteorological Data Coherence Assessment for Tropospheric Monitoring Using ASI's National GNSS Fiducial Network

Ilaria Ferrando, Abubakr Khalid Ahmed Albashir, Bianca Federici, Gabrio Pinnizzotto, Catia Benedetto, Francesco Vespe, and Domenico Sguerso

Abstract

The established research cooperation between University of Genoa (UniGe) and Italian Space Agency (ASI) for the exploitation of the GNSS data acquired through the "New National GNSS Fiducial Network", implemented by ASI, aims to develop and test the procedure named GNSS for Meteorology (G4M), deployed by UniGe's Geomatics Laboratory, for creating Precipitable Water Vapor (PWV) maps covering the Italian territory. The focus of the present work is the coherence assessment between the meteorological data provided by National Oceanic and Atmospheric Administration (NOAA) and the ones made available by MeteoNetwork (MNW), a crowd-sourced sensors network. The comparison is based on the metrics of pressure and temperature differences, also accounting for the different sensors distribution, and on the application of Inter Quartile Range method, to select a set of reliable MNW stations for populating a meteorological DataBase for G4M procedure.

Keywords

Inter Quartile Range (IQR) · Meteorological DataBase (DB) · Precipitable Water Vapor (PWV) · Pressure (P) · Temperature (T) · Zenith Total Delay (ZTD)

1 Introduction

The present contribution assesses the coherence between the meteorological data provided by the National Oceanic and Atmospheric Administration (NOAA)[1] and those made available by MeteoNetwork (MNW),[2] a crowd-sourced sensors network managed by an association of meteorology enthusiasts (Giazzi et al. 2022). The activity is part of the scientific cooperation between the University of Genoa (UniGe) and the Italian Space Agency (ASI) for the exploitation of the Global Navigation Satellite System (GNSS) data acquired through the "New National GNSS Fiducial Network", implemented by ASI. This multi-constellation GNSS network, consisting of 45 permanent stations distributed across Italy (Fig. 1a), supports the global geodetic networks of International GNSS Service (IGS)[3] and EUREF Permanent GNSS Network (EPN)[4] in maintaining the terrestrial reference frame (ITRF),[5] and enables advanced research in GNSS meteorology and climate change.

As it is widely known, the GNSS accuracy is influenced by various factors affecting the observed signal, including

[1] https://www.ncei.noaa.gov

[2] https://www.meteonetwork.it

[3] https://www.igs.org

[4] https://www.epncb.oma.be

[5] https://www.iers.org/IERS/EN/DataProducts/ITRF/itrf

I. Ferrando (✉) · A. Khalid Ahmed Albashir · B. Federici · G. Pinnizzotto · D. Sguerso
Department of Civil, Chemical and Environmental Engineering (DICCA), University of Genoa, Genoa, Italy
e-mail: ilaria.ferrando@unige.it; abubakr.khalidahmedalbashir@edu.unige.it; bianca.federici@unige.it; domenico.sguerso@unige.it

C. Benedetto · F. Vespe
Telecommunications and Navigation Office, Italian Space Agency (ASI), Matera, Italy
e-mail: catia.benedetto@asi.it; francesco.vespe@asi.it

International Association of Geodesy Symposia,
https://doi.org/10.1007/1345_2026_356,

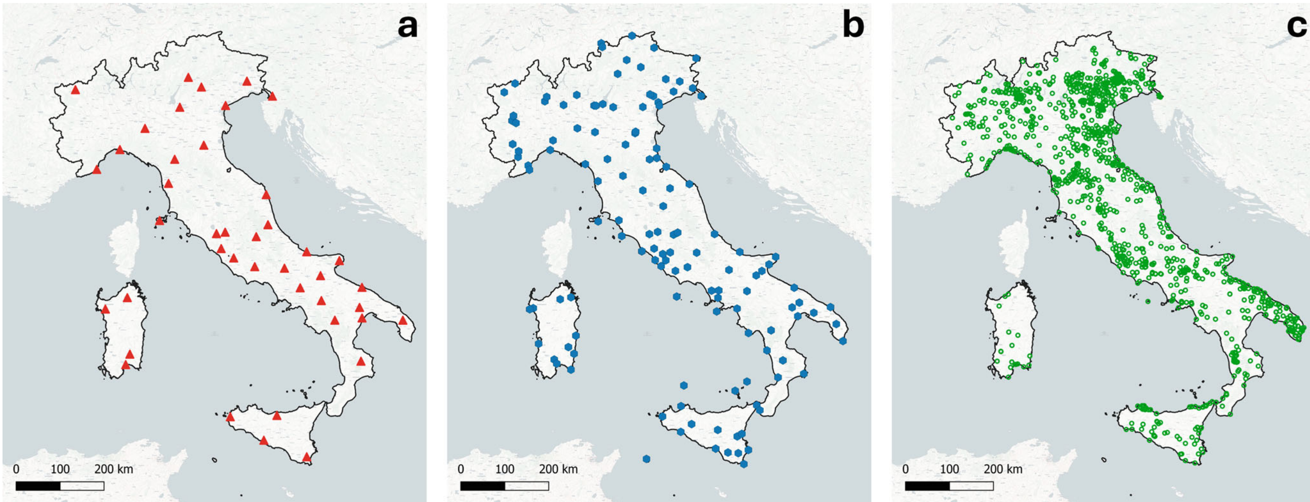

Fig. 1 Distribution of the different networks: (**a**) ASI GNSS, (**b**) NOAA, and (**c**) MNW

the tropospheric effects (Bevis et al. 1992; Davis et al. 1985). Thus, studying their spatial and temporal variability provides relevant information for forecasting and monitoring significant meteorological events (Aragón Paz et al. 2023; Ferrando et al. 2017; Maciejewska 2025; Selbesoglu 2019). In this context, the established research collaboration focuses on the improvement and validation of the G4M (GNSS for Meteorology) procedure (Benvenuto et al. 2018; Ferrando et al. 2018), implemented by UniGe's Geomatics Laboratory, to (1) generate Precipitable Water Vapor (PWV) maps across Italy with high spatial and temporal resolutions, and (2) identify possible correlations between seismic events and PWV anomalies (Doğganalp and Köz 2024; Guo et al. 2023, 2025). Originally, G4M was applied to produce PWV maps at an inter-regional scale from Zenith Total Delay (ZTD) data derived from existing GNSS regional permanent stations (Sguerso et al. 2013, 2016) and non-co-located pressure (P) and temperature (T) observations. The procedure was successfully tested in northern Italy and eastern France during several meteorological events, showing encouraging results when compared with rain gauge data (Benvenuto et al. 2020). The current research will produce high resolution PWV maps over the national territory, intended to serve as a valuable contribution for early-warning systems. Within this framework, the present study evaluates the coherence, availability, and quality of meteorological observations, mainly P and T, as key parameters for PWV retrieval (Jadala et al. 2022; Li et al. 2022; Shen et al. 2024; Zhang et al. 2025). The paper is structured as follows: Sect. 2 describes the adopted methodology, Sect. 3 presents and discusses the obtained results, and Sect. 4 reports conclusions and future developments.

2 Methodology

The methods for analyzing the coherence of environmental parameters, i.e., P and T observations, deriving from open-data providers that ensure stable data collection and publication frequencies over time, is here described. Data sources adopting data exchange technologies via API (Application Programming Interface) or FTP (File Transfer Protocol) were prioritized. Specifically, NOAA and MNW data providers were considered for this study, to pursue the following objectives: (1) to evaluate the number and spatial distribution of meteorological stations to assess their suitability as data sources, and (2) to examine the coherence between the two datasets, using NOAA stations data as a benchmark.

2.1 Datasets

NOAA Integrated Surface Data (NOAA ISD) provides global hourly and sub-hourly meteorological measurements collected from a network of fixed stations. NOAA meteorological stations deliver both historical and continuous records on variables such as temperature, pressure, sky visibility and wind conditions. The data frequency varies by station, depending on individual capabilities. The NOAA ISD stations in Italy were selected as the reference network for this study due to their long-term operational stability, official-status and their extensive historical archive. The distribution of NOAA stations over Italy is shown in Fig. 1b, with an average inter-distance of 91 km.

MNW Citizen Weather Stations (CWSs) initiated in 2002 and actively operated by the MeteoNetwork association since then. The network is providing a high spatial density source of the meteorological observations over Italy, with fewer stations over the surrounding countries. Figure 1c illustrates the spatial distribution of the operated MNW over Italy, with an average inter-distance of 17 km.

2.2 Data Downloading

NOAA ISD provides continuously updated meteorological data for each station with a typical latency of 2 to 4 days through FTP protocol. In this study, complete datasets for 2023, 2024 and the first four months of 2025 were considered. As a pre-processing step, only P and T data indicated by the quality flag "Passed all quality control checks" assigned by the NOAA ISD standards were retained. MNW data can be accessed via API. The performed analysis of data transmission latency indicates that more than 90% of MNW stations deliver observations with a delay of 10 minutes or less. P and T observations for the period spanning from January 2023 to the end of April 2025 were considered, matching the time frame of the NOAA ISD dataset to ensure comparability. Due to the huge volume of datasets, data for five fixed days each month (3rd, 10th, 17th, 21st, and 27th) within this period were extracted.

2.3 Data Synchronization

To ensure a meaningful comparison, MNW stations located within a 10 km radius from NOAA stations in Italy were selected, resulting in 98 NOAA-MNW pairs. MNW observations were temporally synchronized to NOAA's ones. Moreover, T observations were adjusted to match the altitude of the corresponding NOAA station, according to the well-known expression of the vertical thermal gradient, reported in Eq. 1, where $\Gamma = 0.0065$ °C/m.

$$\Gamma = -\frac{dT}{dz} \tag{1}$$

P data required no further adjustment, since they are referred at the same reference height, i.e., the mean sea level height, in both datasets.

2.4 Data Cleaning and Reliability Assessment

To analyze the coherence between MNW and NOAA measurements, the P and T differences (ΔP and ΔT, respectively) were analyzed. The Inter Quartile Range (IQR) method (Tukey 1977) was selected as the core cleaning process to exclude anomalous observations from the considered datasets, based on the assumption that the distribution of ΔP and ΔT is centered around zero. The statistical metrics, i.e., mean value, standard deviation and the 90th percentile of the Root Mean Square Error (RMSE), of ΔP and ΔT were estimated before and after the cleaning process. Additionally, the 90th percentile of the RMSE of the cleaned data was applied as a filter to assess MNW stations reliability (Castell et al. 2017; Sousan et al. 2016).

Table 1 Variation of PWV based on P and T changes within their tolerance intervals

Parameter	Tolerance interval	Variation of PWV
P	$1013.25 \pm 3 \cdot 1$ hPa	1.7 mm
T_m	$277.67 \pm 3 \cdot 0.72$ K	0.5 mm

Thanks to the variance propagation, a sensitivity analysis was performed (Table 1) to determine how the PWV value is influenced by the variation of P and T within their tolerance intervals $\mu \pm 3 \cdot \sigma$, where μ represents the expected value and σ stands for the standard deviation. The standard deviations are set to the conservative values of $\sigma_P = 1$ hPa and $\sigma_T = 1$ K, whereas P and T values are assumed as P = 1013.25 hPa and T = 288.15 K, in accordance with the International Civil Aviation Organization (ICAO) definition of standard atmosphere.

The weighted average temperature T_m is obtained as (Bevis et al. 1992)

$$T_m = 70.2 + 0.72 \cdot T \tag{2}$$

Thus, using the linear variance propagation formula to Equation 2, the standard deviation of T_m is equal to 0.72 K.

A MNW station was considered reliable if its RMSE value is below both the year-specific 90th percentile of all stations and the amplitude of tolerance interval ($\pm 3 \cdot \sigma$). Consequently, data from unreliable stations were excluded, and the statistical parameters were recalculated. The overall coherence analysis procedure is summarized in the diagram in Fig. 2.

3 Results and Discussion

As shown in Table 1, a variation of 6 hPa in P, corresponding to the amplitude of the tolerance interval, results in an effect on PWV of less than 2 mm, while a variation of approximately 4 K in T produces an effect of less than 1 mm. These findings confirm the validity of the reliability thresholds defined in the methodology, that let to identify the MNW stations to be retained for subsequent analysis, i.e., the ones providing data with consistent accuracy.

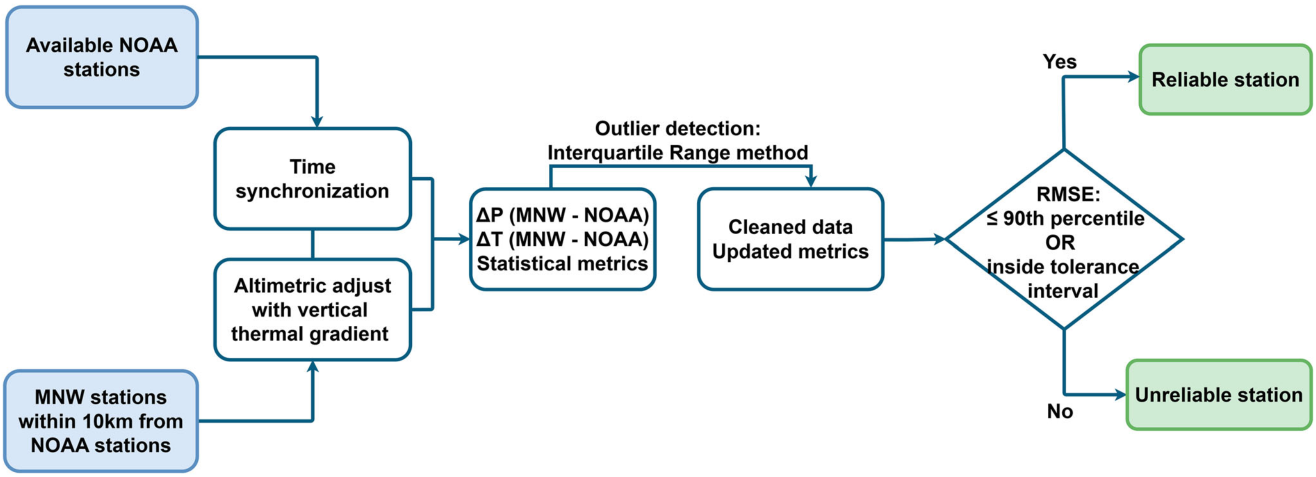

Fig. 2 Coherence assessment workflow

Following this workflow, 91 out of the 98 selected MNW stations were identified as reliable for the considered time period. Table 2 reports the statistical metrics of ΔP and ΔT before and after data cleaning, based only on the IQR method and also after excluding the unreliable MNW stations.

As shown in Table 2, both ΔP and ΔT values improved after data cleaning and the exclusion of unreliable stations: the mean standard deviations decreased from 0.59 to 0.44 hPa and from 1.28 to 1.10 °C, for ΔP and ΔT, respectively, indicating reduced variability. The small magnitude of ΔP and ΔT reflects a high level of coherence between MNW and NOAA observations.

Following data cleaning and metrics computation, plots were generated for the different MNW stations to visually highlight the magnitude of differences between the various years. As an illustrative example, the left panel of Fig. 3 shows the accordance of P and T observations for the randomly selected pair of stations formed by the NOAA Vigna di Valle (in red) and the corresponding MNW laz179 (in blue), over the entire study period, whereas its right panel reports the box-plots of ΔP and ΔT for all the considered NOAA-MNW pairs. The majority of median values, i.e., the horizontal lines within the boxes, of ΔP and ΔT are concentrated within $[-2, +2]$ hPa and $[-1, +1]$ °C, respectively, with relative boxes heights, representing the spread of the central 50% of data, of about 1 hPa and 2 °C.

4 Conclusions and Future Developments

The workflow for data cleaning based on IQR method and statistical metrics of ΔP and ΔT enables a straightforward identification of reliable MNW stations, that show a high level of consistency with NOAA datasets for both environmental parameters. Over the 98 selected MNW stations, only 7 were deemed as unreliable following this criterion. A key advantage of using the MNW stations is the near real-time availability of data, that will enable the generation of PWV maps with minimal latency. These findings demonstrate that the research project can rely exclusively on the MNW network, that has a denser and more homogeneous coverage compared to NOAA (815 vs 52 P stations; 891 vs 134 T stations) over the Italian territory. Ongoing work focuses on performing a similar consistency assessment using the MISTRAL dataset (Meteo Italian Supercomputing poRtAL)[6] (Bottazzi et al. 2021), to enrich the geoDataBase (geo-DB) and to enhance the spatial and temporal accuracy of the PWV maps. Further development will include the integration of environmental data and ASI's ZTD estimates into a geo-DB connected with the G4M procedure. This integration will facilitate the realization of PWV maps for the analysis of meteorological events and the investigation of potential correlations between seismic activity and PWV anomalies.

Declarations This research project is funded by the Italian Space Agency (ASI) under Implementing Agreement No. 2024-25-HH.0, 'Monitoraggio dello stato troposferico a livello nazionale e precursori sismici a partire dai dati della nuova rete fiduciale nazionale GNSS dell'ASI' (CUP: F33D24000060001).

Competing Interests The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

[6] https://meteohub.agenziaitaliameteo.it/ui/homepage?lang=it

Table 2 Metrics for NOAA–MNW comparison: before and after data cleaning, and after excluding unreliable stations

	ΔP [hPa]			ΔT [°C]		
	Mean Error	Mean STD	RMSE 90th	Mean Error	Mean STD	RMSE 90th
Before data cleaning	0.38	0.59	2.19	−0.35	1.28	2.05
After data cleaning	0.39	0.49	2.13	−0.33	1.12	2.01
Only reliable stations	0.34	0.44	2.08	−0.33	1.10	1.90

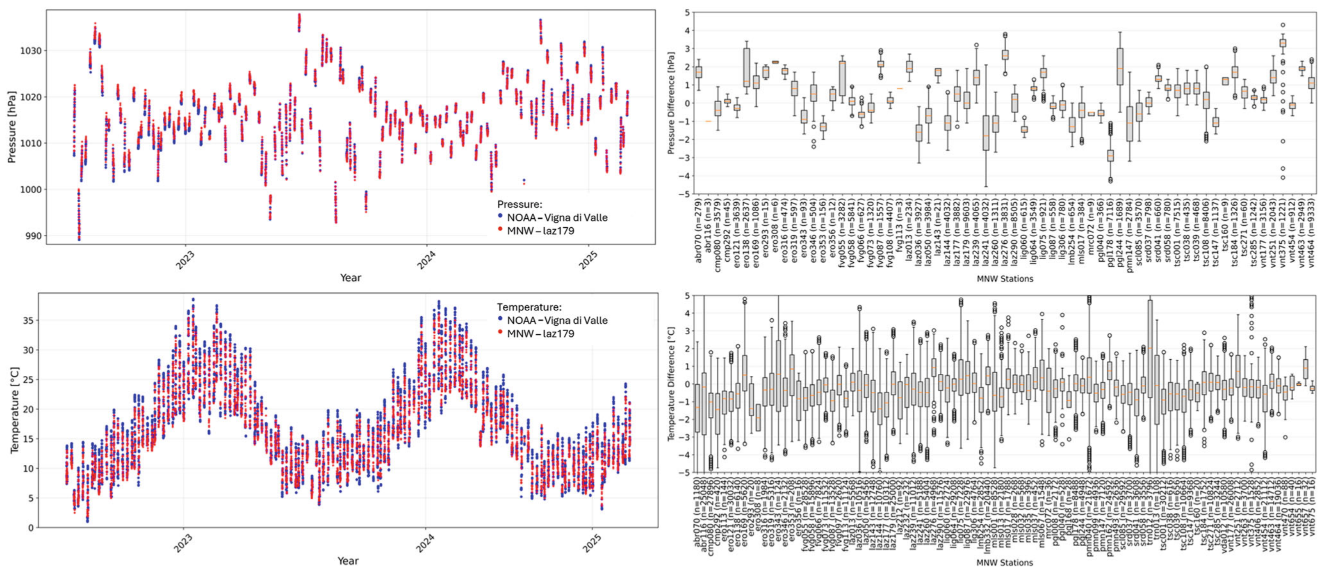

Fig. 3 P and T time-series from a NOAA-MWN stations couple (left) and box-plots of the estimated differences (right) for all paired NOAA-MNW stations. Along x-axis on the right panel, *n* represents the number of coupled observations, and the names refer to MNW stations

References

Aragón Paz JM, Mendoza LPO, Fernández LI (2023) Near-real-time GNSS tropospheric IWV monitoring system for South America. GPS Solut 27(2). https://doi.org/10.1007/s10291-023-01436-2

Benvenuto L, et al. (2018) A procedure to manage open access data for post-processing in GIS environment. Peer J 6(e27227v1). Preprints. https://doi.org/10.7287/peerj.preprints.27227v1

Benvenuto L, et al. (2020) The GNSS for Meteorology (G4M) procedure and its application to four significant weather event. In: Novák P, et al. (eds) International Association of Geodesy Symposia, vol 151. Springer, Cham, pp 137–145. https://doi.org/10.1007/1345_2020_111

Bevis M, et al. (1992) GPS meteorology: Remote sensing of atmospheric water vapor using the global positioning system. J Geophys Res 97(14):15787–15801. https://doi.org/10.1029/92JD01517

Bottazzi M, et al. (2021) The Italian Open data meteorological portal: MISTRAL. Meteorol Appl 28(4):e2004. https://doi.org/10.1002/met.2004

Castell N, et al. (2017) Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates? Environ Int 99:293–302. https://doi.org/10.1016/j.envint.2016.12.007

Davis JL, et al. (1985) Geodesy by radio interferometry: Effects of atmospheric modeling errors on estimates of baseline length. Radio Sci 20(6):1593–1607. https://doi.org/10.1029/RS020i006p01593

Doğganalp S, Köz İ (2024) Monitoring ionospheric and atmospheric conditions during the 2023 Kahramanmaraş earthquake period. Atmosphere 15(12). https://doi.org/10.3390/atmos15121542

Ferrando I, Federici B, Sguerso D (2018) 2D PWV monitoring of a wide and orographically complex area with a low dense GNSS network. Earth Planets Space 70(54). https://doi.org/10.1186/s40623-018-0824-6

Ferrando I, Federici B, Sguerso D (2017) Zenith total delay interpolation to support GNSS monitoring of potential precipitations. Geam Geoingegneria Ambientale E Mineraria 151:85–90. https://unige.iris.cineca.it/handle/11567/888405.

Giazzi M, et al. (2022) Meteonetwork: An open crowdsourced weather data system. Atmosphere 13. https://doi.org/10.3390/atmos13060928

Guo A, et al. (2023) Analyzing correlations between GNSS retrieved precipitable water vapor and land surface temperature after earthquakes occurrence. Sci Total Environ 872. https://doi.org/10.1016/j.scitotenv.2023.162225

Guo A, et al. (2025) Land surface temperature, tropospheric and ionospheric anomalies analysis and implementation of a co-seismic PWV digital twin for the February 6, 2023 Turkey earthquake. Geomat Natural Hazards Risk 16(1). https://doi.org/10.1080/19475705.2025.2491470

Jadala NB, et al. (2022) Integrated water vapor during active and break spells of monsoon and its relationship with temperature, precipitation and precipitation efficiency over a tropical site. Geodesy Geodynam 13(3). https://doi.org/10.1016/j.geog.2021.09.008

Li L, et al. (2022) An improved method for rainfall forecast based on GNSS-PWV. Remote Sens 14(17). https://doi.org/10.3390/rs14174280

Maciejewska A (2025) Use of tropospheric delay in GNSS-based climate monitoring—A review. Remote Sens 17. https://doi.org/10.3390/rs17091501

Selbesoglu MO (2019) Spatial interpolation of GNSS troposphere wet delay by a newly designed artificial neural network model. Appl Sci 9(21). https://doi.org/10.3390/app9214688

Sguerso D, Labbouz L, Walpersdorf A (2013) 14 years of GPS tropospheric delays in the French-Italian border region: a data base for meteorological and climatological analyses. In: The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XL-5/W3, pp. 7–14. https://doi.org/10.5194/isprsarchives-XL-5-W3-7-2013

Sguerso D, Labbouz L, Walpersdorf A (2016) 14 years of GPS tropospheric delays in the French–Italian border region: comparisons and first application in a case study. Appl Geomat 8(1):13–25. https://doi.org/10.1007/s12518-015-0158-z

Shen Y, et al. (2024) An empirical atmospheric weighted average temperature enhancement model in the Yunnan–Guizhou plateau considering surface temperature. Remote Sens 16(23). https://doi.org/10.3390/rs16234366

Sousan S, et al. (2016) Inter-comparison of low-cost sensors for measuring the mass concentration of occupational aerosols. Aerosol Sci Technol 50(5):462–473. https://doi.org/10.1080/02786826.2016.1162901

Tukey JW (1977) Exploratory data analysis. Addison-Wesley, Reading, MA

Zhang Q, et al. (2025) Investigation of the application of measured meteorological observations in real-time precise point positioning. Remote Sens 17(10). https://doi.org/10.3390/rs17101773