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Automation of positional time series acquisition and velocity field generation

Automatização da obtenção de séries temporais posicionais e da geração de campos de velocidades

Krisley Xavier Soares de Freitas[1]; William Rodrigo Dal Poz[2]; Júlio César de Oliveira[3]; Lécio Alves Nascimento[4]

[1] Federal University of Viçosa (UFV), Department of Civil Engineering, Viçosa/MG, Brazil. Email: krisle.freitas@ufv.br
ORCID**:** https://orcid.org/0000-0001-8453-324X

[2] Federal University of Viçosa (UFV), Department of Civil Engineering, Viçosa/MG, Brazil. Email: william.dalpoz@ufv.br
ORCID**:** https://orcid.org/0000-0001-9532-364

[3] Federal University of Viçosa (UFV), Department of Civil Engineering, Viçosa/MG, Brazil. Email: oliveirajc@ufv.br
ORCID**:** https://orcid.org/0000-0003-0894-5597

[4] Federal Institute of Education, Science and Technology of Northern Minas Gerais (IFNMG), Araçuaí/MG, Brazil.
Email: lecio.nascimento@ifnmg.edu.br
ORCID**:** https://orcid.org/0000-0003-2499-4372

Abstract: The aim of this paper is to present the GPTS Downloader software, which allows for the acquisition of positional time series from over 23,400 continuous monitoring stations around the world - provided by the Nevada Geodetic Laboratory - and the automated generation of velocity fields. To demonstrate the potential of GPTS Downloader, velocity fields were generated for the United States using six interpolation methods from 20-year time series from more than 100 stations. The interpolated velocities were applied in temporal coordinate updates, and their discrepancies were analyzed. Among the methods analyzed, Radial Basis Function interpolation proved to be the most reliable for interpolating velocities estimated from positional time series due to its greater consistency. The discrepancies obtained using the interpolated velocities were significantly better than those obtained with the 18 velocity models commonly used by the geodetic community.

Keywords: Positional time series; Velocity field; GPS.

Resumo: O presente artigo tem como objetivo apresentar o software GPTS Downloader, que possibilita a obtenção de séries temporais posicionais de mais de 23.400 estações de monitoramento contínuo ao redor do mundo - disponibilizadas pelo *Nevada Geodetic Laboratory* - e a geração de campos de velocidades de forma automatizada. De forma a demonstrar a potencialidade do GPTS Downloader, geraram-se campos de velocidades para os Estado Unidos com seis métodos de interpolação a partir de séries temporais de 20 anos de mais de 100 estações. As velocidades interpoladas foram aplicadas em atualizações temporais de coordenadas e suas discrepâncias analisadas. Por apresentar a maior consistência entre os métodos analisados, a interpolação de Função de Base Radial se mostrou o método mais confiável para interpolar velocidades estimadas a partir de séries temporais posicionais. As discrepâncias obtidas com as velocidades interpoladas foram significativamente melhores que aqueles obtidas com 18 modelos de velocidades utilizados pela comunidade geodésica.

Palavras-chave: Série temporal posicional; Campo de velocidades; GPS.

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1. Introduction

The Global Positioning System (GPS) plays a fundamental role in modern Earth sciences, enabling the investigation and monitoring of phenomena such as volcanoes, earthquakes, tsunamis, sea level changes, glaciers, aquifers, crustal deformation, and tectonic plate motion (BLEWITT; HAMMOND; KREEMER, 2018). These studies typically rely on the analysis of positional time series - sets of coordinates ordered in time, derived from GPS observations and referenced to a specific coordinate system - as well as on geodetic velocities, which describe long-term trends along with seasonal variations and noise present in the data (HE et al., 2017).

Bogusz et al. (2016) highlight that the number of GPS stations continues to grow steadily, moving toward near-global coverage. At the same time, the increasing length of available datasets, combined with advances in computational capabilities, has expanded methodological and analytical possibilities across various fields that rely on positional time series. For example, Nascimento et al. (2021) used positional and limnimetric time series to investigate deformations associated with hydrological loading in the Brazilian Amazon; Kierulf et al. (2021) developed a velocity field for Fennoscandia to study both local crustal deformation and large-scale geodynamic processes; Ramos, Dal Poz, and Carvalho (2021) estimated station velocities in Brazil while accounting for seasonal signals, trends, and noise; Kılıç and Özarpacı (2022) proposed an Ensemble Clustering approach to estimate station velocities and analyze crustal displacements in Turkey, a region influenced by the interaction of the Arabian, African, and Eurasian plates; Pırtı, Hoşbaş, and Yücel (2023) examined horizontal and vertical displacements in Iceland, located along the Mid-Atlantic Ridge at the boundary between the North American and Eurasian plates; and Savchyn, Brusak, and Tretyak (2023) investigated the kinematics of Antarctic tectonic plates.

Access to high-quality positional time series derived from robust positioning techniques is therefore essential for advancing scientific research and enabling new applications. In this context, the Nevada Geodetic Laboratory (NGL) has developed a system that lowers barriers to data access and supports a wide range of investigations. Currently, the NGL collects raw data from more than 23,400 stations worldwide, with some records spanning over 30 years. These data are processed in-house using the Precise Point Positioning (PPP) approach implemented in the GipsyX software (GNSS-Inferred Positioning System X), developed by the Jet Propulsion Laboratory (JPL). The resulting geodetic and Cartesian coordinates - based on 24-hour observation sessions - are made freely available to users, along with their associated precision estimates and covariance information (BLEWITT; HAMMOND; KREEMER, 2018). However, the availability of such a large volume of data also poses challenges in terms of providing efficient, intuitive tools for data access, spatial visualization, and station selection.

At present, users interested in stations from a specific country must navigate an online map, identify stations individually, and download their data one by one. This process is time-consuming and inefficient, particularly when dealing with large station networks. To streamline data acquisition, automated solutions have been proposed, as described in Zhongshan (2026). Nevertheless, this approach still has important limitations. It is implemented in MATLAB (Matrix Laboratory), requiring both familiarity with the language and access to the software. Moreover, it provides only data in a Local Geodetic System (LGS) and is restricted to stations located within a predefined polygon.

To address these limitations, this paper introduces a Windows-based software tool named GPTS Downloader (GPS Position Time Series Downloader), designed to simplify the selection of stations and access to positional time series provided by the NGL. In addition, the software enables the automated generation of velocity fields derived from the retrieved time series. To demonstrate its capabilities, velocity fields for the United States were generated using six interpolation methods based on time series from more than 100 stations. The interpolated velocities were then used to update coordinates over time, and the resulting discrepancies were analyzed.

2. NGL Positional Time Series

The NGL aggregates raw data collected by GPS stations from more than 130 online repositories, aiming to gather as much useful information as possible in a single platform. These data are collected, managed, and distributed by hundreds of organizations that collaborate through institutions such as the IGS (International GNSS Service) and UNAVCO (University NAVstar Consortium). To handle this vast volume of raw data, the NGL system relies on advanced processing strategies, automated workflows, and robust estimation algorithms and techniques.

It is important to note that raw data processing is carried out using the GipsyX software (BERTIGER et al., 2020). The parameters adopted in the processing strategy are summarized and can be accessed at https://geodesy.unr.edu/gps/ngl.acn.IGS20.txt. After processing, positional time series are made available, including both geodetic coordinates (latitude, longitude, and ellipsoidal height) and Cartesian coordinates (X, Y, Z), along with their respective precision estimates and covariance information for all identified stations. These datasets are provided with different observation intervals and varying latencies (i.e., the time between data acquisition and availability for use) (BLEWITT; HAMMOND; KREEMER, 2018).

It is worth emphasizing that all time series are referenced to a common reference frame, IGS20 (since August 2025) (NGL, 2026). Most of the available positional time series span periods ranging from 5 to 15 years, as illustrated in Figure 1. In addition, a significant number of series extend from 15 to 33 years. This highlights the potential of these datasets to support more comprehensive investigations of long-term effects, trends, and periodic signals.

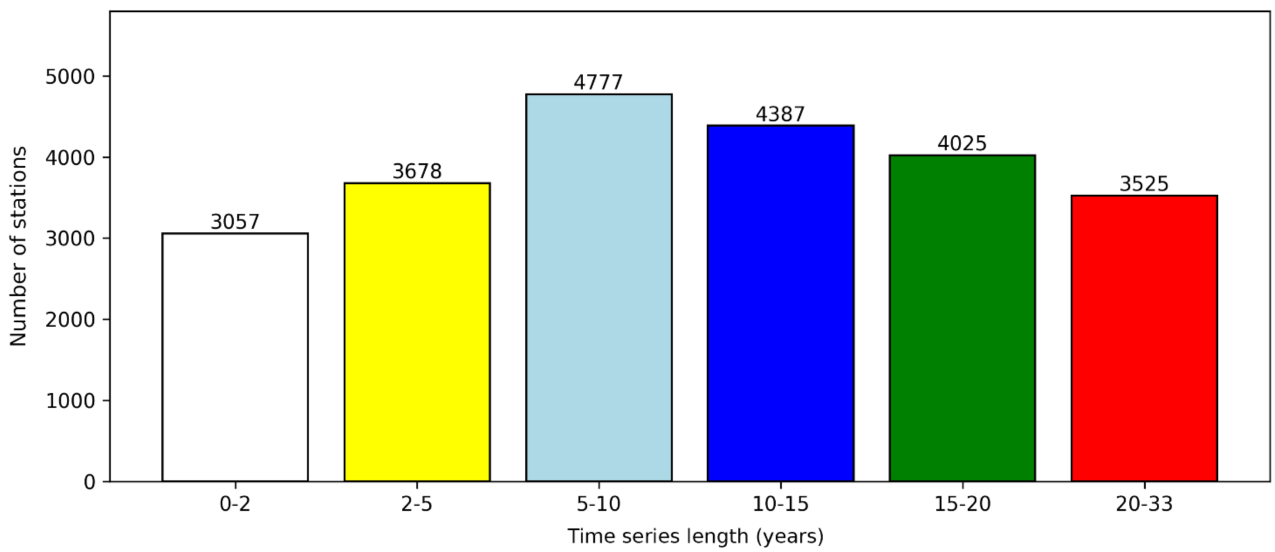

Figure 1 – Number of positional time series available in April 2026 and their respective lengths.
Source: Authors (2026). Data: NGL (2026).

As of April 2026, the NGL updates weekly the processed coordinates based on 24-hour observations from 23,448 stations, and daily the 5-minute coordinates from 8,521 stations (NGL, 2026). The spatial distribution of the stations, as well as the temporal coverage of the positional time series provided by the NGL in 2026, are shown in Figure 2.

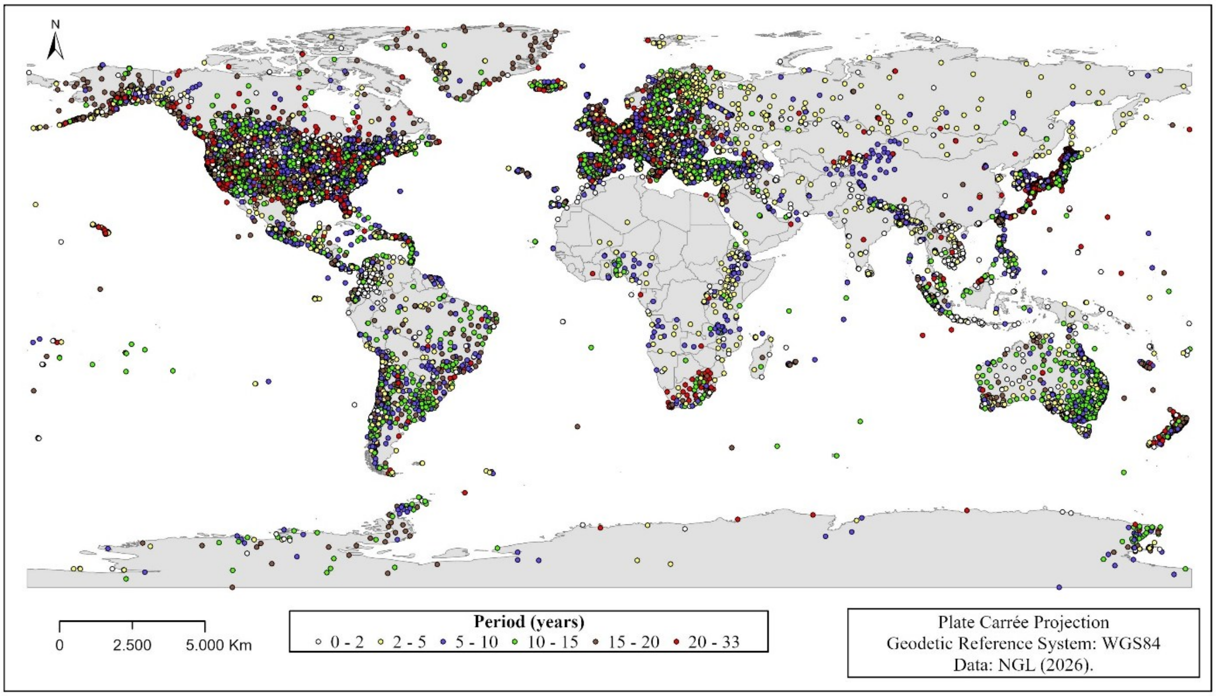

Figure 2 – Spatial distribution and data coverage period of stations included in the NGL as of April 2026. Source: Authors (2026).

In addition to coordinates, station velocities are also periodically updated. These velocities are estimated using MIDAS (Median Interannual Difference Adjusted for Skewness), a method designed to provide robust velocity estimates for GPS stations, being insensitive to outliers, annual seasonality, discontinuities (offsets), and heteroscedasticity (BLEWITT et al., 2016).

The products generated by the NGL are made freely available online at https://geodesy.unr.edu. These include metadata, station lists, positional time series plots, tables of available data, and descriptions of new product releases and updates.

3. GPTS Downloader

The software named GPTS Downloader was developed to facilitate both the selection and acquisition of positional time series. It enables data classification based on the start and end dates of availability, the total time span (in years) between these dates, the number of days with available data, as well as the number of days with missing data for all stations.

In addition, location-based filters were implemented, allowing users to select stations by country, as well as to input their own list of specific stations. The GPTS Downloader interface is shown in Figure 3.

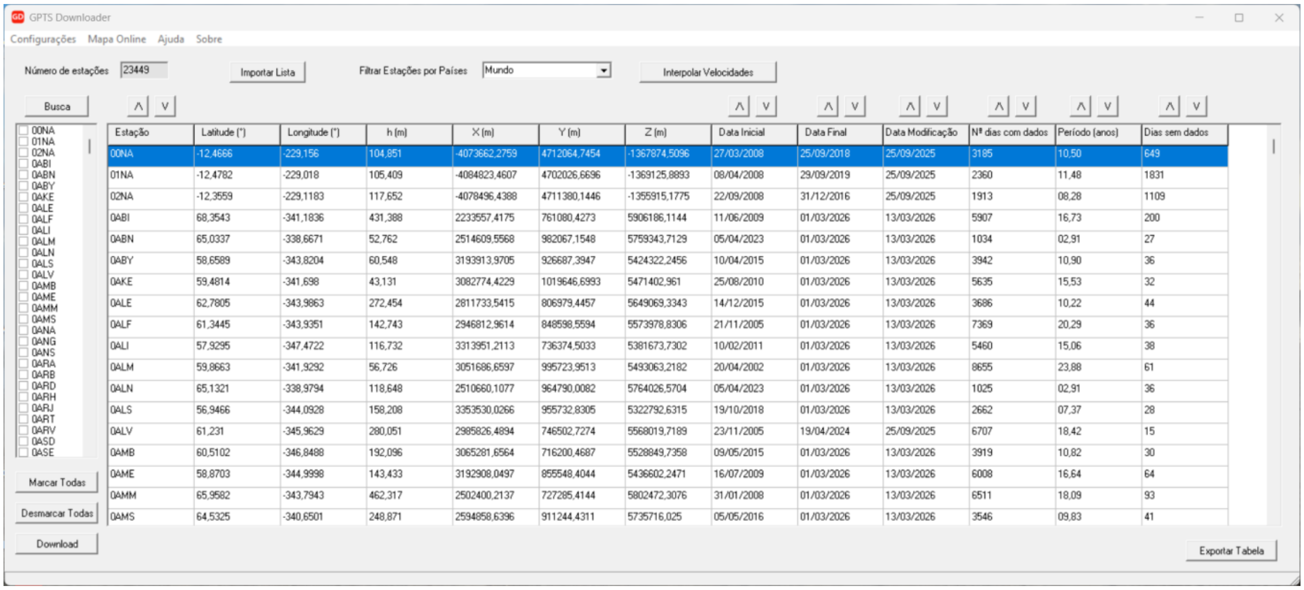

Figure 3 – GPTS Downloader interface. Source: Authors (2026).

Station information is displayed in a customizable table on the program's main interface and is based on the file containing the list and metadata of available stations provided by the NGL. In this regard, GPTS Downloader automatically downloads this file each time it is executed, ensuring that station information is always up to date.

GPTS Downloader includes region-based location filters for all countries with available stations. For example, when selecting the Brazil filter (based on data from April 2026), instead of viewing more than 23,400 stations worldwide, only the 231 stations located within Brazilian territory are displayed. From the available information, it can be observed that 219 of these stations have at least 365 days of data, and 118 span periods longer than 10 years. The station with the longest operational record is BRAZ (over 30 years), with data starting on March 5, 1995, and still in operation, despite having 1,160 days of missing data in its time series.

It is worth noting that these filters are automatically generated using the Python geopandas library, which performs a geospatial selection of station coordinates based on a shapefile of political boundaries provided by Tapiquén (2015). Users can also import their own list of stations using the "Import List" option by simply providing station names in alphabetical order within a text file. This feature allows users to select specific stations or combine stations from different filters for downloading positional time series, thereby improving the efficiency of the data acquisition process.

Once the stations have been selected - ranging from a single station to the entire dataset of over 23,000 stations - the user only needs to click a button to download the corresponding positional time series.

Additionally, the software includes an internal application named "Velocity Interpolation," whose functionality is to read the files generated by GPTS Downloader, compute station velocities, and interpolate these velocities for user-defined points of interest. The following interpolation methods are available: griddata, Inverse Distance Weighted (IDW), K-Nearest Neighbors (KNN), Ordinary Kriging (OK), Radial Basis Function (RBF), and Random Forest Regression (RF).

The GPTS Downloader software is freely available at https://rinexhub.wordpress.com/gptsdownloader . Further details regarding its functionality and operation can be found in the user manual, accessible through the "Help" menu within the software interface.

4. Materials and methods

For the experiments, positional time series derived from daily GPS solutions of 113 stations located in the United States of America were used (see Figure 4). All available stations that met the following two criteria were selected: (i) having a time series covering the period from January 1, 2000, to December 31, 2019 (20 years); and (ii) having RINEX (Receiver Independent Exchange Format) observation data available for six days at the beginning of the time series, which were used to estimate the reference coordinates.

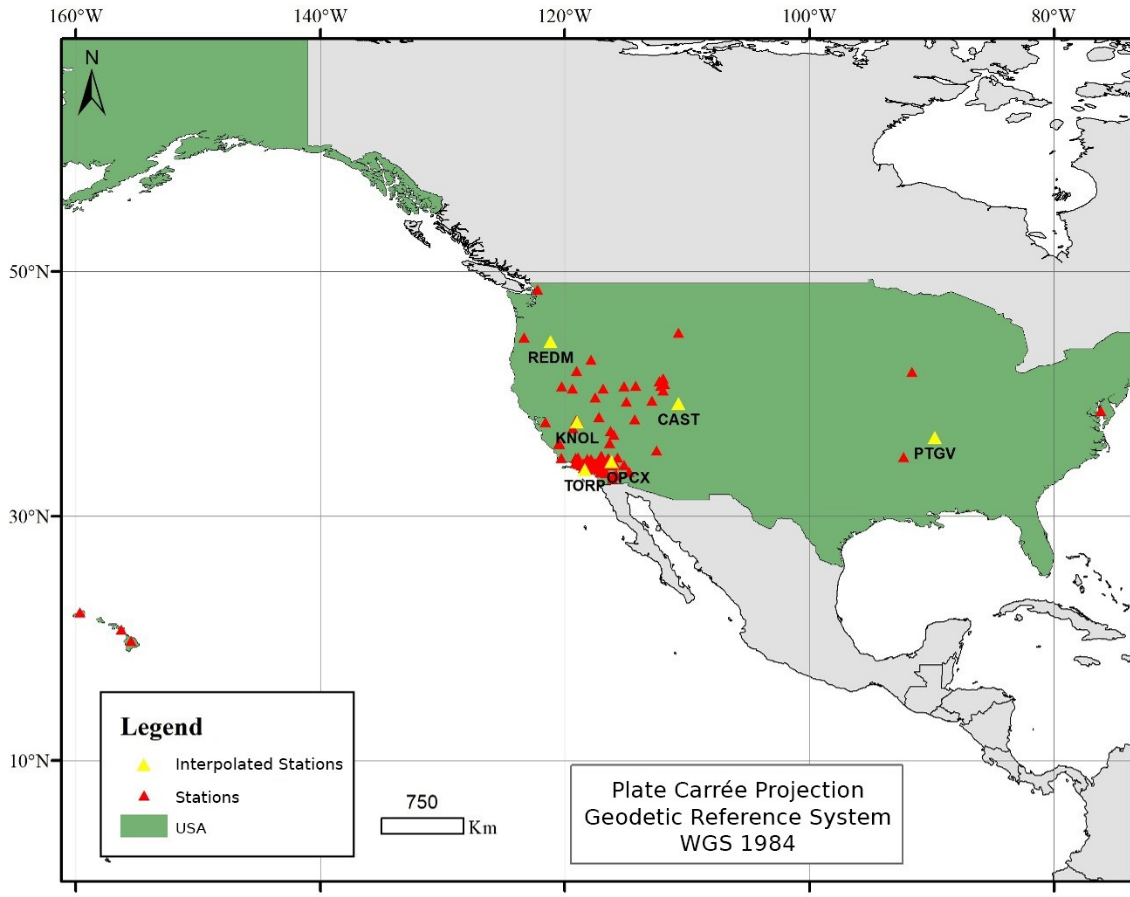

Figure 4 – Spatial distribution of stations across the United States of America. Source: Authors (2026).

To estimate velocities from the positional time series, the simple linear regression method was adopted, as employed by Bogusz et al. (2016), Nascimento, Dal Poz, and Freitas (2021), and Ramos, Dal Poz, and Carvalho (2021). This approach was implemented using machine learning techniques through the Scikit-learn library (PEDREGOSA et al., 2011) in Python.

All positional time series used in this study contained missing data for certain days over the 20-year period. Since velocity estimation depends on the temporal component of the positions, these gaps were filled using linear interpolation, following approaches adopted by Moritz et al. (2015), Klos et al. (2018), and Nascimento et al. (2021).

It is important to note that velocities were estimated directly from the NGL time series without pre-processing steps to remove outliers, seasonal signals, or noise. Ramos, Dal Poz, and Carvalho (2021), when analyzing the impact of seasonality on velocity estimation for Brazilian stations, found that neglecting this aspect does not significantly affect planimetric results. They also reported the presence of white noise and flicker noise in station time series, which did not significantly influence the estimated velocities for datasets spanning seven years. However, Klos, Bos, and Bogusz (2018) point out that if seasonal signals and residual periodicities are not properly removed, velocity uncertainties may be artificially overestimated.

Once station velocities were estimated, six interpolation methods were evaluated to derive velocities at unknown locations: griddata - an implementation of the natural neighbor interpolation technique (SIBSON, 1981); Inverse Distance Weighted (IDW) (SHEPARD, 1968); K-Nearest Neighbors (KNN) (FRANK, 2023); Radial Basis Function (RBF) interpolation (ANJYO; LEWIS, 2011); Ordinary Kriging (OK) (JOURNEL; HUIJBREGTS, 1978); and Random Forest Regression (RF) (BREIMAN, 2001). To assess the results, six out of the 113 stations (CAST, KNOL, PTGV, REDM, OPCX, and TORP) were treated as unknown points, and their velocities estimated from the time series were used as reference values. The remaining 107 stations were used as input data for the interpolation procedures. All aforementioned steps - including data acquisition, gap filling, velocity estimation, and interpolation - were fully automated using GPTS Downloader.

With the interpolated velocities available, temporal coordinate updating was then performed. The coordinates selected for updating correspond to all 365 days of the year 2019 (from January 1 to December 31, 2019; day-of-year 1 to 365) for all stations. These were updated to a reference date/epoch, defined as the initial epoch of the time series (January 1, 2000; epoch 2000.00). To minimize seasonal effects - such as hydrological variations (e.g., wet and dry periods) that can influence the positions of stations located near large water bodies - the mean of the 365 resulting discrepancies was analyzed for each station.

To update station coordinates from epoch t_0 to epoch t, Equation (1) is used (SIRGAS, 2026):

$$\begin{aligned} X_{(t)} &= X_{(t_0)} + v_X(t - t_0) \\ Y_{(t)} &= Y_{(t_0)} + v_Y(t - t_0) \\ Z_{(t)} &= Z_{(t_0)} + v_Z(t - t_0) \end{aligned} \quad (1)$$

where t is the epoch of interest; t_0 is the reference epoch; $X(t_0), Y(t_0), Z(t_0)$ are the Cartesian coordinates of the station at the reference epoch; $X(t), Y(t), Z(t)$ are the coordinates at the epoch of interest; and v_x, v_y, v_z are the velocity components of the station.

It is important to emphasize that all positional time series used in this study are referenced in a common reference frame (IGS14/ITRF2014 - note that the data were obtained prior to August 2025, when the series began to be referenced to IGS20/ITRF2020). Therefore, no reference frame transformation is required for either the coordinates or the velocities, since the latter are estimated within the same reference frame as the coordinates.

As official coordinates for the stations at the desired date/epoch were not available, it was necessary to adopt a processing strategy to estimate reference coordinates directly at the epoch of interest with known accuracy. Ebner and Featherstone (2008), who compared coordinates of 46 stations from a moderately sized geodetic control network (~550 km × ~440 km) processed using the scientific software Bernese v5 and the CSRS-PPP service, recommend processing six consecutive days (144 hours) of observation data—corresponding to the current maximum processing limit of CSRS-PPP—to achieve results comparable to those obtained with Bernese network processing. Accordingly, this approach was adopted to derive the reference coordinates.

For each station, six 24-hour observation files were concatenated, obtained from the GAGE Data File Server (GAGE, 2026). Following the approach of Cunha (2020) and Freitas, Dal Poz, and Nascimento (2022), the selected files correspond to three days before and two days after the reference day, ensuring that the reference epoch is centered within the observation interval.

With both the updated and reference coordinates available, planimetric discrepancies were computed. The sequence of calculations required to obtain these discrepancies is described in Ramos, Dal Poz, and Carvalho (2016) and Freitas, Dal Poz, and Nascimento (2021). It should be noted that altimetric discrepancies were not analyzed, as highlighted by Drewes and Heidbach (2012) and IBGE (2015), since the coordinate updating process is predominantly horizontal.

In addition, a comparison will be carried out between the planimetric discrepancies obtained after updating coordinates using the interpolated velocities and those derived from 18 velocity models commonly used by the geodetic community, namely:

- NUVEL 1 (ARGUS; GORDON, 1991);
- NUVEL 1A (DEMETS et al., 1994);
- HS2-NUVEL1A (*Hot Spot2 Northwestern University Velocity model* 1A) (GRIPP; GORDON, 1990; DEMETS et al.1994);
- APKIM2000.0 (DREWES, 1998; DREWES; ANGERMANN, 2001);
- ITRF2000 (DREWES; ANGERMANN 2001);
- ITRF2000 (ALTAMIMI; SILLARD; BOUCHER, 2002);
- HS3-NUVEL1A (Hot Spot3 NUVEL 1A) (GRIPP; GORDON, 2002);
- GSRM v1.2 (*Global Strain Rate Model*) (KREEMER; HOLT; HAINES, 2003);
- CGPS 2004 (*Continuous* GPS 2004) (PRAWIRODIRDJO; BOCK, 2004);

- REVEL 2000 (SELLA; DIXON; MAO, 2004);
- APKIM2005-DGFI (*Deutsche Geodätische Forshungsinstitu*) (DREWES, 2009);
- APKIM2005-IGN (*Institute Géographique National*) (DREWES, 2009);
- MORVEL 2010 (*Mid Ocean Ridge Velocity* 2010) (DEMETS; GORDON; ARGUS, 2010);
- GEODVEL 2010 (*Geodesy Velocity* 2010) (ARGUS et al. 2010);
- NNR-MORVEL56 (ARGUS; GORDON; DEMETS, 2011);
- ITRF2008 (ALTAMIMI; MÉTIVIER; COLLILIEUX, 2012)
- GSRM v2.1 (KREEMER; BLEWITT; KLEIN, 2014); e,
- ITRF2014 (ALTAMIMI et al., 2016);

The models are provided by the Plate Motion Calculator, developed by UNAVCO, which computes velocities for any location on Earth based on one or more plate motion models (UNAVCO, 2026). It should be noted that no information was found regarding the reference frame of the velocities provided by the Plate Motion Calculator. However, as highlighted by Ramos, Dal Poz, and Carvalho (2016) and Carvalho et al. (2015), the differences resulting from changes in the velocity reference frame can be considered negligible.

5. Results and discussion

The discrepancies calculated for the six stations are presented in Figure 5. For station CAST, where the three nearest neighboring stations are located at approximately 160, 190, and 200 km, the *griddata*, KNN, and RF methods yielded similar values, ranging from 0.030 to 0.033 m, while OK produced a slightly lower value of 0.027 m. The smallest discrepancy was obtained using RBF (0.023 m), which is 0.019 m higher than the reference value derived from linear regression (LR). In contrast, IDW produced the largest discrepancy, reaching 0.160 m. CAST is located in the state of Utah, far from the boundaries of the North American Plate. However, since all neighboring stations are located to its west - resulting in a suboptimal spatial distribution for interpolation - the results still demonstrate sufficient accuracy for compatibility with various practical applications.

Station KNOL, located in northern California, has the closest neighboring stations among the six selected (at distances of 3.5 km, 4 km, and 7.5 km). The largest discrepancy was observed with the *griddata* method (0.042 m), whereas the other methods produced values ranging from 0.015 to 0.026 m. This was the only station for which IDW yielded the best result, reflecting the higher weight assigned by this method to nearby stations, which leads to interpolated values closely matching the observed ones. Furthermore, given the local conditions, such proximity implies minimal variation in crustal motion over distances shorter than 5 km.

Station OPCX, located in southern California, despite being relatively close to its neighboring stations (9.5, 17.5, and 22 km), exhibited results similar to those of CAST. The *griddata*, KNN, RF, and RBF methods produced discrepancies ranging from 0.030 to 0.037 m. The largest discrepancies were observed for OK and IDW, with values of 0.083 m and 0.070 m, respectively. It is worth noting that the reference discrepancy for this station was already relatively high - the only one exceeding 1 cm (0.017 m). During the time series period, three earthquakes with magnitudes between 6.4 and 7.2 on the Richter scale were recorded, with epicenters located approximately 250 to 290 km from the station.

Station PTGV, although having the most distant neighboring stations (290, 620, and 1,200 km), exhibited the smallest discrepancies among the six analyzed stations. The *griddata* method produced a discrepancy of 0.007 m, only 1 mm higher than the reference value (0.006 m), while RBF resulted in a value 3 mm higher (0.009 m). The discrepancies obtained with KNN, OK, and RF were 0.018 m, 0.020 m, and 0.029 m, respectively. This low discrepancy can be attributed to the station's location in the eastern United States, within the interior of the North American Plate, a more stable region. This stability is reflected in its velocity vector $\vec{v}_{m/year} = (-0{,}014,\ 0{,}001,\ -0{,}001)$, with a magnitude of approximately 1.4 cm/year.

It is important to emphasize that seismic activity affects stations differently, depending on factors such as regional topography and proximity to earthquake epicenters. Therefore, if a station used as a known point in the interpolation process contains offsets or discontinuities, this will affect the accuracy of its estimated velocity and, consequently, the reliability of the interpolated velocities.

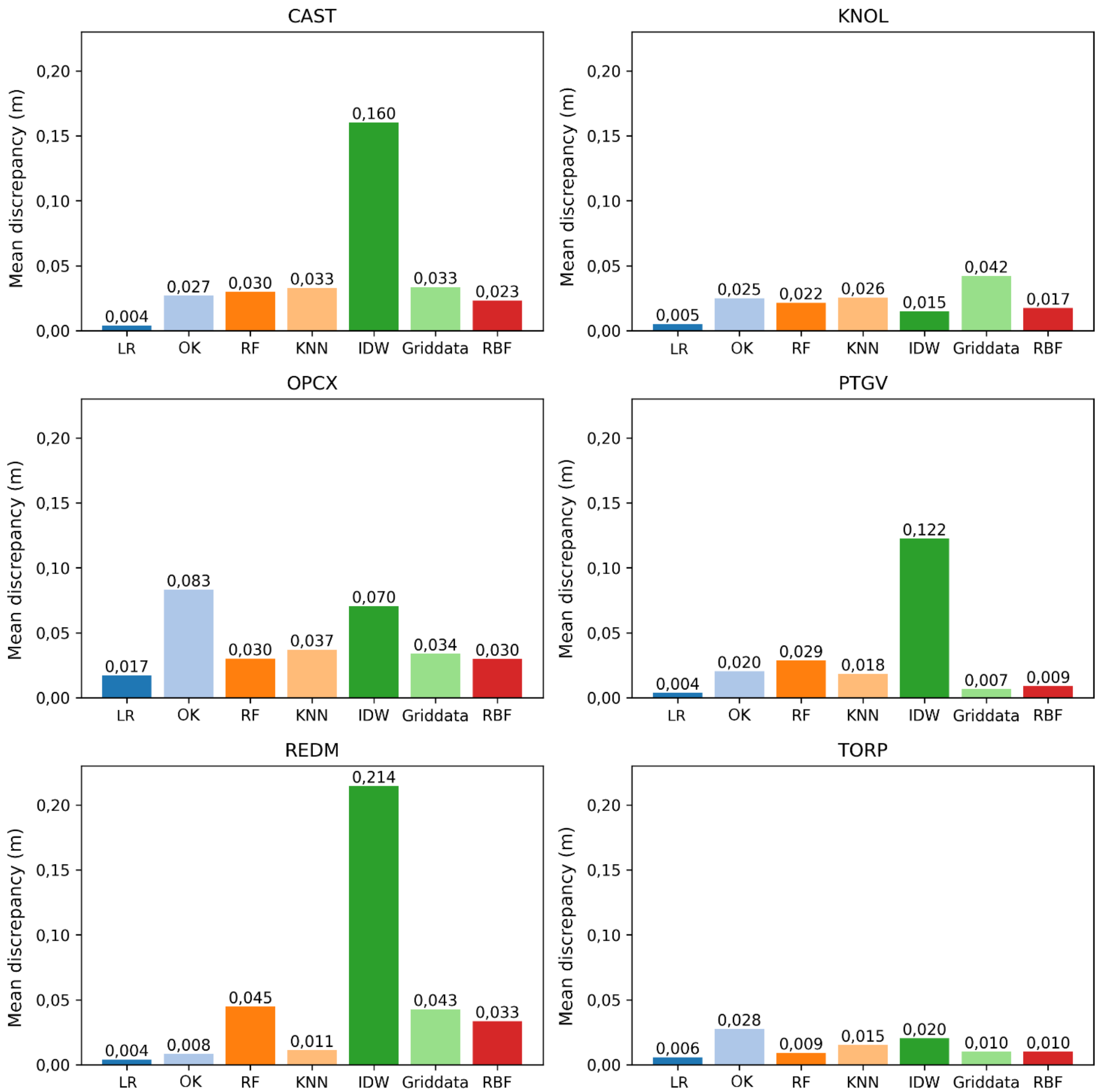

Figure 5 – Mean planimetric discrepancy by interpolation method for each station. Source: Authors (2026).

Station REDM, located in the state of Oregon, has its three nearest neighboring stations at distances of approximately 175, 315, and 320 km. The IDW method produced the largest discrepancy among all results, reaching 0.214 m. In contrast, OK and KNN yielded the smallest discrepancies among the six stations (0.008 m and 0.011 m, respectively), corresponding to 4 mm and 7 mm above the reference value. The remaining methods produced discrepancies ranging from 0.033 to 0.045 m.

Among the selected stations, TORP is located in the region of highest seismic activity (also situated in California, but on the Pacific Plate, near its boundary and less than 10 km from the coastline) - this is reflected in its velocity vector $\vec{v}_{m/year} = (-0{,}0300,\ 0{,}028,\ 0{,}016)$,with a magnitude exceeding 4 cm/year. The three nearest neighboring stations are located at distances of 4.5, 6, and 10 km. Despite the tectonically active setting, the discrepancies were relatively low. The best-performing method was RF, with a discrepancy of 0.009 m (3 mm above the reference value). The *griddata* and RBF methods both yielded 0.010 m, while KNN, IDW, and OK produced 0.015 m, 0.020 m, and 0.028 m, respectively.

Overall, no clear patterns were identified that would allow a specific interpolation method to be consistently associated with a particular spatial configuration of neighboring stations. For instance, IDW performed best at KNOL but yielded the worst results at three other stations. The *griddata* method performed best at PTGV but worst at KNOL. OK performed best at OPCX but worst at REDM and TORP. In contrast, RF, KNN, and RBF demonstrated more consistent performance, producing satisfactory results across all stations.

When considering the mean discrepancy across the six stations for each method, IDW showed the poorest performance, with an average of 0.100 m. OK, *griddata*, and RF produced similar results, with average discrepancies of 0.032 m, 0.028 m, and 0.027 m, respectively. The best-performing methods were KNN (0.023 m) and RBF (0.020 m). Due to its greater consistency across all stations, RBF proved to be the most reliable method for interpolating velocities estimated from GPS positional time series.

It is important to note that these experiments were conducted using more than 100 stations as known points. Interpolations based on a smaller number of neighboring stations - such as only the three closest - may yield different results due to the specific characteristics of each method.

Additionally, these results were compared with those obtained from 18 velocity models commonly used by the geodetic community, as illustrated in Figure 6.

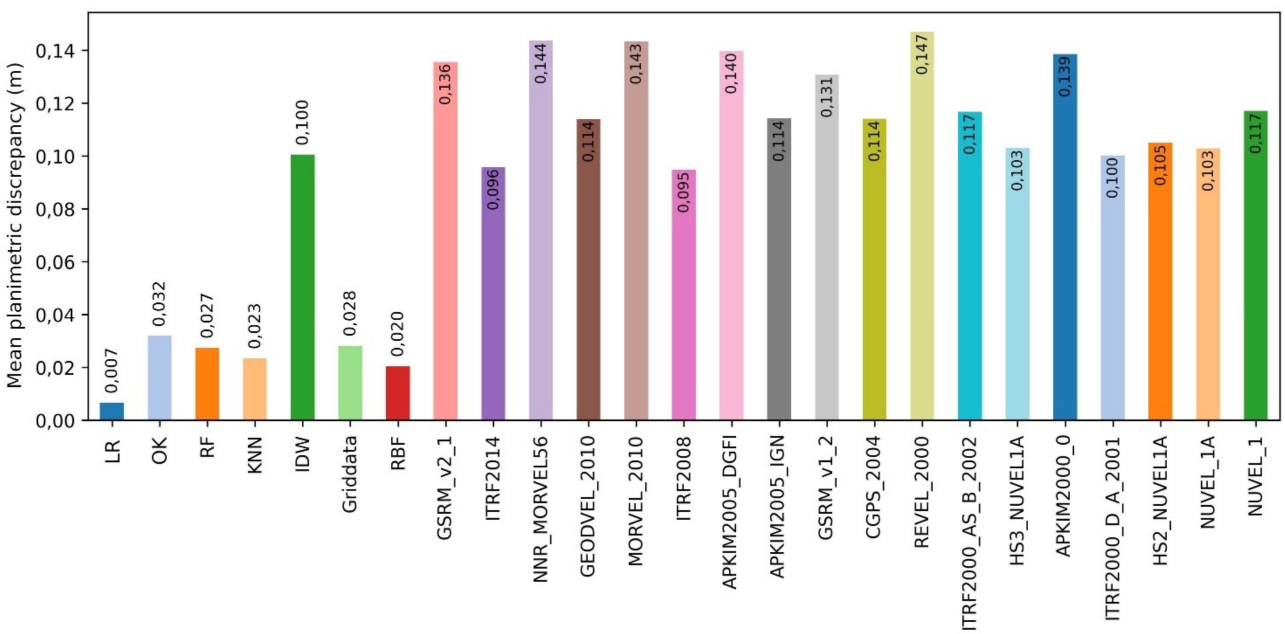

Figure 6 – Mean planimetric discrepancy of the six interpolated stations. Source: Authors (2026).

The mean discrepancy among the 18 models ranged from 0.095 to 0.147 m, significantly higher than those obtained with RF, KNN, *griddata*, OK, and RBF. Among the interpolation methods, only IDW produced results worse than those of some of the evaluated models.

Using the linear regression (LR) values as reference, the RF, KNN, *griddata*, and RBF interpolation methods yielded discrepancies approximately three to four times larger. However, the discrepancies computed using velocities interpolated by these methods were about 3.5 to 7 times smaller than those obtained using the velocities from the 18 analyzed models.

6. Conclusions

This paper aimed to present the GPTS Downloader software and demonstrate one of the many applications of positional time series. Station velocities were estimated for 113 stations based on 20-year time series, and velocities were interpolated for six stations using six different interpolation methods. Planimetric discrepancies were then computed relative to reference coordinates. Among the evaluated methods, RBF showed the highest consistency and proved to be the most reliable approach for interpolating velocities derived from positional time series.

Even without pre-processing the time series and considering regions of high seismic activity - such as the western United States, where there is a high concentration of stations near the boundary between the Pacific and North American plates - it was possible to update coordinates over a 20-year period with low planimetric discrepancies. These results highlight the strong potential of this methodology for velocity estimation, given its ease of implementation, low computational cost, and the quality of the results obtained.

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