C. R. Physique 20 (2019) 171–175

Contents lists available at ScienceDirect

Comptes Rendus Physique

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URSI-France 2018 Workshop: Geolocation and navigation / *Journées URSI-France 2018 : Géolocalisation et navigation*

GNSS: A revolution for precise geopositioning

GNSS : une révolution pour le géopositionnement précis

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ARTICLE INFO

Keywords:
GNSS
IGS
SSR
OSR

Mots-clés :
GNSS
IGS
SSR
OSR

ABSTRACT

Global Navigation Satellite Systems (GNSS) were not initially designed to be used for precise scientific applications. However, a smart signal processing can provide a satellite–receiver range measurement with millimeter accuracy. If the differential technique has become an essential method, the PPP mode is today an increasingly popular alternative. But, whatever the approach, GNSS have revolutionized the realization of space and time frames and the many applications requiring post-processed or real-time precise positioning.

RÉSUMÉ

Les systèmes globaux de navigation par satellite (GNSS) n'avaient à l'origine pas vocation à répondre aux besoins de positionnement pour des applications scientifiques précises. Mais un usage détourné des signaux a permis d'accéder à des mesures de distance satellite–récepteur d'une précision millimétrique. Si la technique différentielle s'est imposée comme une méthode incontournable, le mode PPP est aujourd'hui une alternative de plus en plus populaire. Mais, quelle que soit l'approche, les GNSS ont révolutionné la réalisation des repères d'espace et de temps ainsi que les nombreux usages nécessitant en temps différé ou en temps réel un positionnement précis.

1. GNSS: a geodetic technique by opportunity

Global Navigation Satellite Systems (GNSS), such as the popular US GPS operating since 1995, were not originally intended to be exploited for scientific purposes. Their radio signals are based on the modulation of the phase of an L-band carrier wave (1–2 GHz) by a PRN code with a frequency close to 1 MHz. The demodulation of this code by a receiver makes it possible to measure the distance between the transmitting satellites and the user with an accuracy of a few meters. Since the receivers are multichannel, the user can deduct from simultaneous measurements on several satellites its own position by "tri-lateration" with this same precision. But quickly the idea of measuring directly the phase of the carrier wave appeared. Thanks to the one thousand times higher frequency of this signal, users equipped with specific receivers have had

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https://doi.org/10.1016/j.crhy.2019.05.018

access to measurement of millimeter precision. Scientists have since benefited greatly from these providential observations from an ever-increasing number of satellite constellations such as GLONASS (Russia), Galileo (Europe), or Beidou (China). GNSS measurements have become a precise geodetic technique and are widely exploited for many scientific purposes. At first, this article compares differential techniques and PPP from the point of view of parameter correlation. The essential contribution of GNSS to the realization of space and time references is then recalled, as well as the driving role of the International IGS service, which has made the GNSS technique evolve towards more precision and less delays.

2. Precise GNSS applications: a question of (de)correlation

The exploitation of the millimeter precision of the phase measurements is not immediate, because it must go through a very fine modeling of each of the terms that compose it:

- position of the center of mass of the transmitting satellite at the time of emission;
- center of mass vector of the phase center satellite of the transmitting antenna, which is a function of the geometry and the attitude (orientation in space) of the satellite;
- satellite clock bias with respect to the time scale of the constellation;
- position of the phase center of the receiving antenna at the epoch of reception;
- vector “eccentricity” between the receiver phase center and the point to be positioned;
- propagation delays in the ionosphere and the troposphere;
- relativistic terms;
- phase “wind-up” effect due to the relative rotation between the transmitter and the receiver;
- phase measurement bias corresponding to the unknown initial *integer* number of cycles. This bias called “ambiguity” is common to all phases measurements from the same pass of a satellite (between its rising and its setting);
- hardware biases at the satellite and receiver level that corrupt the integer nature of phase ambiguities.

Monitoring all these terms is the key to a “precise” use of GNSS data. The mathematical problem to be solved is generally oversized, that is to say that the number of observations coming from the satellites in visibility is greater than the number of parameters to be determined. However, a “reliable” solution will only be obtained if a sufficient level of decorrelation between the parameters is reached. Concretely, this means that a sufficient number of equations will have to be accumulated to separate the contributions of the receiver clock terms, coordinates, tropospheric biases, and phase ambiguity, which are “naturally” correlated (or anti-correlated) by more than 90%. Obviously, the situation is more favorable in the case of a post-processing where the whole system of equations can be solved globally afterwards. But for both real-time and non-real-time applications, two types of strategies have been adopted over time to address this problem: the differential approach and the PPP approach.

3. The differential approach

The basic idea is to create new observables from the difference in phase measurements from two near receivers and/or two satellites in simultaneous visibility. Common terms affecting the measurements are thus eliminated. The differentiation of GNSS phase measurements is a form of “ultimate” decorrelation. Indeed, several terms of the measurement model such as clock and hardware biases do not need to be solved any more. On this principle, dense networks of reference GNSS stations (known position) have been deployed in many countries to provide a service of “differential corrections” for users requiring centimeter precision (surveyors, topographers, farmers...). In France, *Teria*, *Orpheon*, or *Satinfo*, for example, provide this type of service. In this case, we speak of an OSR (Observation State Representation), for which a single term corresponding to the sum of the corrections to be applied to the observations is transmitted to the users. In the case of post-processing and “static” receivers, the ratio of the number of observations to the number of unknowns becomes very favorable, and the differential technique makes it possible to reach millimeter accuracies. It became in the 1990s an essential method for many precise applications of GPS.

4. The PPP mode

An alternative approach to the differential technique consists in modeling or estimating each term composing the phase measurements rather than trying to eliminate them. In this case, we speak of SSR representation (State Space Representation). The PPP (Precise Point Positioning) of a GNSS receiver without the need for a reference receiver nearby becomes possible. However, access to a source of precise corrections of satellite orbit and clock, for example, is necessary. Moreover, from a correlation point of view, the situation is less favorable because the number of parameters to be estimated (a clock bias per measurement period, for example) is much larger. Thus, the positioning of a mobile in real time will require a longer convergence time than in the case of a differentiated approach. References [1] and [2] detail the advantages and disadvantages of differential and PPP approaches as well as of OSR and SSR representations.

5. Phase-measurement ambiguity fixing

The ultimate exploitation of GNSS phase measurements involves estimating the integer ambiguity bias. The GNSS measurement becomes accurate and precise, the number of parameters in the problem decreases, and the remaining ones are better de-correlated. Since the satellite and receiver hardware biases make phase ambiguities lose their "integer" nature, the only solution considered for many years was to eliminate them by double-differentiation. In 2007, Laurichesse and Mercier [3] observed that the satellite bias is stable (constant over a day), so they can be de-correlated using a receiver that is simultaneously tracking a sufficient number of satellites. The resolution of integer ambiguities in PPP mode then becomes possible. This mode of processing, called "Integer-PPP" (IPPP) or "PPP–AR" makes possible the positioning of "isolated" GNSS receivers with improved precision, and is becoming a competing technique with the differential mode. The idea that *Galileo* could broadcast free SSR corrections of its own signals is under study.

6. The international GNSS service

The decision of the International Association of Geodesy to create in 1994 the International GNSS Service (www.igs.org) is a founding act. This service is based on an international effort to deploy a network of permanent geodetic stations. The French contribution via the REGINA network [4] comprising of forty CNES and IGN stations globally distributed meets this need as well as the United Nations Recommendation 69/L.53 on "A global geodetic reference frame for sustainable development". The IGS also includes data archiving and processing centers that for example calculate the precise orbit of the GNSS satellite. More than 200 volunteer organizations contribute to the IGS with the aim of freely providing the most accurate GNSS products (IGS 2017). Thanks to the "friendly competition" between the different analysis centers (e.g., NASA, ESA, CODE, CNES…) and the dynamism of its Working Groups, the IGS has progressively pushed GNSS as a major geodetic technique by providing more and more precise products, distributing software packages (e.g., GAMIT, Bernese, GIPSY, GINS...), by imposing standards (RINEX, SINEX, RTCM...), by publishing hundreds of articles. If the first objective was and remains to contribute to the improvement of the realization of the space and time references (see next paragraph) and to measure the Earth kinematics (see article by Pierre Briole in this issue), the heritage of the IGS is considerable. The precise uses of GNSS have extended to areas as diverse as oceanography, hydrology, terrestrial and space meteorology, for example. Since 2010, as part of a pilot project that aims to become an "operational" service, products are calculated and delivered in real time. Thus, IGS has been the breeding ground of numerous innovations and developments that have significantly improved the processing quality and opened the field of application of precise GNSS.

7. The key role of GNSS for space and time reference realization

The International Terrestrial Reference Frame (ITRF) 2014 is today the standard for expressing coordinates of any point on the Earth. It is defined by a set of coordinates and velocities of a network of reference geodetic stations that "materialize" the frame. Regular updates of the ITRF are needed as the extrapolation of the station coordinates is affected by the error propagation of velocities. The solution is based on the analysis of more than 20 years of geodetic observations from more than 1000 sites. The GNSS technique (more economical and easier to implement compared to SLR, DORIS or VLBI techniques) represents the vast majority of these geodetic stations (Fig. 1).

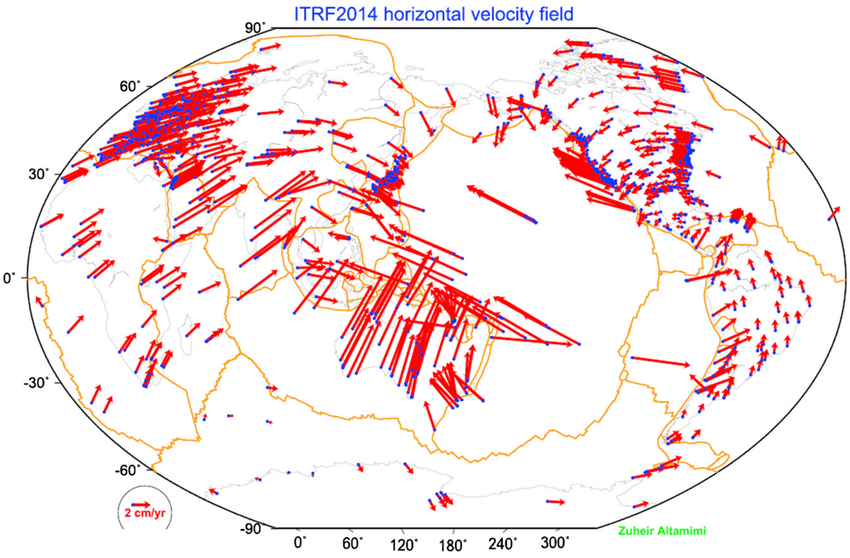

Fig. 1. ITRF2014 horizontal velocity field [5].

The transition from the celestial reference system (in which the orbits of the satellites are calculated) to the terrestrial reference (in which the coordinates of the stations are expressed) is parameterized by five quantities: the precession and nutation angles (from models), the X_p and Y_p coordinates of the pole and the UT1–UTC offset. The latter (which represents the irregularities of the Earth rotation velocity) can be directly observed only by the VLBI technique, which targets celestial objects (quasars) instead of satellites. The X_p and Y_p parameters are estimated by inverse method. Any deviation from X_P and Y_P produces a daily oscillation of the coordinates of stations whose amplitude and phase depend on the position of the station. Thus, GNSS geodetic stations, thanks to their density on the Earth, allow us to measure X_p and Y_p with a remarkable precision of 0.2 milliarcsecond.

The realization of time scales requires the comparison and combination of observations from a global network of more than 200 atomic clocks (https://www.bipm.org/en/bipm/tai/). This fundamental task nowadays essentially relies on the GNSS technique because it allows us to estimate with great precision the offset of an atomic clock connected to a GNSS receiver whose coordinates are known. The PPP technique, which does not even require these "time-receivers" to be in common view of satellites, is widely used by laboratories contributing to the realization of time scales. Recently, Petit et al. [6] showed that IPPP solutions, by ensuring the continuity of integer phase measurement ambiguities between successive satellite passes, allows a significant gain in accuracy. Whether for the realization of space and time references or the determination of the movement of the pole, GNSS have allowed considerable progress and have become unavoidable.

8. From geodesy to centimeter navigation

If, at the creation of the IGS, three orders of magnitude of precision separated the world of geosciences (post-processing static positioning) from the world of navigation (real-time positioning), this situation has since then considerably evolved. The densification of the networks, the modernizations of both the systems themselves, the equipment and the means of communication and calculation, made the delays for positioning a GNSS receiver reduced and the accuracy improved. The GNSS coordinates of the geodetic stations were determined weekly for the realization of the ITRF2008, for example. Today the sampling is daily and various studies are conducted on the modeling and measurement of sub-diurnal movements of the Earth. Melachroinos et al. [7] and Lescarmontier et al. [8], for example, have been able to observe high-frequency oceanic load deformations and glacier vibration modes, respectively, thanks to the accurate positioning of GPS stations over the course of a day. For the precise orbit calculation of satellites carrying a GNSS receiver, the differentiated approach is not suitable, because the common view between a terrestrial station and a satellite in low orbit is very limited. Laurichesse [9] demonstrated the interest of the IPPP technique for this type of problem by determining with centimeter accuracy the trajectory of the GRACE and JASON-1 satellites in post-processing. Using this same technique, Fund et al. [10] have shown that the trajectory of an oceanographic buoy (in post-processing) can be calculated with a similar precision. At CNES, the PPP-Wizard project (http://www.ppp-wizard.net/) aims to demonstrate the feasibility of real-time IPPP with a centimeter accuracy. This service is based on the real-time calculation of both precise orbits of the GNSS satellites and SSR corrections (Fig. 2).

It is on this principle that, for example, the application for smartphones "PPP-Wizlite" developed by CNES [11] should soon allow to navigate with an accuracy 10 to 100 times higher than initially specified for GNSS.

Thus, beyond the economic, technological, or sovereign stakes, GNSS, by providing unprecedented highly accurate (post-processed and real-time) positioning, is playing a growing scientific and societal role.

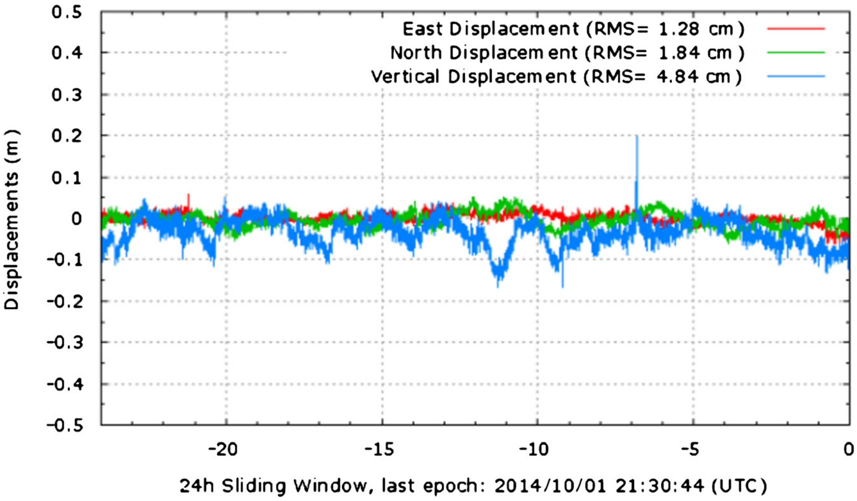

Fig. 2. Real-time (static) rover coordinate determination (http://www.ppp-wizard.net).

References

[1] G. Wubbena, M. Schmitz, A. Bagge, PPP-RTK Precise point positioning using state-space representation in RTK networks, in: Proc. ION GNSS, 18th International Technical Meeting of the Satellite Division, 13–16 September 2005, Long Beach, CA, USA.

[2] S. Choy, S. Bisnath, C. Rizos, Uncovering common misconceptions in GNSS precise point positioning and its future prospect, international federation of surveyors, Article of the Month – September 2016.

[3] D. Laurichesse, F. Mercier, Integer ambiguity resolution on undifferenced GPS phase measurements and its, application to PPP, in: Proc. ION GNSS 2007, 20th International Technical Meeting of the Satellite Division, 25–28 September 2007, Fort Worth, TX, USA.

[4] C. Velut, L. Jolivet, B. Garayt, T. Donal, J.-P. Cardaliaguet, Regina a CNES/IGN worldwide GNSS receivers network for IGS and navigation: overview and perspectives, in: 6th International Colloquium – Scientific and Fundamental Aspects of the Galileo Programme, Technical University of Valencia, Spain, 25–27 October 2017.

[5] Z. Altamimi, P. Rebischung, L. Métivier, X. Collilieux, ITRF2014: a new release of the International Terrestrial Reference Frame modeling nonlinear station motions, J. Geophys. Res., Solid Earth 121 (2016) 6109–6131, https://doi.org/10.1002/2016JB013098.

[6] G. Petit, A. Kanj, S. Loyer, J. Delporte, F. Mercier, F. Perosanz, 1×10^{-16} frequency transfer by GPS PPP with integer ambiguity resolution, Metrologia 52 (2015) 301–309, https://doi.org/10.1088/0026-1394/52/2/301.

[7] S. Melachroinos, R. Biancale, M. Llubes, F. Perosanz, F. Lyard, M.-N. Bouin, F. Masson, J. Nicolas, L. Morel, S. Durand, Ocean tide loading (OTL) displacements from global and local grids: comparisons to GPS estimates over the shelf of Brittany, France, J. Geod. 82 (2007) 357–371, https://doi.org/10.1007/s00190-007-0185-6.

[8] L. Lescarmontier, B. Legresy, R. Coleman, F. Perosanz, C. Mayet, L. Testut, Vibrations of Mertz Glacier ice tongue, East Antarctica, J. Glaciol. 58 (210) (2012) 665–676.

[9] D. Laurichesse, F. Mercier, J.-P. Berthias, P. Broca, L. Cerri, Integer ambiguity resolution on undifferenced GPS phase measurements and its application to PPP and satellite precise orbit determination, navigation, J. Inst. Navig. 56 (2) (2009).

[10] F. Fund, F. Perosanz, L. Testut, S. Loyer, An integer precise point positioning technique for sea surface observations using a GPS buoy, Adv. Space Res. 51 (8) (2013) 1311–1322.

[11] D. Laurichesse, C. Rouch, F.-X. Marmet, M. Pascaud, Smartphone applications for precise point positionning, in: ION GNSS+, 24–28 September 2018, Miami, FL, USA.