

The use of High Precision Global Navigation Satellitary Systems (GNSS) for monitoring deformation of buildings at risk for landslides, in flooding areas

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Land Survey is the backbone for any civil engineering planning and realisation. This is true both for Cartography at large scale (1:5000 and higher) and for studying and solve problems associated to soil movements and territorial disasters. Buildings located on (or close to) a risk area like landslide, etc. are a sensible problem that Public Administration in general, have to take into account. The needs of monitoring part of the territory, in particular sensible public buildings such schools, hospitals, etc. leads to the use of GNSS technologies in addition to classical instruments.

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1. Introduction

The monitoring of the situations and the regions of territory with hydro-geological risk represents an institutional task of Public Administration. In some areas, therefore, becomes necessary to realise systems for real-time survey, able to recording alarm signs of a potentially risk for the population. An early-warning systems also provides the foundation for an effective risk mitigation plan, given the uncertainties connected with the mathematical prediction of natural phenomena and the strong public demand for protection against natural hazards [1].

The real accuracy obtainable by GNSS technology depends on different parameters: the modality (static, fast-static, kinematics, Real Time), windows time observation, baseline length, receivers characteristic (L1 or L1/L2, antenna type, etc.).

Combining these different parameters one can get different location precisions from few millimetres to some centimetres. Moreover, the bridges are part of a country's transportation infrastructure and are typically assessed and maintained by the authorities responsible for the appropriate transportation sector (road or rail). Bridge monitoring is necessary to ensure the safety of those who either use, or are affected by the structure itself and is usually part of the legislature governing the maintenance of the transportation sector.

Recently, the deterioration of bridge structures has become a serious problem due to issues related to modern society; reliance on the car, increased bridge traffic, environmental pollution, and the use of potentially corrosive substances (e.g. cleaning and ice elimination). GNSS (GPS), when used in a differential carrier phase mode, can provide high of the information related to accuracy absolute deformation [2].

The system does not rely on the navigational performance of any of the satellite systems it uses but is based on local, short-baseline differenced carrier phase positioning techniques. The effects of any ephemeris errors (along with other common space, atmospheric and local error components) will be removed in the processing scenario.

In this article are presented the basic principles of high precision GNSS measurement.

2. Point Positioning

In the Point Positioning technique (Absolute Positioning of a single point into the assigned reference system) the observables coming from a single receiver are usually elaborated inside the equipment itself in order to determine the receiver position. No other GNSS observables (e.g. from other receivers) are considered for this method. The method can be applied in track time to have an estimation of vehicles paths and velocity. The accuracy depends directly from the GNSS system accuracies and the receiver performance [3].

A different and great opportunity is provided by EGNOS, currently in the pre-operational phase. In fact a single user, with a single EGNOS receiver is able to increase the accuracy to a level of few meters. Moreover an integrity message is provided thus increasing the knowledge of the real status of the signals received.

With EGNOS and in the future with the GALILEO, together with a real intero-perability between GALILEO and GPS systems and with the integrity message, the absolute point positioning could become more and more interesting and also help the growth and development of applications that at the moment are not enough convenient

(due to cost, difficulty in operations, etc.) to be widely used.

3. Differential code positioning

The aim of differential correction techniques is to improve the overall positioning accuracy by reducing or eliminating unaccounted biases in the signal propagation delay.

Differential corrections are based on simultaneous or near-simultaneous measurements [1] taken by a reference station located in a known position, compared with the expected values (based on the “a priori” known location, and the differences transmitted in real-time [2] to the users over the area of interest. Three techniques have been “historically” proposed to implement differential corrections:

1. differential corrections based on individual pseudorange measurements (measured value minus expected value);

2. differential corrections based on the geographical coordinates (again computed value, from measurements, minus expected value);

3. differential corrections broadcast together with a navigation-like signal, properly synchronized with the signals transmitted by the satellites, to augment the user data set with an independent measurement.

Differential corrections can be used to cover a limited area with high accuracy (the implementation is generally referred to as Local Area Augmentation Systems – LAAS) or to cover a wider area with somewhat reduced accuracy (Wide Area Augmentation Systems – WAAS). The latter are satellite based, where the differential correction signal (data and possibly an additional navigation signal, see the technique [4] above) is broadcast over the visibility area of a geo-synchronous satellite. This implementation is the basis of the GPS/Glonass overlay systems currently in development in Europe, the United States and Japan.

For the differential correction technique, the geometry is shown in fig. 1, where $S(\text{true}, t)$ is the true satellite position at the time t , $S(\text{assumed}, t + \Delta t)$ is the assumed satellite position at the time $t + \Delta t$, the position error being d .

These errors (position and time) can result from the uncertainties in the satellite ephemeris or clock offset estimation or can be introduced as a selective availability technique. Propagation biases² can always be reduced to an offset in the measured pseudoranges (corresponding to the Δr or $\Delta r'$, that are the difference between the true and the assumed range) and therefore treated as ephemeris or clocks offsets.

A distance δ separates the reference station and the user location.

Following the derivation given in ref. [5], at the reference station the time at which the signal is received and the time at which the signal is expected are:

$$t_{\text{signal, received}} = \frac{r}{c} + t ; \quad (1)$$

$$t_{\text{signal, expected}} = \frac{r + \Delta r}{c} + t + \Delta t$$

the total time error being $\frac{\Delta r}{c} + \Delta t$. For the user, at a distance d from the reference point, the time error will be: $\frac{\Delta r'}{c} + \Delta t$.

Therefore, the range error introduced at the user location by correcting his measurements with the data gathered at the reference location will be:

$$e = \Delta r - \Delta r' \quad (2)$$

and:

$$e \equiv d \cdot \sin \alpha - d \cdot \sin(\alpha - \varepsilon) = d \cdot (\sin \alpha - \sin \alpha \cdot \cos \varepsilon + \sin \varepsilon \cdot \cos \alpha)$$

Assuming ε small, $\sin \varepsilon \approx 0$ and $\cos \varepsilon \approx 1$; therefore, the equation becomes

$$e \equiv \varepsilon \cdot d \cdot \cos \alpha \quad (3)$$

The value of ε depends upon the distance δ between the reference and user locations, and for our scope can be

bounded to be: $\varepsilon \leq \frac{\delta}{r}$, which leads to:

$$e \leq \frac{d \cdot \delta}{r} \cdot \cos \alpha .$$

The worst case will be for $\alpha = 0$,

since $\cos \alpha = 1$ (along-track offset), and in this case:

$$e \leq \frac{d \cdot \delta}{r} .$$

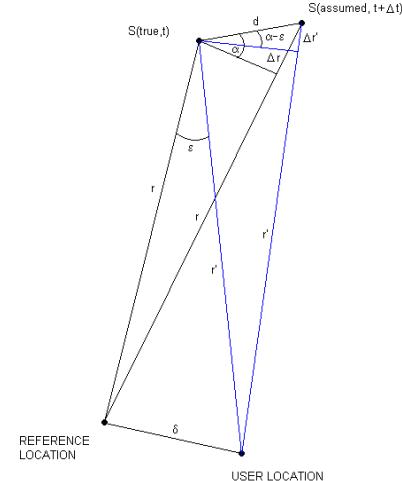


Fig. 1. Differential correction geometry.

For $d = 100$ km and $d = 1$ km, since r is approximately 20000 km, we get: $|e| \leq 5$ m, and for typical errors (with S/A) in the order of 30-100 m it is easy to reach sub-meter accuracy (for GPS) over distances of hundreds of km.

The pseudo-range correction at the reference point is $\Delta r + c \cdot \Delta t$. It is obtained by taking the difference between the expected (computed, being known the position of the satellite and the reference site) and measured reception times. This difference will include all propagation delays, and its value (for each visible satellite) will be broadcast to the users.

The ranging error, after the corrections are applied, using this technique, is (approximately³) linearly proportional to the distance δ from the reference station.

In case geographic⁴ corrections (Δx , Δy and Δz , or Δ_{latitude} , $\Delta_{\text{longitude}}$ and Δ_{height}) are broadcast, the geometry must be taken into account. An error in position is related to an error in range by the Position Dilution of Precision (PDOP). Assuming a PDOP of 3 the error will be three times more, but the effect is partially compensated that, in any case, the user will use the pseudo-ranges to compute its geographical position, and in doing this the same PDOP factor is introduced.

However, the PDOP for a given geometry is dependent upon the reciprocal user and satellites positions. Moving far away from the reference location the geometry may change considerably, and therefore the PDOP will be different for the user and the reference station. Transmitting the geographical corrections does not allow the user to correct for this difference, and therefore a larger error will result from this type of correction.

Moreover, a geographic correction will compel the user to apply the same navigation solution to its data processing for the correction to be effective. Therefore, users working with different navigation solutions ("best-4-in-view" or "all-in-view") or using different satellites because of the different geometry (over a wide area) or different selection criteria will not be able to use the corrections effectively.

Therefore, it is suggested to prefer pseudo-range corrections to geographical corrections whenever possible. The corrections, to be effective, must be synchronous: the S/A changes the error with time, and the propagation conditions may change with time too, even if more slowly. Therefore, for real-time application of the technique, the corrections must be distributed and applied in real-time. Non real-time users require only a reasonably accurate time-tagging of the data.

3. Interferometric carrier-phase positioning

Space geodesy techniques are available since the early days of space explorations. Transit satellites were used for the first determinations of geodetic positions by translocation methods, the forerunners of the modern satellite geodesy techniques. The main advantage in the introduction of space-based techniques in geodesy was the migration from local datums to global, worldwide datums, since the measurements could now span the globe and

observations could be inter-related, while astronomical observations were local in nature. At the same time, space geodesy made available to the specialists in the field techniques and measurement precisions that before were exclusive domain only of observatories or scientific institutions.

The basic principle of interferometric surveying, the fundamental technique in space geodesy, is shown in Fig. 2.

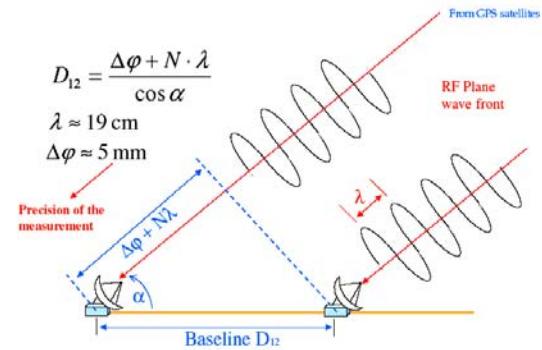


Fig. 2. Basics of interferometric surveying.

Two antennas at different locations receive the signals transmitted by the satellites overhead. Let D_{12} be the distance between the two antenna; D_{12} is commonly referred to as **baseline** between the two antennas. Space geodesy provides relative measurements between the two antennas by measuring the baseline length D_{12} .

Since the distance from the antennas to the satellites is generally much greater than the length of the baseline D_{12} , we can assume that the signal from each satellite simultaneously received at the two antennas can be assimilated to a plane warfront. The phase difference between the two signals at the antennas will be given by:

$$\Delta\phi = \Delta\varphi + N \cdot \lambda \quad (4)$$

where $\Delta\phi$ is the geometric (path length) distance, unknown, $\Delta\varphi$ is the electric phase difference, measured, and $N \cdot \lambda$ is an integer number of wavelengths to make up $\Delta\phi$ for a particular satellite elevation α with respect to D_{12} .

For the particular case of the GPS satellites observables, the carrier frequency is in the L-band, precisely at 1575 MHz, corresponding to a wavelength $\lambda \approx 19$ cm. The resolution of the ambiguity related to the periodical nature of the un-modulated signals (carrier phase tracking) presents the greatest challenge in the solution for the baseline length. The lack of the second carrier at L2 prevents the use of the wide lane technique for carrier resolution, where the wide lane is a fictitious signal that can be obtained by the difference of the L1 and L2 carriers, providing a ≈ 384 MHz fictitious carrier equivalent to an effective wavelength of ≈ 86 cm.

For geodetic applications, the constraint related to a fixed baseline mitigates somewhat the problem, since the ambiguity can be, in principle, resolved once. However, cycle slips due to the receiver, sudden ionospheric disturbances (scintillations) or phase slips in the satellite transmitting equipment require a continuous monitoring of the ambiguity to avoid errors that will appear in the solution as integer number of wavelengths in the measure of $\Delta\phi$, and as such generate errors when projected on the estimation of the baseline length D12.

The resolution in the physical measurement of $\Delta\phi$ is instead related to the received signal power, the thermal noise, the noise figure of the antenna and the receiver, the bandwidth of the carrier phase locked loop in the receiver (as well as the loop implementation, the equivalent noise bandwidth being a function, for instance, of the order of the loop integrator/filter) and the frequency stability of the local oscillator. Accounting for all these parameters, a typical modern receiver is capable of recovering the carrier phase with a ≈ 5 mm r.m.s. noise superimposed, mainly due to thermal noise, at a 1 Hz rate, which is a suitable rate for real-time monitoring in surveying applications.

The measurement is made more difficult by the fact that the two receivers form a non-connected elements interferometer, where the two local oscillators are independent. The need follows to recover the phase and frequency offset between the two oscillators as a part of the baseline length estimation processing. In general, more than one satellite is required to resolve all the unknowns in the solution, as we shall see in the following when considering how to form the observables for the solution, and using all the satellites in view will allow to solve for the oscillators offset, monitor the ambiguity and reduce the stochastic errors in the solution.

Navigation signals are ideal for space geodesy since they are generated from very stable sources and the location of the transmitters is precisely known to the extent required to carry on some ancillary computations, such as the estimation of the angle α . Navigation signals are generally used in the form of pseudoranges, which results from a pseudo-random noise (PRN) code of finite length modulated on the carrier. The PRN code spectral properties made it an ideal signal for ranging applications and the code is generally used for position estimation in general purpose satellite navigation receivers. The pseudorange measurement ΔR_i can be modelled as:

$$\Delta R_i = \rho_i + c \cdot \Delta t + \Delta \rho_{iono,i} + \Delta \rho_{tropo,i} + \varepsilon_i \quad (5)$$

where:

ρ_i is the slant range between the i-th satellite and the receiver;

Δt_i is the time offset between the navigation system time and the receiver clock; additional receiver and cable delays are included in this term since (or if) they are common to all the observations;

$\Delta \rho_{iono}$ is the additional path-induced error due to the ionospheric delay (this is frequency dependent since the ionosphere is a dispersive medium at RF frequencies);

$\Delta \rho_{tropo}$ is the additional path-induced error due to the tropospheric delay (this is frequency independent at RF frequencies);

ε_i are residual errors depending on the observations of the i-th satellite, including multipath.

Pseudorange measurements, while not affected by ambiguity because of the signal structure (the ambiguity in GPS remains at the 1.5 s level, which is the period of the public part of the P code, so that the residual ambiguity translates to a value of $\approx 1.245e+7$ km, well outside any common application of GPS), are limited by bandwidth and signal-to-noise ratio to the meter level in precision, even for a differential system where propagation delays can be removed: this is clearly insufficient for high-precision geodetic or surveying applications.

This was recognized quite early in the history of GPS, and carrier phase became the signal of choice for high-precision measurements at the cm- and mm-level since the 1980's (carrier tracking of GPS satellites and precursors was already done in the 1970's by DMA and other organizations, but Doppler measurements were at that time exploited mainly for orbit determination).

Similarly to pseudorange (code) measurements, carrier phase-derived pseudoranges ϕ_i (expressed in cycles of the carrier) can be modelled as:

$$\phi_i = \frac{\rho_i}{\lambda} + \frac{c}{\lambda} \cdot \Delta t + N_i - \frac{\Delta \rho_{iono,i}}{\lambda} + \frac{\Delta \rho_{tropo,i}}{\lambda} + \frac{\varepsilon_i}{\lambda} \quad (6)$$

The negative sign of the ionospheric propagation term (here it really accounts to a phase advance) is due to the fact that, in a dispersive medium, the product of the phase and group velocities for an electromagnetic wave is c^2 , and therefore the phase travels at a speed higher than the speed of light.

Carrier phase, while providing the more accurate measurements, is plagued by the ambiguity resolution: many techniques were developed to overcome the problem, mainly based on successive differencing the observations, leading to single difference, double difference and triple difference observables.

By inspection of eq. (3), we may notice immediately that differencing two observations of the same satellite A taken by the two receivers at the ends of an arbitrary baseline will remove the terms which are not dependent upon the individual satellite; we may then form a first difference of phase and write:

$$\Delta \phi^A = \frac{\Delta \rho^A}{\lambda} + \left[\left(\frac{c}{\lambda} \cdot \Delta t \right)_1 - \left(\frac{c}{\lambda} \cdot \Delta t \right)_2 \right] + N^A + \frac{\varepsilon^A}{\lambda} = \frac{\Delta \rho^A}{\lambda} + \left(\frac{c}{\lambda} \cdot \Delta \tau \right) + N^A + \frac{\varepsilon^A}{\lambda} \quad (7)$$

for the new observable, where the propagation terms (ionosphere and troposphere) have vanished, $\Delta\tau$ is the instantaneous offset between the two oscillators (clocks) in the receivers, N^A is the single difference integer ambiguity ($N^A = N_1 - N_2$) and ε^A is the residual noise term (stochastic and multipath).

Considering that:

$$\Delta\rho^A = \vec{b} \cdot \vec{s}^A \quad (8)$$

where:

\vec{b} is the baseline vector, and

\vec{s}^A is the line of sight unity vector to the satellite A ; we can further write:

$$\Delta\phi^A = \frac{\vec{b} \cdot \vec{s}^A}{\lambda} + \frac{c \cdot \Delta\tau}{\lambda} + N^A + \frac{\varepsilon^A}{\lambda} \quad (9)$$

The first difference still leaves the instantaneous offset between the two oscillators in the model. This can be removed by a second difference, subtracting the first differences formed on two satellites. generally the solution forms the double differences by taking a common satellite H and forming double differences with each of the remaining satellites; for instance, the second difference for the satellite A (always with respect to H) is:

$$\begin{aligned} \nabla\Delta\phi^{AH} &= \Delta\phi^A - \Delta\phi^H = \frac{\vec{b} \cdot \vec{s}^A}{\lambda} + \frac{c \cdot \Delta\tau}{\lambda} + N^A + \frac{\varepsilon^A}{\lambda} - \frac{\vec{b} \cdot \vec{s}^H}{\lambda} - \frac{c \cdot \Delta\tau}{\lambda} - N^H - \frac{\varepsilon^H}{\lambda} = \\ &= \frac{\vec{b} \cdot (\vec{s}^A - \vec{s}^H)}{\lambda} + N^{AH} + \frac{\varepsilon^{AH}}{\lambda} \end{aligned} \quad (10)$$

where:

N^{AH} is the difference between the ambiguities for the baseline considered with respect to the two satellites A and H;

ε^{AH} is the difference between the two noises.

The receivers clock has been removed from the double differences. **The double differences are the basic observable used in the data processing [6].**

In practice, an arbitrary receiver in the network will be set as the net reference; baselines will connect the reference to any other receiver, the network assuming a star topology. Couple of baselines will form triangular subnets, so that the entire network will be resolved into triangular modules with a GPS antenna on each vertex and one vertex common to all triangles. When this topology is extended to large areas, sub-nets will be formed interconnected by receivers common to adjacent sub-networks. Each elementary triangle will be solved by the combination of two single baseline solutions with the constraints imposed by the angle subtended: this solution leads to the adjusted coordinates of the vertices with

respect to the reference station (the vertex common to the two baselines in the triangle).

Therefore, for each sensor in the network, the displacement resulting from deformations of the network geometry will be decomposed by projecting the baseline solutions in the coordinates of a local topocentric coordinate system, namely into the Easting, Northing and local vertical components relative to the net reference receiver. If this receiver is in turn referenced to an absolute position by including a surveyed receiver in the network, then the network itself will be absolutely geo-referenced with respect to an established reference frame.

4. Conclusions

GNSS are one of the most important technologies that permit an accurate and all-weather system to monitor landslide. These systems are able to monitor wide area (also in real time) with some restriction as sky visibility and possibility to perform observation site on the landslide.

The deformation control or the monitoring of an area is one of the most important aspects that can take great advantages from precise positioning by satellite techniques.

The broad variety of positioning strategies, ranging from the single point positioning to the static relative positioning, offers the opportunity to develop applications such as mapping and deformation monitoring of land, building and flooding etc.

Real-time monitoring based on GNSS technique has a key role in developing a multi-risk approach to natural disasters, with particular focus on landslides and flooding hazards.

Some geodesy techniques may use non-real time data in post-processing of the measurements.

Care must be exercised when applying ionospheric corrections to single frequency receivers using a model, since different receivers may use different models. Differential corrections to pseudo-range, not including ionospheric corrections, should be used (and the user will not apply any ionospheric model correction, but use just the received differential corrections). The same applies to tropospheric delays if some model (based, for instance, on the elevation angle) is introduced in the processing.

Since the same propagation conditions may not exist along the two paths (r and r') due to different atmospheric (ionosphere and troposphere) conditions. This term will generally produce an additional increase with the distance δ .

These are ECEF coordinates (Earth-Fixed, Earth-Centered).

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