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Analysis and Quality Study of GNSS Monitoring Stations' Pseudorange and Carrier-Phase Measurements

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BIOGRAPHIES

Olivier Julien is an assistant professor at the signal processing laboratory of ENAC (Ecole Nationale de l'Aviation Civile), Toulouse, France. His research interests are GNSS receiver design, GNSS multipath and interference mitigation and GNSS interoperability. He received his B.Eng in 2001 in digital communications from ENAC and his PhD in 2005 from the Department of Geomatics Engineering of the University of Calgary, Canada.

Christophe Macabiau graduated as an electronics engineer in 1992 from the ENAC (Ecole Nationale de l'Aviation Civile) in Toulouse, France. Since 1994, he has been working on the application of satellite navigation techniques to civil aviation. He received his Ph.D. in 1997 and has been in charge of the signal processing lab of the ENAC since 2000.

Jean-Luc Issler is head of the Transmission Techniques and signal processing department of CNES, whose main tasks are signal processing, air interfaces and equipments in Radionavigation, Telecommunication, TT&C, High Data Rate TeleMetry, propagation and spectrum survey. He is involved in the development of several spaceborne receivers in Europe, as well as in studies on the European RadioNavigation projects, like GALILEO and the Pseudolite Network. With DRAST and DGA, he represents France in the GALILEO Signal Task Force of the European Commission. With Lionel Ries and Laurent Lestarquit, he received the astronautic prize 2004 of the French Aeronautical and Astronautical Association (AAAF) for his work on Galileo signal definition.

Olivier Nouvel is working at M3Systems (Toulouse, France) as a Radionavigation Engineer since 2002. He is involved in Radionavigation projects (GPS, SBAS, GNSS2, etc.) and is specialized in modeling and simulation of Radionavigation signal processing chain (Galileo Signals, effect of interference/multipath). He graduated from ESIGELEC (Ecole Supérieure d'Ingénieurs en Génie Electrique – option télécommunication Hyperfréquence; Rouen, France).

Willy Vigneau is head of the Radionavigation Unit at M3 Systems. He graduated as a telecommunication engineer from SUPAERO (Ecole Nationale Supérieure de l'Aéronautique et de l'Espace) in 1999, he joined M3 Systems, a French SME (Toulouse) involved in various Radionavigation projects : GPS/EGNOS/Galileo signal processing and critical applications of satellite Radionavigation.

ABSTRACT

The control of EGNOS Ranging and Integrity Monitoring Stations (RIMS) is a constant task in order to verify the correct functioning of the RIMS network, and to detect or identify possible receiver malfunctioning. Each EGNOS station currently uses a minimum of two independent RIMS, to ensure a constant back up. The availability of different observables and quality parameters from these two receivers allows studying in details potential observed disturbances, to detect unnoticed behaviours, or to investigate accidents. Among the different tasks, the study of the quality of the code and phase measurements is very important to quantify any problems affecting the tracking process.

The errors affecting measurements are well known: unmodelled satellite clock and motion, receiver clock (static receiver), multipath, thermal noise, atmospheric delays, interference. RIMS code measurements are dominated by noise and multipath, while phase measurement will be more sensitive to smaller range variations such as the satellite and receiver clock, or ionosphere activity. Thus, a different analysis tool is necessary in these two cases.

Because carrier-phase measurements are much more sensitive (in relative magnitude) to most of the sources of errors than to tracking errors, it is also more difficult to observe phase lock loop tracking errors compared to the code tracking case. It is then understandable that phase measurement quality assessment is more difficult. The manipulation of L1 and L2 measurements allows the cancellation or reduction of most of the non-tracking errors, but it might not allow isolating a specific error. Thus, it is preferable to work on each measurement separately. The goal of this paper is to present a methodology to assess code and carrier-phase measurement quality, as well as to show the tools used to define this methodology.

The first part of the paper concentrates on the use of polynomial interpolation to model the measurements and thus study the corresponding residuals for quality control. It is seen how this method is suitable for pseudoranges, but not for phase measurements due to the aforementioned reasons.

To understand exactly the errors preventing the use of polynomial interpolation for phase measurements, the second section of the paper shows a tool that was realized to allow the visualization of measurements variations over time. This is obtained by using models for most of the known components of the transmission time. This tool is particularly interesting to have a visual access to the residual phase error variations of different RIMS. It can then be used to isolate specific local errors, or to understand the source of these residuals, such as satellite clock variations, excited ionosphere, or tracking problems.

INTRODUCTION

EGNOS (European Geostationary Navigation Overlay System) is the European contribution to the augmentation of the currently operating GPS. Its aim is to complement the American system in order to be able to use it for critical applications, such as landing an aircraft. When such an augmentation is getting close to its operational phase, it is important to spend time assessing and checking the behavior of each component constituting the system. In particular checking the correct installation and performance of the ground stations is of main importance since they will constitute the core of the EGNOS monitoring system.

The EGNOS ground stations are constituted of several Ranging and Integrity Monitoring Stations (RIMS) receivers in order to have a constant back-up and control in case of failure of one of the receiver. An unavoidable step to check the good behavior of these ground stations is the thorough check of the RIMS raw measurements. Within this frame, this study was undertaken targetting at analyzing and explaining (independently from receiver internal messages) anomalies encountered through the investigation of RIMS stations raw measurements. Different types of anomalies were looked for:

- local ones (RIMS located in a severe multipath environment or vulnerable to surrounding interferers),
- Unexpected receiver tracking (coming from hardware or software problems).

The anomalies considered can be visible on several measurements (high multipath, presence of interferer, front-end problem, etc…) or on one code or phase measurement (hardware problem, tracking loop misbehavior, etc…). They can affect code and/or phase measurements. Thus, if a suspicious behavior is detected, each measurement (potentially of different RIMS stations) should be analyzed in a certain time-window. The detailed analysis of each measurement is a cumbersome process due to the high number of RIMS stations. Thus, a simple assessment tool would be useful in order to have a first glance at potential problems.

A possible way to assess the RIMS measurements quality is to have a thorough measurement model that could be used as a reference to investigate the potential local divergence of the raw measurements with respect to that model. Monitoring stations have a very particular characteristic, which is to be fixed. This means that the measurements' dynamic will mostly be affected by the satellite motion and should not be of a high order. Consequently, it seems that a simple model for the raw measurements can be obtained using a polynomial interpolation. The goal of this paper is thus to show how a polynomial fit can be used to model ground stations raw code and phase measurements and to detect the aforementioned anomalies.

The first part of this paper studies the feasibility of this method as well as its short-coming when carrier-phase measurements are considered. The second part focuses on phase measurements in order to deeply understand the misbehavior of the polynomial interpolation method in this case. A more thorough measurement model, obtained from the exact computation of the true satellite-receiver range, is presented. It allows a sharper analysis of phase measurements contributors. They underline how satellite

and receiver oscillators prevent the use of polynomial interpolation to fit phase measurements analysis in our expected way. Finally, before concluding, the third part investigates methods that associate single or double differenced phase measurements with polynomial interpolation in order to still be able to assess in a simple way phase measurements quality.

POLYNOMIAL INTERPOLATION OF RAW CODE AND PHASE MEASUREMENTS

It is well known [Kaplan, 1996] that pseudorange and carrier-phase measurements can be modeled as:

$$P = \rho + d\rho + c\left(\Delta T_{Sat} - \Delta T_{Rx}\right) + I + T + \varepsilon_{MP}^{P} + \varepsilon_{P}$$

$$\phi = \rho + d\rho + N\lambda + c\left(\Delta T_{Sat} - \Delta T_{Rx}\right) - I + T + \varepsilon_{MP}^{\phi} + \varepsilon_{\phi}$$

where

ρ is the satellite-receiver true range,

$d\rho$ is the satellite ephemeris error,

c is the speed of light,

ΔT_{Sat} is the satellite clock offset wrt GPS time,

ΔT_{Rx} is the receiver clock offset wrt GPS time,

I is the ionospheric delay,

T is the tropospheric delay,

ε_{MP}^{P} and ε_{MP}^{ϕ} are the multipath-induced errors on the code and phase measurements respectively,

ε_{P} and ε_{ϕ} are the interference or noise-induced errors on the code and phase measurements respectively,

N is the ambiguity (integer) inherent to phase measurements, and

λ is the GPS L1 carrier wavelength.

From a tracking point of view, the anomalies of interest are the ones linked with the local phenomenon inherent to the station environment affecting tracking (interference or multipath), or the receiver tracking performance. Ignoring the case of tracking divergence that could be easily noticed by other means, these cases can be incorporated in the last two terms of the previous two equations: ε_{MP}^{P}, ε_{MP}^{ϕ}, ε_{P}, and ε_{ϕ}. Thus, our measurement model should mostly allow the estimation of these components.

The main parameters affecting polynomial interpolation (other than the measurements themselves!) are the window size and the interpolation order. Because the analysis aims at analyzing local errors (presence of local interferer for instance), as well as potential inherent tracking problem (high measurements error standard deviation for instance), it was decided, in the frame of this study, to run a polynomial interpolation over 2-hour periods. This means that local anomalies can be compared to normal behaviour, while still enabling the computation of relevant measurements statistics. The choice of the interpolation order will be discussed later.

Considering the common code and phase measurements errors, unless in some extreme conditions, the ionospheric and tropospheric delays are usually slowly changing biases that will not imply fast range variations. Olynik (2003) showed that even during high atmospheric activity, the correlation of the ionospheric delay was of 90% after 5 minutes and 90% after 10 minutes for the tropospheric delay. The same applies to ephemeris-induced errors. Finally, the true range variation is very smooth due to the static receiver. Thus, intuitively, it can expected that all these slow variations will be almost perfectly modeled by the polynomial interpolation (pending the right choice of its order).

The satellites and RIMS receivers oscillators are based on atomic oscillators that are very stable. However, their short to mid-term stability might induce sudden range variations, but with a reduced amplitude (see [Julien 2006; Rebeyrol et al. 2006] for examples). According to the part of these variations in the measurements error budget, it can be detrimental to the polynomial model. In particular, it will have a different impact on pseudorange and phase.

Pseudorange Measurements

Raw pseudorange measurements are shown in Figure 1. Although not visible, its noise-, multipath- and interference-induced errors are significant factors in the GPS tracking error budget. In particular, they significantly dominate atomic clock instabilities. Moreover, they have irregular variations compared to the errors mentioned above (although multipath error might vary slowly in static cases, it has a correlation time lower than the other errors most of the time). Thus, it means that apart from the true range variation, the dominating local pseudorange variation is due to noise, multipath and interference errors that can be assumed to be Gaussian (in a first approximation). Therefore, polynomial interpolation, optimal for Gaussian errors, should be an excellent candidate to model everything but the errors of interest. Note that even if there is a loss of lock, this should not be a problem for polynomial interpolation due to the 'continuity' of the measurements.

In order to confirm the potential use of polynomial interpolation, a reference estimated noise and multipath-induced error was created using Code-Minus-Carrier (CMC) measurements:

$$P_{CMC} = P - \phi = -N\lambda + 2I + \varepsilon_{MP}^{P} + \varepsilon_{MP}^{\phi} + \varepsilon_{P} + \varepsilon_{\phi}$$

Knowing that code multipath and noise errors are significantly greater than their phase counter part, it gives:

$$P_{CMC} \approx -N\lambda + 2I + \varepsilon_{MP}^{P} + \varepsilon_{P}$$

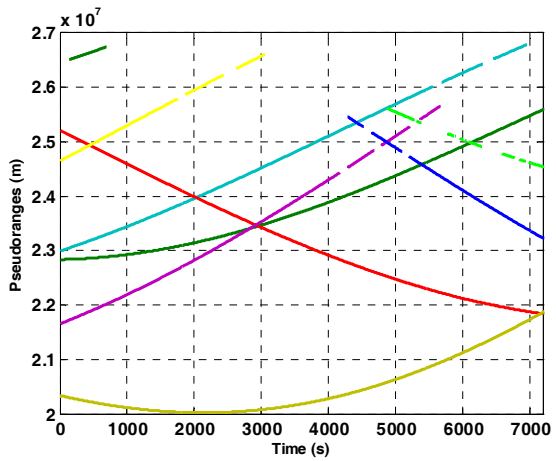


Figure 1 – Example of Pseudorange Measurements

Finally, assuming a slow variation of the ionosphere over the 2-hour period, it can be accepted that:

$$P_{CMC} - E[P_{CMC}] \approx \varepsilon_{MP}^{P} + \varepsilon_{P}$$

Thus, this gives a good reference to check if the polynomial interpolation produces good results. The last unknown now is the order of the polynomial function to use to model the pseurdorange measurements in a relevant way. Indeed, a low order might not allow modeling the slowly varying atmospheric delays. On the other hand, an order too high could result in modeling the slowly varying multipath error. Figure 2 shows the residuals (polynomial model minus raw pseudorange) standard deviation obtained using different interpolation order for a 2-hour window with different satellites from different RIMS. It can be seen that the residuals standard deviation usually decreases as the interpolation order increases, meaning that the interpolation fits better and better the pseudoranges, and then it levels before becoming chaotic due to a close-to-singular matrix operation that provokes instabilities.

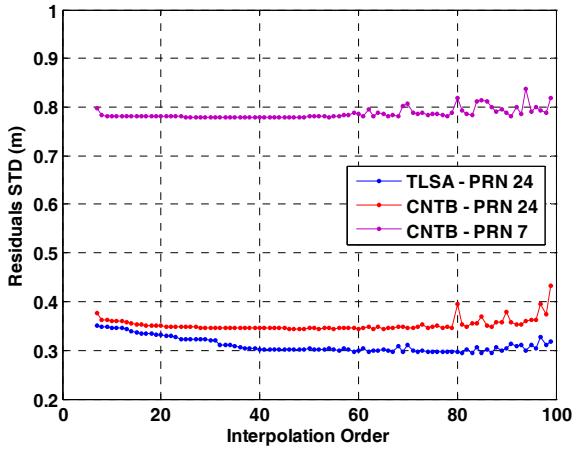


Figure 2 – Residual Standard Deviation Obtained Using Different Interpolation Order for Different Satellites and RIMS Stations

Comparing the pseudorange residuals obtained from the interpolation process against the CMC residuals, an interpolation order of 24 was considered relevant for most of the cases. Indeed, intuitively, a too high order is useless since it will only consist in modeling slowly changing multipath errors. Obviously, another order could be chosen, but for comparison purpose, this order was always used and was deemed relevant for the examples taken. Figure 3 shows the residuals obtained from the polynomial interpolation and from the CMC operation for two different RIMS stations at two different locations using a 24th-order polynomial function. They seem to have very close behaviour and multipath-induced errors and thus model the same errors. Thus, for fast assessment of the pseudorange quality and to ensure correct tracking, polynomial interpolation is a very simple and powerful tool. Compared to CMC measurements, the polynomial interpolation method does not rely on phase measurements and thus provides an independent analysis. Note that it would allow quick detection of:

- Biases due to biased tracking, oscillator jump, or hardware problem,
- Abnormal noise (or interference-induced) levels,
- High multipath environment

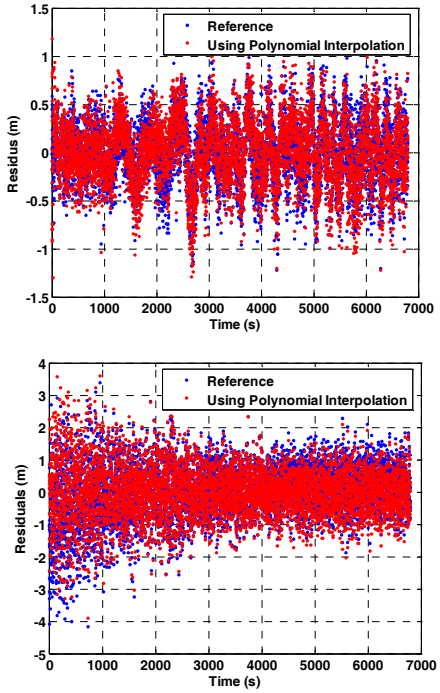


Figure 3 – Comparison of Pseudorange Residuals Obtained Through Polynomial Interpolation and CMC

Phase Measurements

When considering phase measurements, the interpolation approach is different for several reasons:

- Tracking losses induce phase jumps due to cycle slipping, as shown in Figure 4. This means that the

data set has to be split into pieces in order to work on sections without any phase jump.

- Multipath-induced errors and noise are not dominating the tracking error budget. Thus, the errors considered negligible for the pseudoranges (oscillators instabilities, atmospheric effects) might now be dominating. Since these errors (especially oscillator-induced variations) cannot be considered as Gaussian, the result from polynomial interpolation is not guaranteed, especially in order to assess phase measurements' multipath and noise errors.

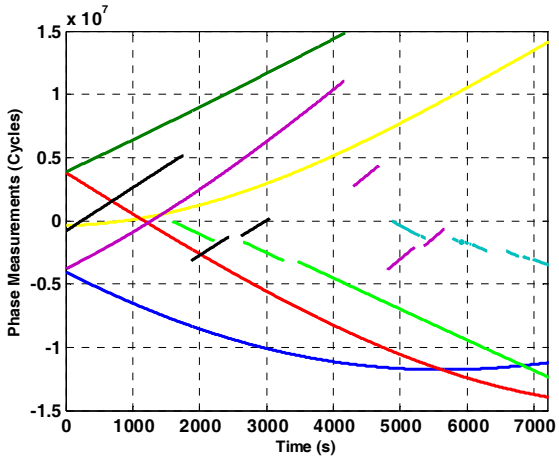


Figure 4 – Example of Carrier-Phase Measurements

After isolating a 2-hour time-window with continuous phase tracking on several satellites and several RIMS far geographically, a first test of the polynomial interpolation method was realized with an interpolation order of 24 and is shown in Figure 5. Several remarks can be extracted from these plots:

- The magnitude of the residuals reaches values close or greater than 5 cms. It is well known that multipath-induced errors on phase measurements cannot be greater than a quarter of the wavelength. In real conditions, this extreme case is extremely rare and thus, such a magnitude for the phase residuals has to come from another origin.
- It seems that there is a common trend for PRN 24. This however is less obvious for PRN 7. Since the two stations tested are geographically far, it cannot come from atmospheric effects, and since different RIMS were used, it cannot come from one type of receiver. Thus, it seems that the satellite clock and/or polynomial interpolation limitations for phase measurements should be responsible for this common behaviour.

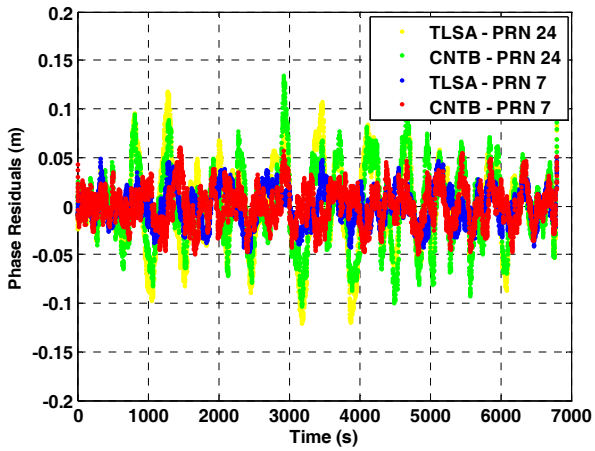


Figure 5 – Phase Residuals Obtained Through Polynomial Interpolation

It is now important to understand why it seems that certain measurements are more perturbed than other ones (PRN 24 vs PRN 7 in Figure 7). The remaining possibilities for the residuals variation are:

- atmospheric delay variation, but since the same behaviour is encountered on two different stations and not on PRN 7, this is very unlikely,
- the receiver clock error, but it should not be correlated between different RIMS receivers from different stations,
- the ephemeris error and the satellite oscillator instabilities, which are the last options.

A test using a known environment was realized. A Spirent 4500 simulator was used to generate GPS signals and a Septentrio PolaRX receiver was used to process the signal. No errors were simulated in order to have a perfectly clean signal. In this configuration, only thermal noise as well as the simulator and receiver clocks drifts can affect the measurements. Although the oscillator of these instruments cannot be compared with atomic clocks, it can still show how the clock can affect code and phase measurements. Two tests were run.

- A test was realized with a common oscillator (the simulator oscillator fed the receiver), and
- A test was realized keeping each separate clock.

A polynomial interpolation was then conducted to analyze the residuals. The results are shown in Figure 6. It can be seen that when the same oscillator is used, only noise is present in the phase residuals and thus the interpolation works perfectly. However, when different oscillators are used, residuals reaching the meter-level are observed, with a signature similar to that observed with the RIMS phase measurements (but with a different magnitude due to the different oscillator grades used).

It thus seems like the extreme variations of phase residuals fit with clock instabilities. Thus, now, it has to be figured out why phase measurements issued from different GPS satellites result in different interpolation residuals.

To better understand the issue, it was decided to design a more accurate model of the measurements in order to visualize the phase variations, trying to leave out as many known errors as possible.

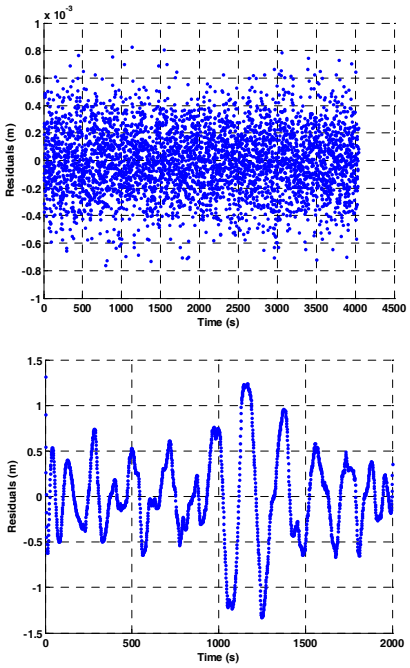


Figure 6 – Interpolation Residuals Obtained Using a Common Oscillator (Top) and Separate Ones (Bottom)

ENHANCED MEASUREMENT MODEL FOR PHASE ANALYSIS

The idea here is to try to reproduce as accurately as possible the true satellite-receiver range to compare it against raw measurements. As already explained, the RIMS stations coordinates are precisely known. Thus, by determining the satellite position and its clock bias, it should be possible to model the true signal transit time. An approach similar to [IS-GPS-200D] to compute the measurements. To do so, the first step is to use .sp3 files provided by the International GNSS Service (IGS). These files are created after post-processing of code and phase measurements by a network of ground stations and provide precise satellite position and clock offset. The accuracy of these satellite parameters is a few centimetres, which is enough for our analysis. However, the sampling rate of these data is 15 minutes. Thus over-sampling is realized to obtain a 1-second rate. the resulting data set is $\left(\hat{x}_{Sat}, \hat{y}_{Sat}, \hat{z}_{Sat}, \Delta\hat{T}_{Sat}\right)$.

The estimated satellite clock offset has then to be corrected from the relativity effect (computed from the raw measurements assessing the satellite elevation and azimuth) and the time group delay inherent to the satellite payload. This gives the new estimated satellite clock offset $\Delta\hat{\hat{T}}_{Sat}$ fitting with the reference GPS time. For a typical GPS satellite-receiver link, the propagation time is around 70 ms. It can then be concluded that, due to the high quality of atomic clocks, the satellite oscillator offset $\Delta\hat{\hat{T}}_{Sat}$ does not change during the transmission time. Consequently, the satellite estimated transmit time $\hat{t}_t$ can be obtained through:

$$\hat{t}_t \approx t_r - \frac{\left(P + c\Delta\hat{\hat{T}}_{Sat}\right)}{c}$$

where t_r is the signal received time.

Having an estimated transmit time, it is now possible to compute the true range between the satellite and the receiver at each epoch. For that, the rotation of the Earth during the signal propagation has to be taken into account. The solution is recursive in order to converge toward the true solution [Dong, 2003].

This estimated range is then subtracted to the raw phase measurements to obtain the residuals. To refine the accurate measurement model, a Saastamonien tropospheric model is used in order to remove most of the dry tropospheric delay from the measurements (using the satellite elevation and azimuth information already calculated). The resulting residuals are then averaged in order to remove the phase ambiguity effect.

Finally, applying this to several satellites, the receiver clock should be visible and should affect the residuals in the same way. Thus, a simple bias/drift model is used to reproduce the receiver clock error and clean the phase residuals from this effect. An example of residuals is given in Figure 7 for the same satellites, RIMS and time window as in Figure 5. It can be observed that the phase measurements residuals variations are well contained within ±50 cms, which allows their thorough visualization, differently from what is shown in Figure 4. As in the case of the polynomial interpolation residuals, one satellite seems to lead to stronger variations, and this is true for both RIMS.

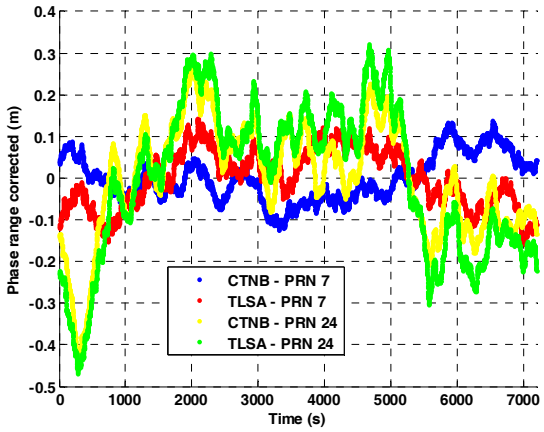


Figure 7 – Example of the Phase Measurement Refined Model Residuals

In order to validate the previous refined model, a polynomial interpolation was run on the refined model residuals, and on the raw measurements, both with the same order. The residuals obtained from these two interpolations were then subtracted to be compared. The result is shown in Figure 8. It can be seen that the difference is on the order of a few millimetres which confirms that the refined model allows visualizing the local variations disturbing the interpolation process that was applied to the raw phase measurements.

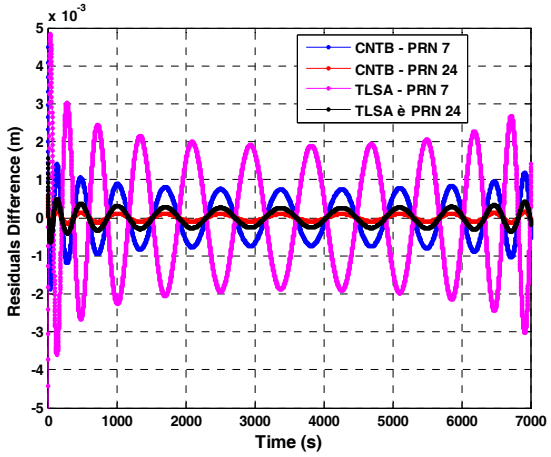


Figure 8 – Difference between Residuals Obtained from Polynomial Interpolation using Raw Phase Measurement and Refined Measurement Model

The sudden variations observed are thus the phenomenons limiting the attractiveness of polynomial interpolation since this type of model does not work well with this type of behaviour.

Separately from the context of measurements quality check through polynomial interpolation, this refined model is a very powerful tool to inspect phase measurements. Indeed, it allows the actual observation of the remaining errors, including oscillators offset, ionosphere variation, multipath, noise, interference impact. This means that it allows a different view on the measurements anomaly. In Figure 4 for instance, the level of information is different from the residuals obtained in Figure 5.

Looking at Figure 7, it is noticeable how the variations disturbing the use of a direct polynomial interpolation are sudden (tens of centimetres within a few hundredth of seconds). It was previously mentioned that the satellite oscillator and the satellite trajectory might be the main contributor to these variations for PRN 24 (then meaning a deviation from the .sp3 model during the 15-minute-length gap between 2 IGS data samples). The chaotic behaviour of the refined model residuals seen in Figure 7 does not fit with an expected smooth satellite trajectory. The last option is then the satellite clock instabilities as the main contributor to sudden local phase variations.

Looking at the GPS constellation status shown in Figure 9, it can be seen that PRN 24 uses a Rubidium atomic clock while PRN 7 uses a Caesium clock. To confirm that this oscillator type could be the reason looked for, an analysis of the residuals, using the polynomial interpolation method, was conducted for all the visible satellites over one day. The results are shown in Figure 10. Although probably not completely representative of the true oscillator quality of each satellite (other residuals errors are present such as the receiver clock that is common to all the analysis, but might different according to the time in the day the satellite was visible, …), it can be seen that the residuals associated with Caesium oscillators have a higher standard deviation compared to the ones associated with Rubidium clocks. This probably explains why all the new satellites use Rubidium oscillators.

LAUNCH ORDER	PRN	SVN	LAUNCH DATE	FREQ STD+	PLANE+	US SPACE COMMAND **
*II-1		14	14 FEB 1989			19802
*II-2		13	10 JUN 1989			20061
*II-3		16	18 AUG 1989			20185
*II-4		19	21 OCT 1989			20302
*II-5		17	11 DEC 1989			20361
*II-6		18	24 JAN 1990			20452
*II-7		20	26 MAR 1990			20533
*II-8		21	02 AUG 1990			20724
II-9	15	15	01 OCT 1990	Cs	D5	20830
*IIA-10		23	26 NOV 1990			20959
IIA-11	24	24	04 JUL 1991	Cs	D1	21552
IIA-12	25	25	23 FEB 1992	Cs	A2	21890
*IIA-13		28	10 APR 1992			21930
IIA-14	26	26	07 JUL 1992	Rb	F2	22014
IIA-15	27	27	09 SEP 1992	Cs	A4	22108
IIA-16	01	32	22 NOV 1992	Cs	F6	22231
*IIA-17	29	29	18 DEC 1992	Rb	F5	22275
*IIA-18		22	03 FEB 1993			22446
*IIA-19		31	30 MAR 1993			22581
IIA-20	07	37	13 MAY 1993	Rb	C4	22657
IIA-21	09	39	26 JUN 1993	Cs	A1	22700
IIA-22	05	35	30 AUG 1993	Rb	B4	22779
IIA-23	04	34	26 OCT 1993	Rb	D4	22877
IIA-24	06	36	10 MAR 1994	Rb	C1	23027
IIA-25	03	33	28 MAR 1996	Cs	C2	23833
IIA-26	10	40	16 JUL 1996	Cs	E3	23953
IIA-27	30	30	12 SEP 1996	Rb	B2	24320
IIA-28	08	38	06 NOV 1997	Cs	A3	25030
***IIR-1		42	17 JAN 1997			
IIR-2	13	43	23 JUL 1997	Rb	F3	24876
IIR-3	11	46	07 OCT 1999	Rb	D2	25933
IIR-4	20	51	11 MAY 2000	Rb	E1	26360
IIR-5	28	44	16 JUL 2000	Rb	B3	26407
IIR-6	14	41	10 NOV 2000	Rb	F1	26605
IIR-7	18	54	30 JAN 2001	Rb	E4	26690
IIR-8	16	56	29 JAN 2003	Rb	B1	27663
IIR-9	21	45	31 MAR 2003	Rb	D3	27704
IIR-10	22	47	21 DEC 2003	Rb	E2	28129
IIR-11	19	59	20 MAR 2004	Rb	C3	28190
IIR-12	23	60	23 JUN 2004	Rb	F4	28361
IIR-13	02	61	06 NOV 2004	Rb	D7	28474
IIR-M1	17	53	26 SEP 2005	Rb	D6	28874

* Satellite is no longer in service.
** US SPACE COMMAND, previously known as the NORAD object number; also referred to as the NASA Catalog number. Assigned at successful launch.
*** Unsuccessful launch.
\+ Source: 2SOPS GPS Operational Advisory dated 31 OCT 2005

Figure 9 – GPS Constellation status as of October 31, 2005

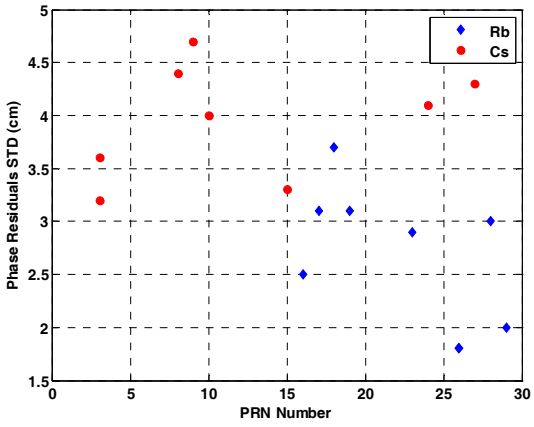


Figure 10 – Phase Residuals Standard Deviation Obtained from Polynomial Interpolation

This result is very interesting because it underlines how different high quality oscillator can perform differently. It is also extremely interesting to be able to observe that behaviour through the refined measurement model.

If the attention is only on very local measurement behaviour, it is possible to use polynomial interpolation on raw phase measurements over a short time window. However, as the time window of interest increases, it is likely that the oscillators irregularities will affect more and more the polynomial model.

In order to cancel the clock offset that impairs the proper use of polynomial interpolation, a simple phase manipulation, such a single or double differencing can be used.

PHASE COMBINATIONS FOR PHASE MEASUREMENTS QUALITY ANALYSIS

Figure 11 shows the use of between-receivers single differenced phase measurements for the PRN 24, as well as double differenced phase measurements. The same interpolation process (24^{th} order interpolation) is used in all the cases. It can be observed that the single difference combination reduces the variation of the residuals observed on raw phase measurements. However, it still suffers greatly from the receiver oscillator instabilities. The double difference combination completely cancels that effect, and residuals on the order of a centimetre are now observed. Assuming slow variations of the ionospheric and troposheric biases, it can be assessed that the residuals are mostly composed of double differenced multipath-induced errors, double-differenced noise error.

The objective of the study was to have an independent assessment of each measurement. The fact that several phase measurement are necessary does not fit with this objective. However, it has to be reminded that the redundancy of RIMS in one ground station and the high number of stations constituting the EGNOS network can be used to isolate misbehaviour on one of the phase measurements. The use of two RIMS receivers located on the same ground stations would result in a better cancellation of atmospheric effect and thus a more relevant interpolation, especially since the variation of slowly varying multipath and atmospheric activity could be, in certain cases, of the same order.

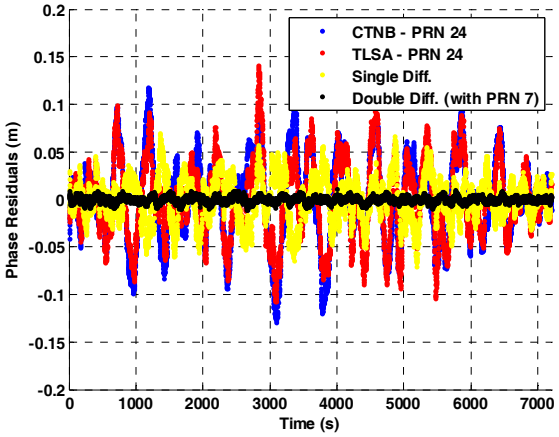


Figure 11 – Polynomial Interpolation Residuals for Raw, Single-Differenced and Double-Differenced Phase Measurements

In order to limit as much as possible the increase in the noise and multipath-induced errors due to measurements combination, a test was realized using a common external oscillator for two of the RIMS present in one ground station. By doing so, a single difference between the raw measurements of both RIMS receivers realized on a same satellite result in the cancellation of both the satellite and receiver clock offset at the same time, and a minimization of the atmospheric delays (since although not sharing the same antenna, the two RIMS of a same site have very similar locations). The result is shown in Figure 12. It can be seen that the residuals of each raw measurements are very similar. Assessing the single differenced phase residuals, it can be seen that they are contained within 1 cm, which represents expected values for multipath and noise errors in phase measurements. However, note that in this case, the single difference increases the multipath and noise errors since they are not correlated from one receiver to the next.

The use of only one measurement from two different RIMS, though, cancels the risk of unseen tracking errors (that could disappear when differencing between satellites with the same receiver). Indeed, the two receivers use different tracking algorithms, and it is unlikely that local tracking errors could happen at the same with the same signature on both phase measurements. Thus, it is possible to isolate local errors from that analysis, a potential more thorough investigation using the more accurate measurement model could then be used to find the receiver that delivered the anomaly.

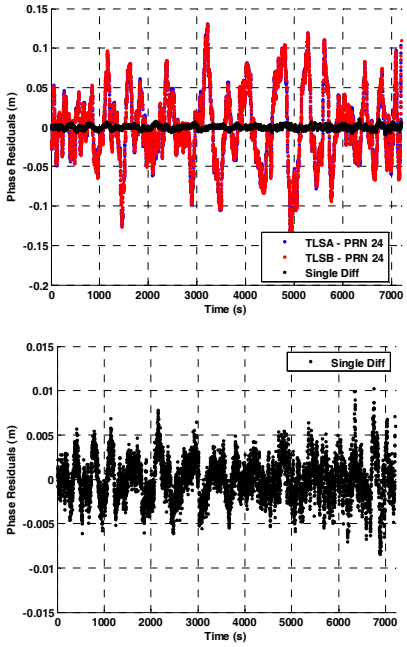


Figure 12 – Polynomial Interpolation of Raw Measurements and Single Differenced Phase Measurements Using RIMS Sharing a Common Oscillator (Zoom on the Bottom)

CONCLUSIONS

This study showed several interesting points applied to the study of RIMS receivers raw measurements in the context of quality control:

- The good behaviour of polynomial interpolation in order to independently (from any manipulation) study the pseudorange measurements quality. This can be used to check correct tracking error standard deviation, as well as local anomalies such as presence of interferers.
- For the same objective, polynomial interpolation cannot be used on raw phase measurements. It has been seen how mainly satellite and RIMS receivers variations dominate the noise and multipath errors. However, polynomial interpolation can be used after single or double differencing of phase measurements. In particular, the use of two RIMS on the same ground station allows removing almost entirely atmospheric delays and thus really focus on tracking misbehaviour. However, in case of anomaly, it then requires the thorough analysis of each measurement separately to find the one actually carrying the defaults.
- In order to study each phase measurements accurately, a refined measurement model was built that allows the observation of the phase variations without the true range variations. Consequently, it is

possible to isolate certain anomalies visible on the phase measurements.

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