SBAS C/A code interferences: observations and induced tracking errors

Olivier Nouvel, Matthieu Sihrener, Jean-Luc Issler, Laurent Lestarquit, Christophe Macabiau, Olivier Julien

SBAS C/A Code Interferences: Observations and Induced Tracking Errors

O. Nouvel, *M3Systems*
M. Sihrener, *M3Systems*
J.L. Issler, *CNES*
L. Lestarquit, *CNES*
C. Macabiau, *ENAC*
O. Julien, *ENAC*

BIOGRAPHY

Olivier Nouvel has been working at M3Systems (Toulouse, France) as a Radio Navigation Engineer since 2002. He is involved in various 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).

Matthieu Sihrener graduated in 2006 from ENAC (Ecole Nationale de l'Aviation Civile) in Toulouse, France. He joined M3Systems (Toulouse, France) in 2006 as a Radio Navigation Engineer and he is specialized in Signal processing algorithms development.

Laurent Lestarquit is a Navigation Engineer in the Transmission Techniques and signal-processing department, at CNES since 1996. He is currently working on Formation Flying. He proposed innovative Galileo Signal Modulations like ALT-BOC and BOC-cosine. He contributed to the C-BOC and MBOC definitions, and initiated this work on X-correlation error correction.

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, TT&C, propagation and spectrum survey. He is involved in the development of several spaceborne receivers and RF Formation Flying equipements in Europe, as well as in studies on the European RadioNavigation projects, like GALILEO and the Pseudolite Network.

Christophe Macabiau graduated as an electronics engineer in 1992 from 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.

Olivier Julien is an assistant professor at 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.

ABSTRACT

It is well known that GPS C/A codes present cross correlation peak potentially causing false acquisitions. These cross-correlations peaks can in addition cause tracking errors and C/No degradation *[1], [2], [3]* and *[4]*, not in traditional GPS tracking situations, but for applications where signals are received with low Doppler.

There are several applications that can have low relative Doppler, and thus more frequent Doppler collision causing code cross-correlation interference : the first application occurs with the use of ranging signal broadcasted from geostationary satellites (SBAS systems) when two or more geostationary satellites are in common views of a fixed or low dynamic receiver (control station, reference station for differential positioning or any ground user with none or little motion), the second application occurs when ground pseudolites are used, with a receiver either on board a geostationary satellite or in a plane and on the ground as well.

The findings described in this paper are part of the work performed by M3 Systems under a project initiated by the CNES (French Space Agency) which aims at studying the EGNOS RIMS performances.
The work presented here aimed at:

- Characterizing precisely these C/A codes interference tracking errors,
- Identifying the exact factors driving the occurrence of these errors

INTRODUCTION

The goal of this study is to show that, when specific conditions are met, large tracking errors can occur with C/A code due to C/A code cross-correlation interference.

The interference mechanism is physically the same than for multipath error. Actually, multipath can be viewed as C/A code interference on itself. For multipath error, the cross correlation peak of the reflected signal adds its contribution to the correlation function and causes an offset of the zero-crossing of the discrimination function. This offset is the tracking error. For C/A code interference, the cross-correlation peak of the interfering code causes the same effect. Normalized cross-correlation peak values are either +63/1023 or -65/1023. A simple analysis shows that the error can reach up to 18 meter for a half chip spacing correlator. If the cross-correlation function of the desired and interfering codes has a secondary peak that falls within the receiver chip spacing of the relative code offset, there is potential for a tracking error.

A necessary condition for C/A code interference to take place is to have the relative Doppler between the 2 interfering signal lower than the receiver code loop bandwidth that is typically lower than 1 Hz. The reason is that the signed amplitude of the interfering peak is function of the relative phase, and if the relative phase moves too much during the code loop integration period, the interfering peak (and the tracking error) will be filtered. We can name this condition as "Doppler Collision" or as having "quasi-stationary code" because from the receiver point of view, the received codes will not move one relative to another, the cross-correlation peak of the interfering signal will not move relative to the main auto-correlation peak of the desired signal, and the interference will result in a lasting bias.

For common GPS application, having a Doppler collision smaller than 1 Hz is quite a rare phenomena:, indeed the Doppler due to the satellite motion is high (ranging from –4.5kHz to 4.5kHz for standard use) so there is a low probability to have Doppler collision lower than 1 Hz leading to a tracking errors, and even if it happens, it will only last a few seconds. Therefore, for common GPS applications, C/A code interference rarely leads to a noticeable tracking error.

However, with the development of the Satellite Based Augmentation Systems (SBAS) using geostationary satellite, like EGNOS, WAAS, GAGAN, or MSAS, the dynamics are much lower, in the range of a few 10's of Hz. Doppler collision will happen twice a day and last several minutes. Interference due to C/A code cross-correlation will happen. These C/A code interferences can cause false acquisition, C/No degradation and tracking error. This paper will focus on the tracking error due to the C/A code cross-correlation encountered in real situations using GNSS data collected by EGNOS's Range and Integrity Monitoring Stations (RIMS). It will also show the impact of several factor, including the navigation message on the tracking error This work is subsequent to previous papers where theoretical cross-correlation tracking error have been already studied *[1]*, *[2]*, *[3]*, *[4]* and simulated in laboratory *[2]*.

The first section of this paper presents the applications concerned by this phenomenon. The second section introduces theoretical aspect of this interference. The next section shows the real-life identification of the C/A code interference tracking errors, based on GNSS data collected by EGNOS RIMS. Finally, the last section introduces the possible interferences mitigation techniques.

1- APPLICATIONS

A- Geostationary Satellites Motion

Geostationary satellites motion is supposed to be fixed relative to the earth, therefore, signals from SBAS geostationary satellites would always be in Doppler collision with one another when received by a fixed receiver.
In reality, geostationary satellites move slowly within a station-keeping window, mostly along the N-S and the E-W axis, with a 24-hour period. This generates relative Doppler with an harmonic pattern and an amplitude of several 10's of Hz, so Doppler collision inside the code loop (~1Hz) occurs only twice a day during a few minutes (see figures 4 and 5).

B- SBAS Satellites Applications

The first application concerns the ranging signal broadcasted from geostationary satellites, when two or more satellites are in common view of a fixed receiver or with low dynamic (control station, reference station for differential positioning or any ground user not moving).

To resolve integrity problems and to improve GPS performances, the Satellite Based Augmentation System (SBAS) has been developed with different inter-operable regional complements like EGNOS, WAAS, GAGAN, and MSAS, for instance.

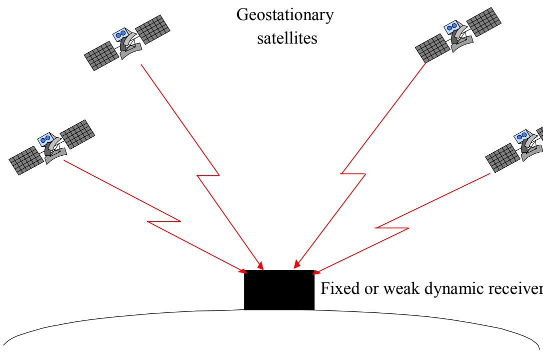


Fig. 1 : SBAS application

A tracking error due to C/A code cross-correlation can occur when at least two geostationary satellites are visible from a fixed receiver and increase strongly with more geostationary satellites. Indeed it is thus possible that all the signals will be interfering at the same time, or sequentially, one after another.

C- Pseudolites

The use of pseudolites can also induce low dynamic signals.
Two applications can involve pseudolites:

- pseudolites and receiver on board geostationary satellite
- pseudolites and fixed or low dynamic receiver

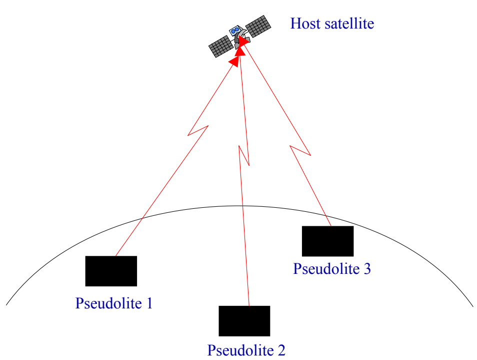


Fig. 2 : Pseudolite application

2- TRACKING ERRORS – THEORY

In presence of interfering signal, the receiver delay lock loop does not track only the desired signal delay but the delay of the sum of the desired signal (index k) and all interfering signals (index 1 to N).

The received signal can thus be written as follows:

$$c_r(t)=\sum_{i=1}^{N} a_i.d_i(t-\tau_i).p_i(t-\tau_i).\cos(\omega.t+\varphi_i(t))$$

Where:

$p_i(t)$: PRN code sequence of the ith satellite

$d_i(t)$: Data from the ith satellite

ω : Pulsation of the reference signal

$a_i(t)$, $\tau_i(t)$ and $\varphi_i(t)$: Power, Propagation delay and Phase of the ith signal wrt. the desired one

With an early minus late power code discrimination function and in presence of low Doppler, **the error function** induced by C/A code interference can be written as follows [*1*]:

$$\begin{aligned}V_e(\Delta\hat{\tau}_k)=2.\sum_{i=1}^{N} a_k.a_i\Big[&R_{k,k}\Big(\Delta\hat{\tau}_k-\frac{T_c}{n}\Big)R_{k,i}\Big(\Delta\hat{\tau}_k-\Delta\tau_{k,i}-\frac{T_c}{n}\Big)-\cdots\\ &R_{k,k}\Big(\Delta\hat{\tau}_k+\frac{T_c}{n}\Big)R_{k,i}\Big(\Delta\hat{\tau}_k-\Delta\tau_{k,i}+\frac{T_c}{n}\Big)\Big]\int_{1/B_n} d_k(t-\tau_k).d_i(t-\tau_i).\cos(\Delta\varphi_{k,i}(t)).dt+\cdots\\ &\sum_{\substack{i=1\\ i\neq k}}^{N} a_i^2\Big[R_{k,i}^2\Big(\Delta\hat{\tau}_k-\Delta\tau_{k,i}-\frac{T_c}{n}\Big)-R_{k,i}^2\Big(\Delta\hat{\tau}_k-\Delta\tau_{k,i}+\frac{T_c}{n}\Big)\Big]+\cdots\\ &2.\sum_{\substack{i=1\\ i\neq k}}^{N-1}\sum_{\substack{j=i+1\\ j\neq k}}^{N} a_i.a_j\Big[R_{k,i}\Big(\Delta\hat{\tau}_k-\Delta\tau_{k,i}-\frac{T_c}{n}\Big)R_{k,j}\Big(\Delta\hat{\tau}_k-\Delta\tau_{k,j}-\frac{T_c}{n}\Big)-\cdots\\ &R_{k,i}\Big(\Delta\hat{\tau}_k-\Delta\tau_{k,i}+\frac{T_c}{n}\Big)R_{k,j}\Big(\Delta\hat{\tau}_k-\Delta\tau_{k,j}+\frac{T_c}{n}\Big)\Big]\int_{1/B_n} d_i(t-\tau_i).d_j(t-\tau_j).\cos(\Delta\varphi_{i,j}(t)).dt\end{aligned}$$

Where:

$R_{k,i}$: Cross-correlation between the desired signal "k" and the ith signal

B_n : Bandwidth of the Delay Lock Loop

T_c : Code C/A period

n : Length of the code C/A

From this mathematical expression we observe that the tracking error induced by C/A code interference will depend on different parameters:

- the relative code delay: $\Delta\tau_{k,i}=\tau_i-\tau_k$
- the power factor : $a_i a_k$
- the relative carrier phase: $\Delta\varphi_{i,k}=\varphi_k-\varphi_i$
- the relative Doppler
- the cross-correlation function: $R_{k,i}$
- and the message data : d_i

3- TRACKING ERRORS - OBSERVATIONS

All the analyzed data are real data, RINEX format and other receiver raw measurements (C/No, receiver flags) being issued from EGNOS RIMS collected by the EGNOS PACF (Performance Assessment and Check-out Facility).

A- Detection of the C/A Code Interference

These results are based on the analyze of GNSS data collected by the RIMS station type A of Toulouse

(France) on 21st of January 2007 (TLSA) for which the interference error was clearly visible.

The following figure is a map showing the location of the TLSA RIMS station and the two interfering satellites:

- EGNOS satellite PRN 120 (Inmarsat 3F2 - AOR-E located on 15.5°W)
- and EGNOS sate1llite PRN 126 (Inmarsat 3F5 located on 25°E)

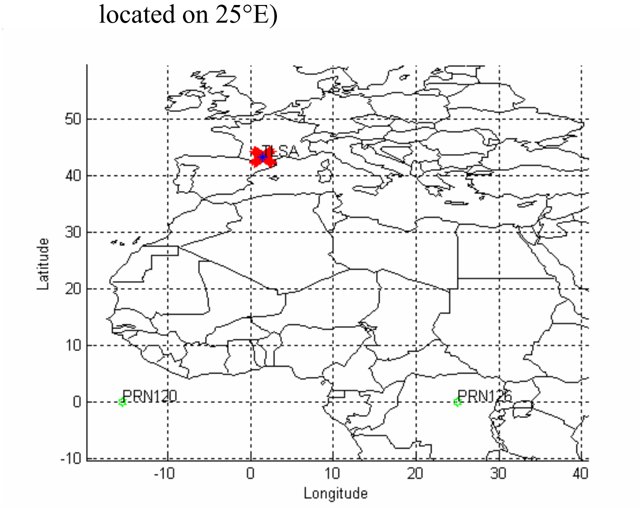


Fig. 3 : TLSA RIMS Locations

The following figure presents the Doppler evolution and the relative Doppler between geostationary satellites PRN 120 and 126, seen from TLSA:

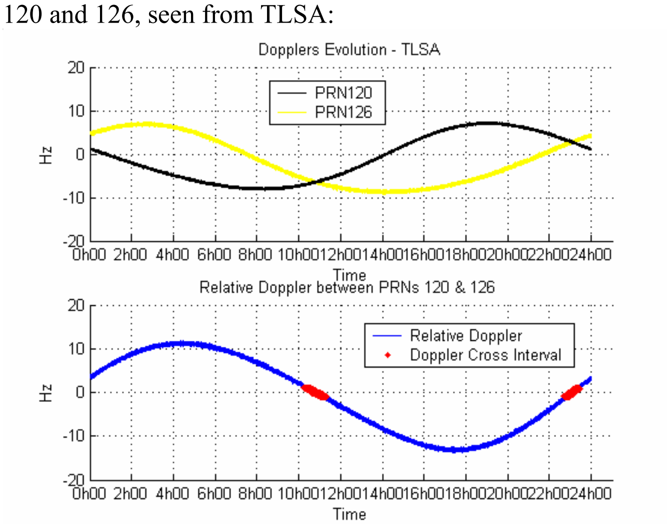


Fig. 4 : Relative Dopplers and Doppler Collisions between geostatinary satellites PRN 120 and 126 (TLS station)

On this figure, we observe two periods of approximately 1 hour (in red in the figure) where the relative Doppler is less than 1 Hz (approx. the code bandwidth) between those 2 EGNOS satellites. This implies that, during 2 hours per day (more than 8% of the time), C/A code interference can occur.

In addition, a third GEO is visible from TLSA: PRN124 (Artemis), but the station keeping of this GEO is very bad due to exhausted ergols, its Doppler is very high, and the Doppler collision is short. Interference with this GEO wasn't studied.

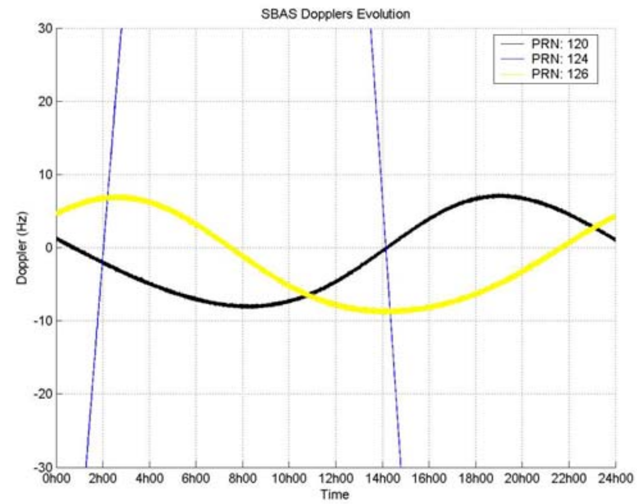


Fig. 5 : Dopplers evolution for geostationnary satellites including PRN 124 (Artemis) for TLSA station

B- Characterization of the C/A Code Interference

The characterization of the C/A code interference is made using three complementary methods:

- Computing the 3rd degree derivative of the C1 pseudo distance (code C/A on L1). This allows to have a first estimation of the noise which affects the C1 measurement. The tracking bias is characterized by an increase of the noise.
- Analyzing the residuals errors on C1 measurement obtained by polynomial interpolation of C1 by a 15th order polynomial and a sliding window of 2 hours.
- Analyzing the enabling causes for fine analysis:
    - Relative Doppler,
    - Gold sequences cross correlation function,
    - SBAS navigation messages correlation.

The 3rd Derived of C1 shows an increased noise on the measurement of the SBAS PRN 120, which only happens during the second Doppler collision between PRNs 120 and 126 (EGNOS). This noise reaches a maximum value at about 23h10min.

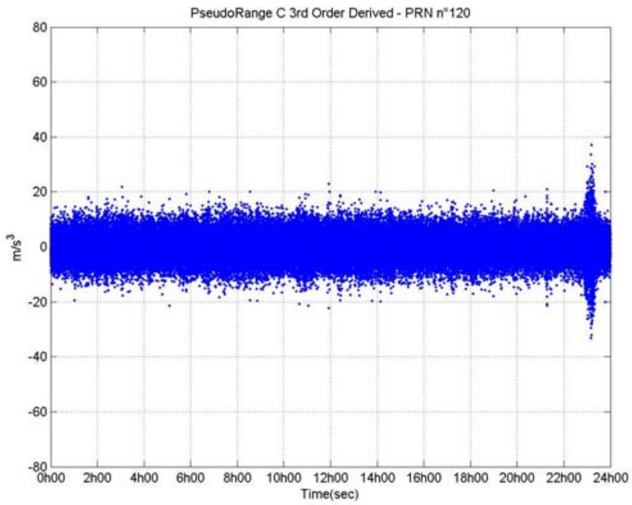


Fig. 6 : 3rd Derived of C1 – PRN120 – TLSA0210.07o

For the SBAS satellite PRN 126 (EGNOS), the same thing is observed even more clearly, as illustrated on the next figure:

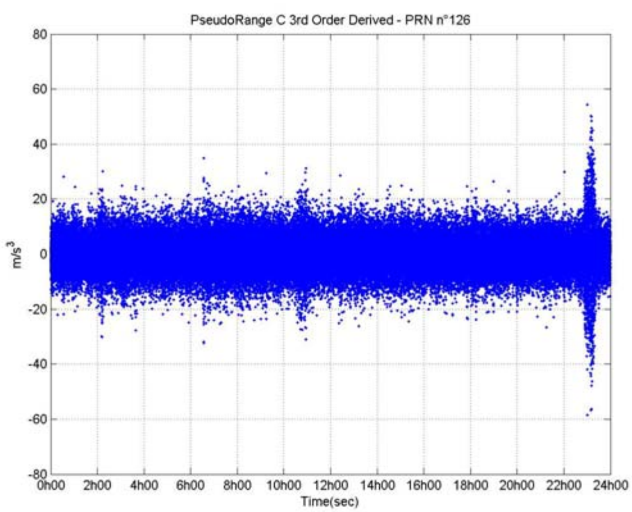


Fig. 7 : 3rd Derived of C1 – PRN126 - TLSA0210.07o

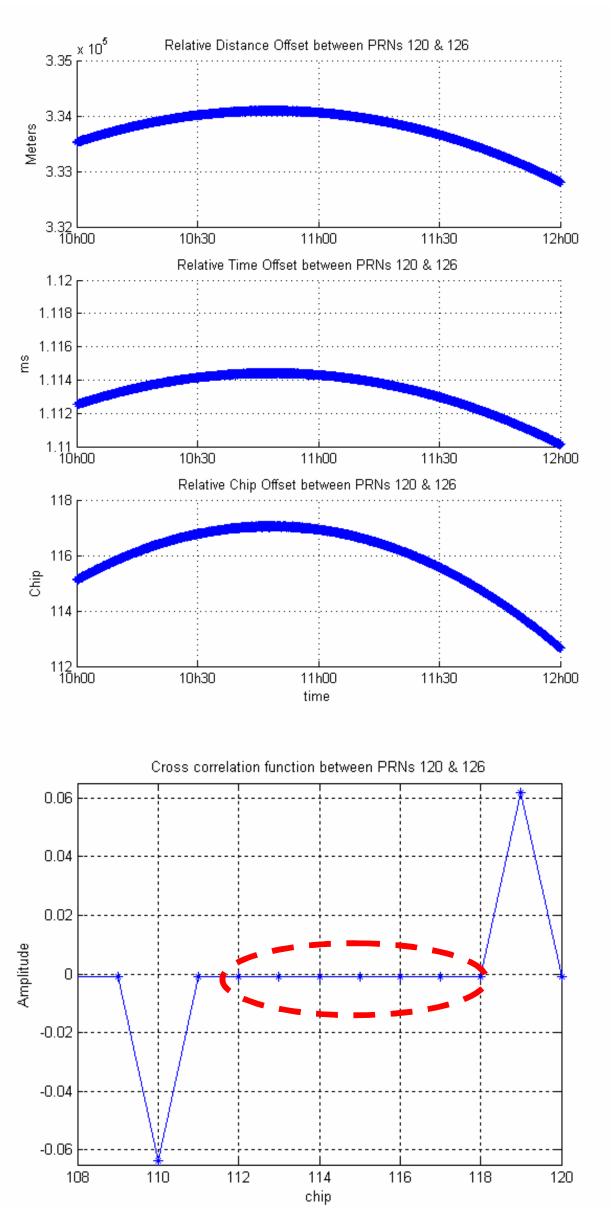


Fig. 8: Relative Distance, Time, Chip Offset and Cross Correlation between PRNs 120 & 126 -1St Doppler Collision

Analysis of the 1st Doppler collision (between 10h and 11h30)

We note that during the 1st Doppler collision, there is no interference between codes. This can be explained by the cross-correlation function between PRN 120 and 126.

In the time frame during which the Doppler collision occurs, the relative pseudo-distance between those PRN corresponds to a code offset ranging from 115 to 117 chips. We notice that the X-correlation function has no secondary peak for code offset ranging from 111 to 118 chips. This explains why there is no tracking error during the first Doppler Crossing.

Analysis of the 2nd Doppler collision (between 22h30 and 23h30)

Residual values on C1 for PRN 120 and 126 are presented on the next figures:

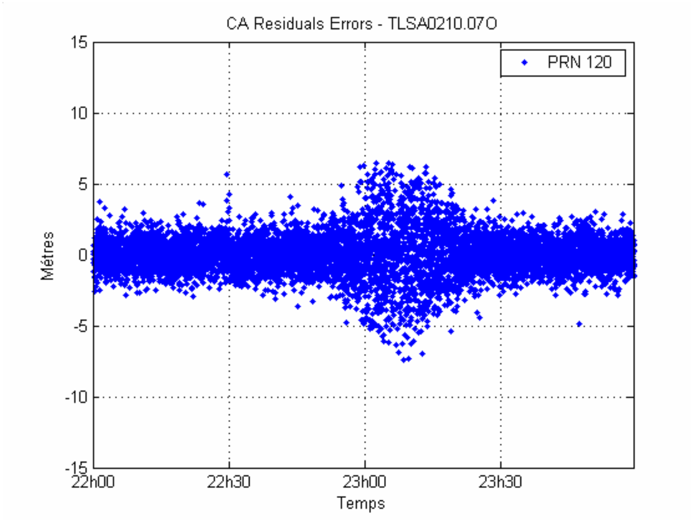


Fig. 9 : Residuals Error on C1 – PRN120 - TLSA0210.07o

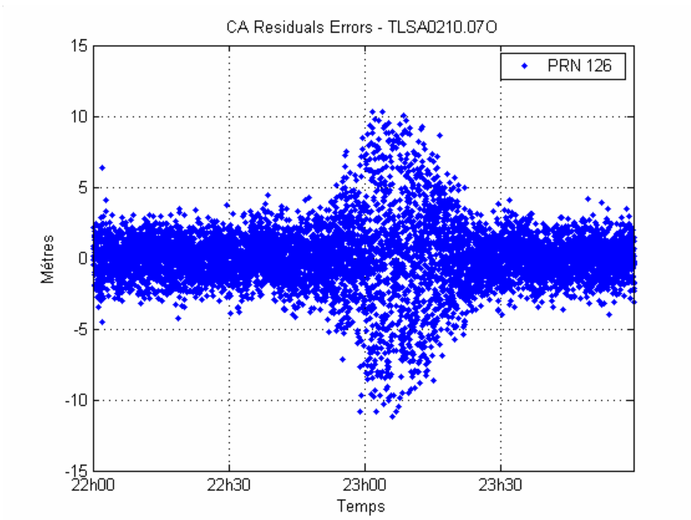


Fig. 10 : Residuals Error on C1 – PRN126- TLSA0210.07o

These figures show that we have residual errors up to 10 meters on C1 measurements on PRN 126 (EGNOS) and about 7 meters on PRN 120 (EGNOS), during the second Doppler collision between PRN 120 and 126.

The following figure shows the code relative pseudo-range and the Cross Correlation function of the PRNs sequences during time. We note that between 22h45 and 23h30 the relative chip offset is between 906 and 908 chips, and figure 13 shows that this corresponds to a secondary peak of the X-correlation function.

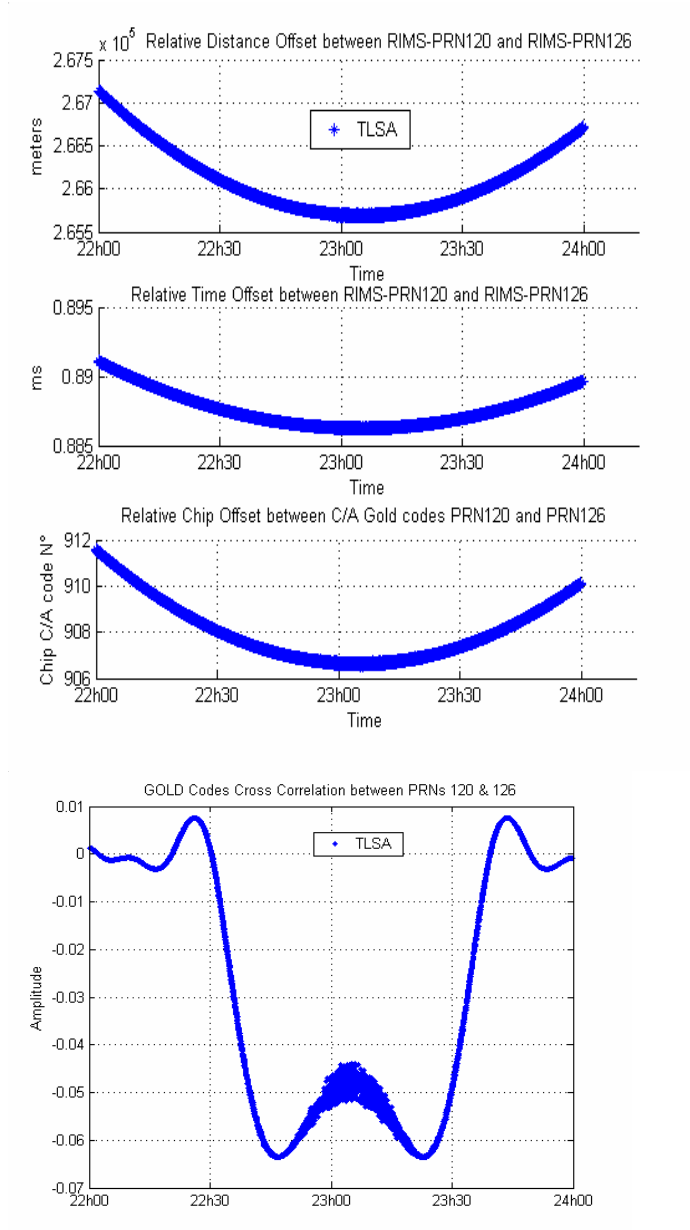


Fig. 11: Relative Distance, Time, Chip Offset and Cross Correlation between PRNs 120 & 126 -2nd Doppler Collision

The following figure is a zoom between 22h45 and 23h30 of the Chip relative offset, Cross Correlation function and cross correlation value for the prompt correlator over time:

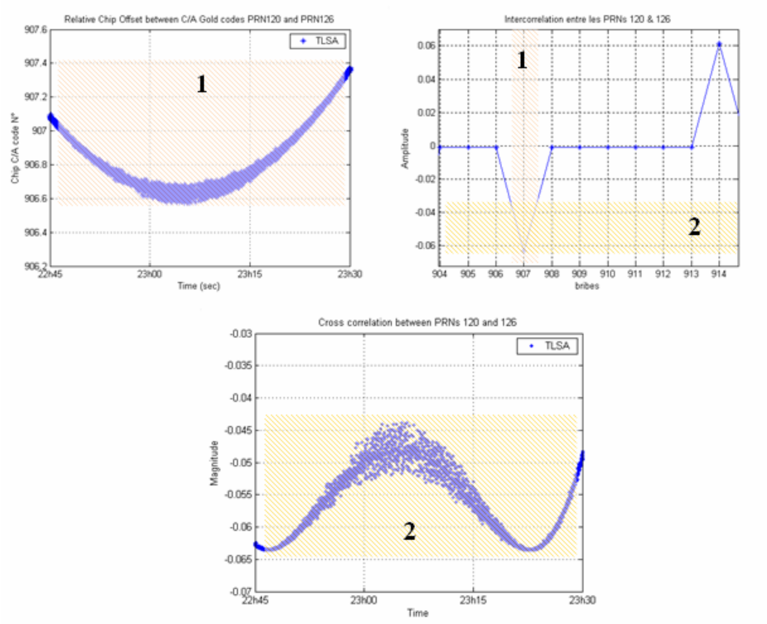


Fig. 12: Cross Correlation functions exact and interpolate during 2nd Doppler Collision

RELATIVE POWER

In addition, we note that PRN 120 is received with 2 dB more power than PRN 126. This explains why the tracking error is larger on PRN 126, the reason is PRN 120 interfers more on PRN 126 than PRN 126 interfers on PRN 120.

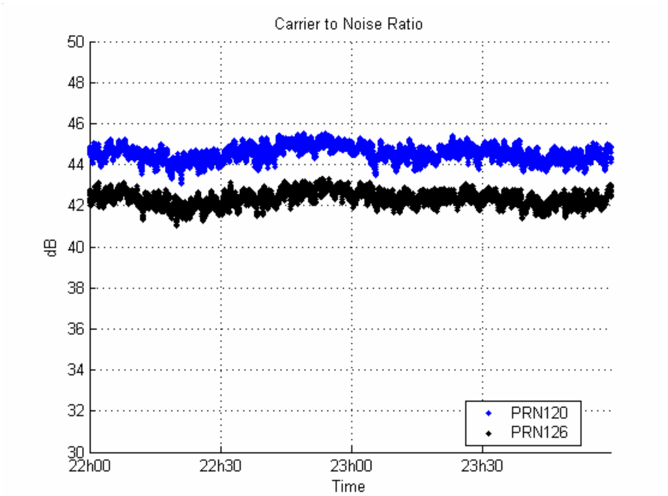


Fig. 13 : Carrier toNoise ratio between PRNs 120(blue) & 126(black)

NAVIGATION MESSAGE

Remark:

The raw navigation message of the SBAS signal contains 500 symbols, transmitted each second. This sequence is the convolutional encoding of the 250 bits of the SBAS navigation message available on the ftp://ems.estec.esa.int. With the convolution encoder logic described in MOPS DO229C presented below, it is possible to recover the 500 original SBAS symbols.

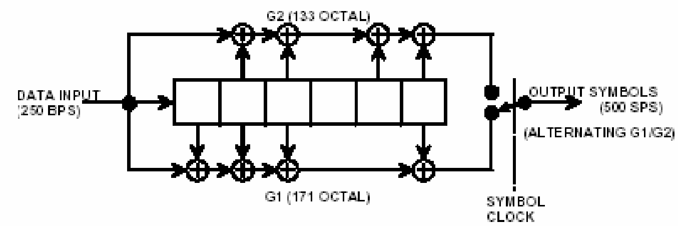


Fig. 14::Convolutional Encoding

If the navigation message symbol sign is reversed, then the sign of the interfering peak will also be reversed. Therefore, for the tracking interference to reach full scale, the navigation symbols of the interfering signal have to be the same.

If this is not the case, then we expect the tracking error to be modulated according to the data message symbol x-correlation function.

Next figure shows the x-correlation computed over 1s data frame for the data symbols coming from PRN 120 and 126:

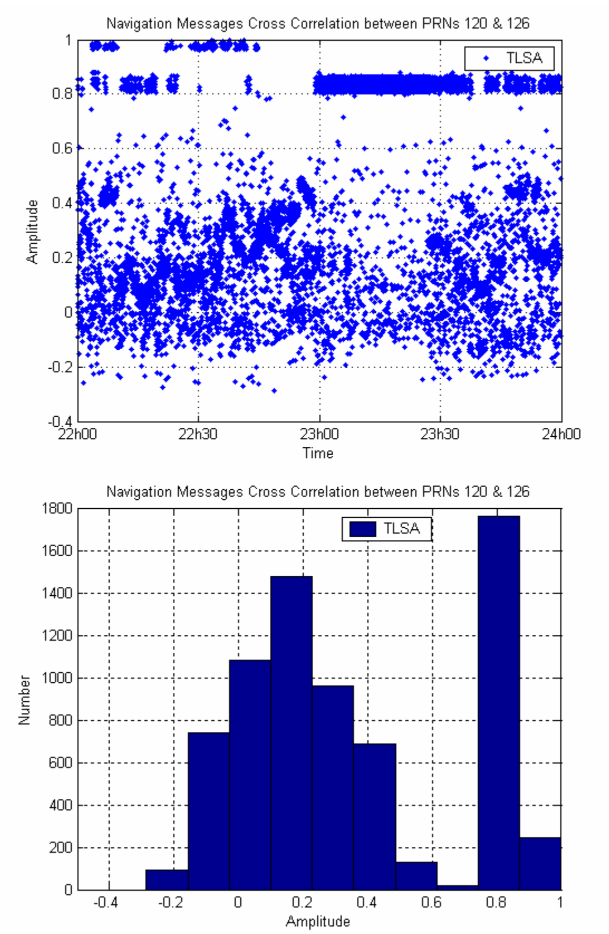


Fig. 15: Navigation messages correlation function and distribution of PRNs 120 and 126

It appears that raw transmitted navigation symbols are sometimes strongly correlated (correlation function reaching 0.8 to 1), a 0.8 correlation values means that over a 1s frame, 90% of the data symbols have the same sign, and 10% are of opposite sign), and at other times weakly correlated (correlation function between -0.2 and 0.4).

On next figure, we clearly see that the interference is smaller when the navigation message is weakly correlated, which happens between 22h45 and 23h00.

Summary of the 2nd Doppler collision

The following figure summarizes the C/A code interferences observed during the 2nd Doppler collision between 2 EGNOS satellites at TLSA RIMS station.

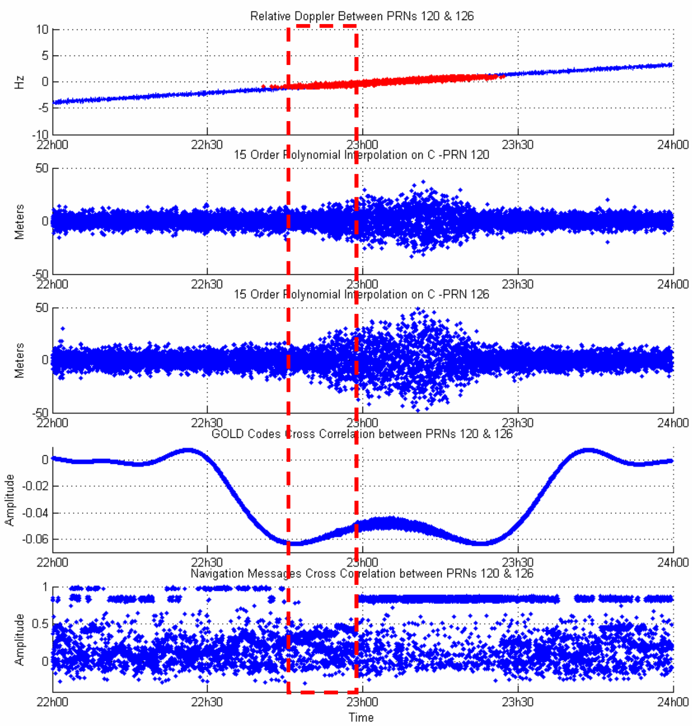


Fig. 16: Overview of the C/A code interference during 2nd Doppler collision

During this Doppler collision between 2 SBAS satellites, we can observe tracking errors on C1 measurement (residuals errors up to 8 meters for both PRNs 120 & 126) when:

- PRNs sequences are close to a cross correlation peak,
- and navigations messages are correlated.

This tends to show that tracking error due to C/A code interference is a phenomenon that needs specific conditions to happen, but it can happen.

NEXT GENERATION GEO

Next generation GEO satellite shall have ionic propulsion and station-keeping windows are expected to become tighter. Thus, the amplitude of the relative Doppler will be lower. Doppler collision inside the code loop will still happen twice a day but will last much longer, meaning that in the future code interference will happen more often, unless GPS L1C and GALILEO E1 OS signals replace C/A code for SBAS.

4- C/A CODE INTERFERENCE MITIGATION

A -Carrier Smoothing

As C/A code interferences looks like multipath, some multipath-like mitigation techniques can be envisaged. But other techniques can not.

Narrow correlator or double delta correlator is a technique that can't be used, because WAAS or EGNOS signal are band limited.

Carrier smoothing can be used to reduce code tracking noise as well as tracking error

For EGNOS end-users, the smoothing of pseudorange observations using integrated carrier phase observations is given by the following equation [4]:

$$\tilde{P}_n = \frac{1}{K}\cdot P_n + \left(\frac{K-1}{K}\right)\cdot\left[\ \tilde{P}_{n-1} + \left(\frac{\lambda}{2\pi}\right)\cdot(\phi_n - \phi_{n-1})\ \right] \quad \text{(eq. 1)}$$

Where:

- P_n is the raw pseudorange,
- $\tilde{P}_n$ is the smoothed raw pseudorange,
- Φn is the phase measurement in radian,
- λ is the wavelength,
- K is the filter parameter (time constant).

The following figures show the residual errors on the C1 measurements for different carrier smoothing time: 20 and 100 seconds (as recommended in [5]) for PRNs 120 & 126 on TLSA RIMS station.

For PRN 120, with carrier smoothing of 20 seconds, we observed that the C/A code interference errors have been reduced by a factor 5 approximately to reach maximum values about 1.5 meters. With carrier smoothing of 100 seconds, all the tracking errors are filtered.

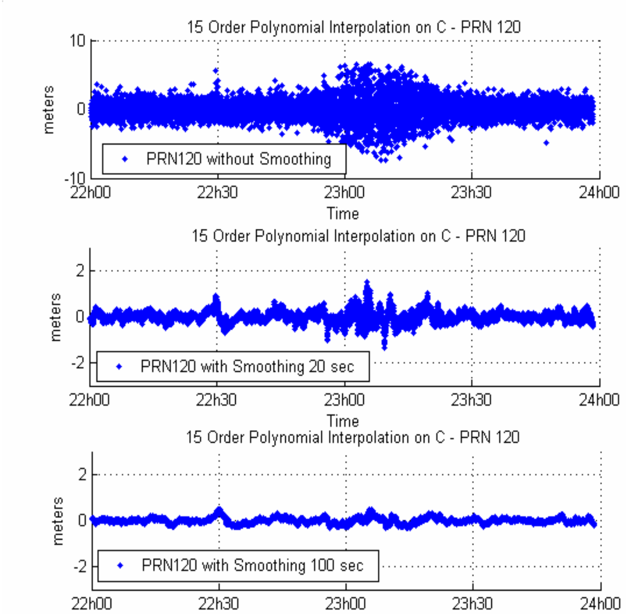


Fig. 17 : Residuals Error on C1 with Carrier Smoothing of 20 and 100 seconds on PRN120

The same behavior is observed for PRN 126; with carrier smoothing of 20 seconds, we note that the C/A code interference errors have been reduced by a factor 5 approximately to reach maximum values about 2 meters. For carrier smoothing of 100 seconds, almost all the tracking errors are filtered.

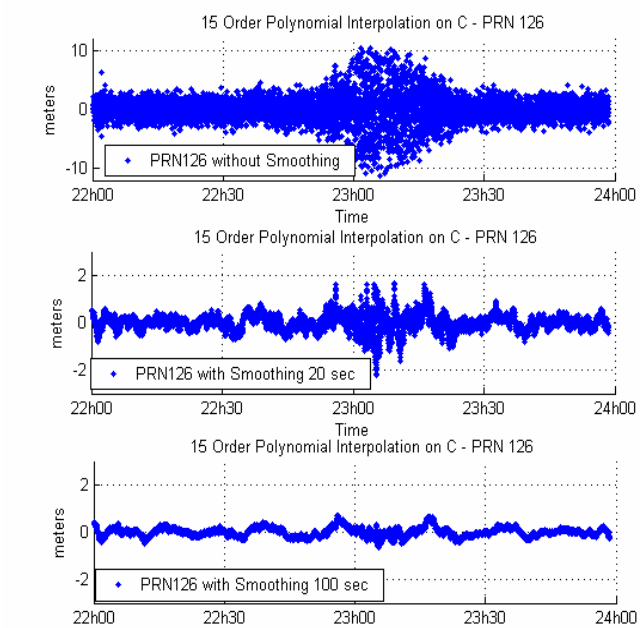
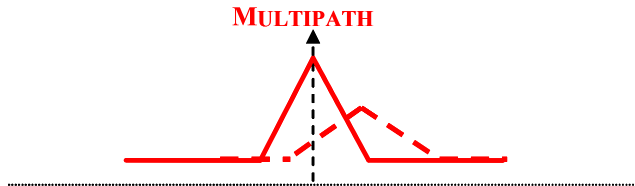


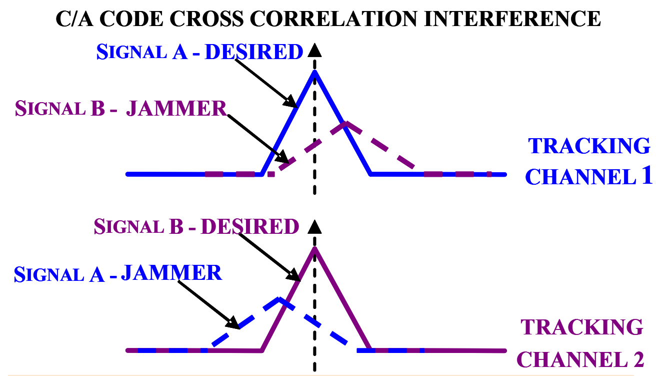
Fig. 18 : Residuals Error on C1 with Carrier Smoothing of 20 and 100 seconds on PRN126

As we can see, applying a carrier smoothing on 100 seconds, as recommended by EGNOS MOPS [5], gives good results in terms of C/A code interference mitigation..

B- C/A Code Interference Correction Algorithm

Fortunately, mutual C/A code interferences have an interesting difference wrt multipath: if the receiver tracks all the signals in view, we can assume that the interfering signal is tracked on another receiver channel, and is therefore observable.





	Tracked Code	InterferingCode
Channel A	Code 1	Code 2
Channel B	Code 2	Code 1

Table 1: Correction algorithm principle

The idea is to let the receiver track each signal. The correction comes as a post processing on the raw measurements.

The receiver provides code delay, phase, power, Doppler and data for each satellites and knowing the cross-correlation function for each code pair, it is possible to predict the tracking error and then to subtract it from the raw code pseudo-range measurements. This has been demonstrated with simulated signals (same data symbols) coming from a Spirent Simulator in *[2]* and *[3]*.

Results with this C/A code interference correction algorithm, using real data, will be presented in forthcoming publications.

CONCLUSION

Analysis of real GNSS data collected by EGNOS RIMS allowed to highlight that C/A code interference can cause tracking errors with signals coming from SBAS satellites.

A larger scale analysis showed that on the same day as for the above results (21/01/07), 11 RIMS stations (marked with red cross) on a total of 24 analyzed RIMS showed a non-negligible error up to 10 meters.

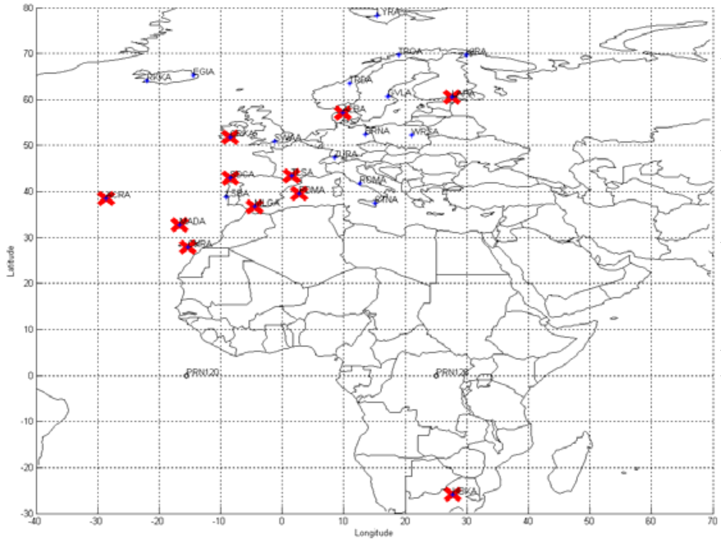


Fig. 19 : RIMS A Location and Tracking Errors caused by C/A CodeIinterferences

This works has shown that C/A code interference can induce tracking error of several meters in situations where:

- Doppler collision with Doppler difference lower than the DLL bandwidth,
- PRN code cross-correlations exhibit peaks,
- Navigation messages are correlated.

A great number of applications have low relative Dopplers (SBAS, pseudolites) and can thus be affected by this interference.

Fortunately, in this case, carrier smoothing gives good mitigation and unlike a multipath interference situation, the receiver can provide the interfering signal parameters (C/No, delay, phase and Doppler) and thus a correction algorithm can be developed *[2]*.

In the future GEO satellites with new ionic propulsion might have even lower Doppler variations leading to increased chances of having code interference errors.

ACKNOWLEDGMENTS

The authors would like to thanks the CNES for its technical support in the area of the presented findings.

The authors also thank EGNOS PACF for providing RIMS data in the frame of the study.

REFERENCES

[1] O.NOUVEL and all, « SBAS C/A Code Interferences: Observations and Induced Tracking Errors», ESA-GNSS SIGNALS 2007.

[2] L.LESTARQUIT, M. MALICORNE, « Correction Algorithm for SBAS C/A Code Interference», ION GPS 2003.

[3] L.LESTARQUIT, J.L. ISSLER, « Low Doppler C/A Interference, Test of an Improved Algorithm », ION GPS 2000.

[4] D. BERGES, J.L. ISSLER, « The CE-GPS RGIC Experiment: Theoretical and First Practical Results», ION GPS 1993.

[5] "MOPS for Global Positioning System/Wide Area Augmentation system Airborne Equipment" - RTCA DO-229C, version C – 28/11/01