Analysis and modeling of high and low frequency ionospheric disturbances and its impact on navigation

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The results presented in this talk have been done in the framework of the SCIONAV project developed under the ESA call ITT-18214/15/NL/LvH: Improved Modelling of Short and Long Term Characteristics of Ionospheric Disturbances During Active Years of the Solar Cycle.

Here we will focus on the analysis of low and high latitude scintillation and its impact on high accuracy navigation. The results on modelling and bubbles will be presented by other colleagues in this session.
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1. The Geodetic De-trending
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Introduction

- Ionospheric scintillation is a challenging problem for GNSS users, degrading the navigation of both, dual and single frequency solutions.

- It happens when the GNSS signals pass through ionospheric irregularities, producing rapid changes in the refraction index. When such ionospheric irregularities are at scale lengths below 400m, diffractive effects on the signal appear. All these effects can lead to cycle-slips, loss of lock of GNSS signal and increased noise.

- In this presentation we are going 1) to introduce the Geo-De-trending technique to identify scintillation and 2) to characterize the scintillation phenomena, from the navigation point of view, and 3) to assess the feasibility of high accuracy positioning under scintillation conditions.
1.- Geo-De-trending to characterize scintillation

- Objective:
  - Characterize Scintillation from a **navigation point of view**

- Method:
  - Geodetic de-trending of \( L_X \) carrier measurements:
    \[
    \Delta L_X = L_X - \rho - c (dt_{rec} - dt^{sat}) - Trop - \lambda_X \omega^{sat} = -STEC + B_X + \epsilon_X
    \]
  - Geodetic de-trending of \( L_{IF} \) carrier measurements:
    \[
    \Delta L_{IF} = L_{IF} - \rho - c (dt_{rec} - dt^{sat}) - Trop - \lambda_N \omega^{sat} = B_{IF} + \epsilon_{IF}
    \]

- Metrics:
  From the de-trended carriers, we can estimate the \( \sigma_{\phi L_X} \) or \( \sigma_{IF} \) over a sliding window (e.g. 60 sec, with 1Hz data).
    - They can be used as an indicator of the expected degradation of the navigation accuracy.

More details in:
\[ L_{IF} - \rho + c dt^{sat} - Trop - \lambda_N \omega^{sat} = B_{IF} + c dt_{rec} + \epsilon_{IF} \]

\[ \Delta L_{IF} = L_{IF} - \rho - c (dt_{rec} - dt^{sat}) - Trop - \lambda_N \omega^{sat} = B_{IF} + \epsilon_{IF} \]

**Example of Geo-De-trending**

Seychelles Island (55ºE, 5ºS)

6th International Colloquium on Scientific and Fundamental Aspects of the Galileo Programme

25-27 October 2017. Technical University of Valencia, Valencia, Spain
• Noise is at the level of few cm, thence, small (1-cycle) cycle-slips can be easily identified, avoiding contaminating the sigma estimates.

• This technique can be applied even to measurements collected at 1Hz sampling rate by standard geodetic receivers, which opens the door to use the huge data bases available (from IGS and other centres), for scintillation studies, involving hundreds of worldwide receivers along several years.

→ This overcomes the current limitations using scintillation receivers, as only few ISMR receivers are available and the data is provided just for short periods of time.

• The receiver clock is estimated in the geo-de-trending process, then no external oscillator is needed to stabilize the receiver clock.

\[ \Delta L_{IF} = L_{IF} - \rho - c (d_t^{rec} - d_t^{sat}) - Trop - \lambda_N \omega^{sat} = B_{IF} + \varepsilon_{IF} \]
2.- High latitude scintillation

- In high latitude, scintillation is mostly associated to space weather or geomagnetic storms. It is produced by fast variations on the refractive index, associated to fast moving (up to several km/s) large-scale irregularities. As result, fast variations of STEC, with time scales of few seconds are experienced.

- It causes fast fluctuations on the carrier phase (large $\sigma_\phi$), while the amplitude of the signal is not strongly affected (low S4 values).

- Although phase shifts rapid enough can challenge the receiver’s tracking loops, usually they do not produce frequent carrier cycle-slips.

![Graph showing scintillation index](image)

**ISMR Rx (KIR1) (20°E, 68°N)**

- $\sigma_\phi > 1.8$ rad $\Rightarrow$ Strong scintillation
- $S4 < 0.2$ $\Rightarrow$ Low
Example of $\sigma_{fL1}$, $\sigma_{fL5}$, $\sigma_{fIF}$ and comparison ISMR determinations

From this plot it follows:

1. $\sigma_{fL1}$ estimated by the ISMR receiver (50Hz) and by the geo-de-trending technique (1Hz) are quite similar.

2. The effects are proportional to the inverse squared frequencies ratio (in length units): 
   
   $\sigma_{fL1} = \frac{f_5^2}{f_1^2} \, \sigma_{fL5}$

3. The peak experienced by the $L_1$ and $L_5$ signals disappears in the Iono-free combination $L_{IF}$.

→ Thence, this is **Refractive scintillation** phenomenon.
3.- Low latitude scintillation

- Here scintillation is mostly associated to the ionospheric depletions appearing around sunset hours.
- Among the previous effects, in low latitude, ionospheric irregularities at scale lengths of below 400 m are experienced (Fresnel length for GNSS signals). Then, the signals are scattered (*diffracted*) reaching the receiver through multiple paths.
- This diffractive effect can seriously challenge the GNSS receivers, causing signal power fades, which results in large variations of signal amplitude (and then **high S4 values**), and experiencing fast phase fluctuations. They can cause loss of lock and frequent *cycle slips*.
- It appears after sunset and last for several hours. It has a seasonal component, being most intense at the equinoxes.

![Large SNR fading due to the diffractive scintillation on DoY 057, 2014](image)

![AATR index](image)
Low latitude scintillation
Effect on the $L_{IF}$ combination

Seychelles Island (55ºE, 5ºS)

**Geodetic de-trending of $L_{IF}$:** Ionosphere-free combination of $L_1$, $L_2$ carriers, after removing, geometry, clocks, troposphere and wind-up.

→ **Diffractive** Scintillation degrades the $L_{IF}$ (increases noise) and produces cycle-slips.

$$L_{IF} = \frac{f_1^2 L_1 - f_2^2 L_2}{f_1^2 - f_2^2} \quad (L_{IF} \text{ in length units})$$

Large noise

But the main problem are the cycle-slips!

The geodetic de-trending of $L_{IF}$ allows to depict the increased noise and the 1-cycle jump. The enhancement of noise in $L_{IF}$ indicates that here scintillation effects are also diffractive.
Low latitude scintillation
Cycle-slips effect

With a geodetic de-trending of $L_{IF}$, it is possible to distinguish between these 1-cycle jumps occurring in L1 (0.484 m) and L2 (0.377 m)

Seychelles Island (55°E, 5°S)
Low latitude scintillation: Example with KOUR (1Hz) (-53°W, 5°N)

- **Deep fades on the L2 amplitude**, which are typical in low latitude scintillation, **producing cycle-slips in L2 carrier**. Thence, the two largest peaks in the $\sigma_{\phi L2}$ are, in part, artifacts of the receiver tracker.

- No cycle-slips in L1, but a slight **increase of noise is found**, but unlike the high latitude, some **high frequency effect is still present in L$_{IF}$**, which means that part of this scintillation effects are not refractive.
Navigation under scintillation

As already pointed by several authors, one of the main problems to achieve precise navigation under scintillation conditions is the occurrence of carrier cycle-slips, which can involve just one-cycle.

However, as shown before, they can be identified by the geodetic de-trending and, even, it is possible to distinguish between cycle-slips in the different carriers (e.g. L1 or L2).

Next, we are going to show that Precise Point Positioning (PPP) can take benefit of this cycle-slip detection, achieving high accuracy navigation in this difficult scenario.
• Cycle-slips are mostly experienced in L2 carrier, then the navigation with L1 GRAPHIC combination of single frequency C1 code and L1 carrier seems to be quite unaffected.
• Large errors are experienced when using standard cycle-slip detectors during periods with high ionospheric activity.
• Centimeter level navigation is maintained when no misdetections occur.

Note: cycle-slips are detected in post-process using the geo-de-trending detector
High latitude: Navigation under scintillation

KIRU station: (21ºE, 68ºN): Saint Patrick Storm

Scintillation activity
N. satellites/10

PPP solution

Note: PPP navigation filter is daily reset to assess convergence time.

- Although having strong scintillation, **the number of measurements discarded by jumps in carrier are quite low** (Cycle-slips detected by geodetic detrending)

- In general, cycle-slips are not too frequent in high latitude and the accuracy is maintained at the level of few centimeters as expected in PPP.
Low latitude: Navigation under scintillation

FAA1 station: (150°w, 17°N)

- Unlike in high latitude, here **the number of discarded observations** (due to cycle-slips) **increase more clearly with the scintillation events.** Carrier phase jumps are associated to the amplitude scintillation, which is characteristic of low latitude.

- The reduction in number of satellites, together with the increased noise in the iono-free combination (L₁F), degradates the position accuracy.

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Note: PPP navigation filter is daily reset to assess convergence time.
4.- Conclusions

• The Geodetic de-trending has been proven to be a powerful tool to analyze scintillation effects.

• High latitude, scintillation is less likely to cause signal loss and usually does not produces large number of cycle-slips.
  • It is mostly refractive, and then, dual frequency users can accurately navigate also during high ionospheric activity.
  • But, due to the large space-temporal gradients it is challenging for single frequency users.

• Low latitude is a more difficult scenario were scintillation can lead frequent cycle-slips and loss of lock of GNSS signals.
  • Multi-constellation helps under GNSS signals loss.
  • It is challenging to detect 1-cycle slips in real-time.
  • The carrier noise is increased, but high accuracy navigation with dual-frequency signals is still possible, provided that the cycle-slips are detected in a reliable way.
Thank you
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<th>RCV name</th>
<th>Longitude (Degrees)</th>
<th>Latitude (Degrees)</th>
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<td>67.743</td>
<td>JAVAD TRE_G3TH D.</td>
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</table>
Figures show the RMS of position error (with 1 minute bins) v.s. the RMS of (1 minute) $\sigma_{\phi L_1}$ (from all satellites in view at each epoch).

Red points correspond to the first 2 hours after the daily reset (convergence period) while the blue points correspond to the comparison during the rest of the day.

The green squares depict the mean values of the 3D position error per bins of $\sigma_{\phi L_1}$ (0.1, 0.3, 0.5 and greater than 0.6).
• In both cases, the analyzed periods include observations under strong scintillation activity. In spite of this, the high accuracy navigation (5 cm of 3D error) is achieved.

• An increase on the position error with the $\sigma_{\phi L_1}$ is experienced at low latitude. This is because:
  1. At low latitudes the scintillation effect on the signal does not disappear in the iono-free combination ($L_{IF}$).
  2. Due to the deep amplitude fades associated to low latitude scintillations, cycle slips are much more frequent than in high latitude.

Then, in spite of the fact that the cycle-slips can be detected with our technique, there are more measurements discarded, and consequently, the geometry becomes worse, affecting the navigation accuracy.
High latitude: Navigation under scintillation

KIRU, KIR0 stations: (21ºE, 68ºN), baseline= 2km

\[ \Delta L_X = L_X - \rho - c (dt_{rec} - dt^{sat}) - Trop - \lambda_X \omega^{sat} = -STEC + B_X + \epsilon_X \]

• As expected, similar ionospheric disturbances affect both receivers (KIRU, KIR0), with 2 km of baseline, but, NO cycle-slip happens in KIR0 (different receiver types, configuration…)

KIR0: JAVAD TRE_G3TH DELTA, 1 Hz.
KIRU: SEPT POLARX4, 1 Hz.

Notice how carrier changes, in a continuous manner instead jumping.
How these cycle-slips perform?

**STEC** from Geodetic de-trending of $L_5$ and $L_1$ (50 Hz data)

The shift is due to 1-cycle shift in $L_5$. (-0.87 TECUs)

1-cycle jump in $L_5$ (32.1 cm on $L_{IF}$)

**Geodetic de-trending of $L_{IF}$** (1 Hz data)

With 50Hz measurements, the geodetic de-trending of L1 and L5 carriers allows to depict the trend producing the 1-cycle shift. It last for several tens of milliseconds.
High altitude scintillation
Example with an ISMR Rx (KIR1) (20°E, 68°N)

**Geodetic de-trending of \( L_{IF} \):**
Ionosphere-free combination of \( L_1, L_5 \) carriers; after removing, geometry, clocks, troposphere and wind-up.

→ Scintillation effects are mostly removed on \( L_{IF} \)

\[
L_{IF} = \frac{f_1^2 L_1 - f_2^2 L_5}{f_1^2 - f_5^2}
\]

(\( L_{IF} \) in length units)

**Geometry-free combination of carriers** \( (L_1 = L_1 - L_5) \).

→ Large oscillations due to the refractive scintillation.

\[
L_1 - L_5 = \alpha \text{STEC} + B_I + \epsilon_I
\]

- Few cm noise
- Pattern due to miss-modelling (APC...)

\[
\Delta L_{IF} = L_{IF} - \rho - c \left( dt_{rec} - dt^{sat} \right) - Trop - \lambda_N \omega^{sat} = B_{IF} + \epsilon_{IF}
\]
Iono-Free
• No cycle-slips
• 2-freq users can navigate with the Iono-Free comb.

STEC
• Large temporal and spatial gradients make difficult to compute ionospheric corrections for 1-freq. users

Results on *High-Latitude Scintillation*:
• Mostly refractive \( \rightarrow \) proportional to \( f^{-2} \) in length units (or \( f^{-1} \) in rad)
• Low number of cycle-slips
• Canceled with \( L_{IF} \) \( \rightarrow \) Dual-Freq. users can navigate with high-accuracy
• Large space-temporal gradients \( \rightarrow \) Challenging for Single Freq. users
• Bubble
2.- High latitude scintillation

- Conclusion:
  - After analyzing several days at different frequencies
  - The scintillation at high-latitude is mostly refractive
Low latitude scintillation
Amplitude fading

In red the values over the days 050-053, with lower solar activity

Large SNR fading due to the diffractive scintillation on DoY 057
Low latitude scintillation
How small cycle slips can be detected?

Geodetic de-trending of $L_1$
Geodetic de-trending of $L_5$

STEC from Geodetic de-trending of $L_1$ and $L_5$

The shift is due to a cycle-slip in $L_5$.

Geodetic de-trending of $L_{IF}$
- Noise of detrended $L_{IF}$ is few cm $\Rightarrow$ iono. Effects in $L_{IF}$ are almost cancelled, including fast fluctuations.

- L1 geodetic and polynomial detrending are quite similar (in this case) $\Rightarrow$ similar sf.
High latitude scintillation
Navigation under strong scintillation

Yellowknife

Geometry-free combination of carriers ($L_{IF} = L_1 - L_2$).

Geodetic de-trending of $L_{IF}$

$$L_{IF} = \frac{f_1^2 L_1 - f_2^2 L_2}{f_1^2 - f_2^2}$$

($L_{IF}$ in length units)

DST = -100nT
High latitude scintillation
Navigation under strong scintillation

Being mostly refractive scintillation and not producing large number of cycle-slips, dual frequency users can navigate also during high ionospheric activity. But, due to the large space-temporal gradients it is challenging for single frequency users.
High latitude scintillation
Navigation under strong scintillation

Navigation performance with $L_{IF}$

Being mostly refractive scintillation and not producing large number of cycle-slips, dual frequency users can navigate also during high ionospheric activity. But, due to the large space-temporal gradients it is challenging for single frequency users.
High (YELL) and Low (SEY1) latitude scintillation on $L_{IF}$ comparison (DoY 058, 2014)

They are small cycle-slips (involving just 1 cycle in L1 or L2), being difficult to detect!
Low latitude scintillation
Navigation example

Large error due to the scintillation effects:
- Undetected small cycle-slips.
- Degraded carrier.
• In both cases, the analyzed periods include observations under strong scintillation activity. In spite of this, the navigation solution remains, in general, at the same level than during quiet scintillation conditions (5 cm of 3D error).

• An increase on the position error with the $\sigma_{\phi L1}$ is experienced at low latitude. This is because:
  1. At low latitudes the scintillation effect on the signal does not disappear in the iono-free combination ($L_{\text{IF}}$).
  2. Due to the deep amplitude fades associated to low latitude scintillations, cycle slips are much more frequent than in high latitude.

Then, in spite of the fact that the cycle-slips can be detected with our technique, there are more measurements discarded, and consequently, the geometry becomes worse, affecting the navigation accuracy.
With a geodetic de-trending of $L_{IF}$, it is possible to distinguish between these 1-cycle jumps occurring in L1 (0.484 m) and L2 (0.377 m).
Low latitude scintillation
Navigation example

Satellite down-weighting has been done as a function of SNR
The challenge is to detect 1-cycle jumps “in real-time”. Although the equatorial scintillation increase the carrier noise, high accuracy navigation with dual-frequency signals is possible, if the cycle-slips are detected.
Low latitude scintillation
How 1-cycle jumps can be detected at 1Hz?

STEC from Geodetic de-trending of $L_5$ and $L_1$

The shift is due to 1-cycle jump in $L_5$.

Melbourne-Wübben (L1,L5)
Melbourne-Wübben (L1,L2)

Loss of Lock Indicators (LLI)

Some internal information for receiver can be used, but is it reliable?