Mapping and investigating phase anomalies in GPS data onboard Low Earth Orbiters

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Introduction

GPS observations play an important role in Precise Orbit Determination (POD) of Low Earth Orbiters (LEO). The quality of the orbit, especially in kinematic mode, directly depends on the quality, availability and reliability of the measurements. As final precision is obtained with phase data, any phase anomaly (residual cycle slip, data gap…) will directly impact the solution. Ionospheric scintillations, which are defined as rapid fluctuations in phase and amplitude of the GNSS signals, are known to produce such anomalies. The occurrence of scintillations exhibits large day-to-day variations and depends mainly on geomagnetic latitude, season and local time. At low latitudes, maximum occurrence of scintillations is observed 15-20° on either side of the geomagnetic equator. Scintillations also occur at auroral and polar latitudes, where their intensity increases with increasing geomagnetic activity.

The goal of this paper is to investigate the relationship between phase anomalies and the presence of scintillations for two periods in 2015: autumn equinox and winter solstice.

1. Data and methodology

1. Data

RINEX observations for GRACE (A-B) and SWARM (A-B-C)

- GRACE. 10 s data from GRACE project : http://isdc.gfz-potsdam.de/grace
- SWARM. 1s data from SWARM project : ftp://swarm-diss.eo.esa.int

LEO precise orbits for GRACE A-B and SWARM A-B-C

- GRACE: computed by CNES
- SWARM: from SWARM project : ftp://swarm-diss.eo.esa.int (level 2)

GNSS precise orbits from CNES-CLS IGS analysis center

2. Methodology

Pre-processing

- Determination of passes: detection of cycle slips, data gaps and removal of short passes (< 30 observations)
- For SWARM: decimation to 10s data after pre-processing step

↳ **1st output:** maps of phase anomalies (data gaps & cycle slips) onboard LEOs

Computation of a high-frequency ionospheric index

- 4th order time-difference of Geometry-Free (GF) phase combination, running variance on 20-epoch intervals
- Spatial binning: 2° X 2°, function = average

↳ **2nd output:** maps of high-frequency ionospheric activity as « seen » from the LEO

Spacecraft couples SWARM-A and B as well as GRACE-A and B have nearly identical orbits and fly very close to each other → results are grouped by couple of satellites.

3. Analysis periods in 2015

- 20 days around autumn equinox (DOYs 255-275/15) and winter solstice (DOYs 345-365/15)
- Ascending and descending tracks are separated for winter solstice. The reason is that observations at local time around 8 P.M. are of particular interest for post-sunset enhancement in equatorial regions, which is generally associated with strong scintillations (*see satellite phase in Table 1*).

	SWARM (A & C)	SWARM B	GRACE (A & B)
Altitude [km]	450	530	380-390
Inclination [°]	87.35	87.95	89
Period [min]	93.7	94.7	92.1
$\dot{\omega}$ [min/day]	-1.45	-1.08	-0.56
LT on 255/15 (A/D)	3h36 – 15h36	5h56 – 17h56	4h10 – 16h10
LT on 355/15 (A/D)	18h34 – 6h34	21h22 – 9h22	20h39 – 8h39

Table 1: Characteristics of LEOs and their related ascending node drift ($\dot{\omega}$), together with Local Time (LT) of the ascending (A) and descending (D) nodes for the related period.

2a. Autumn equinox 2015

- Geomagnetic context: Kp values

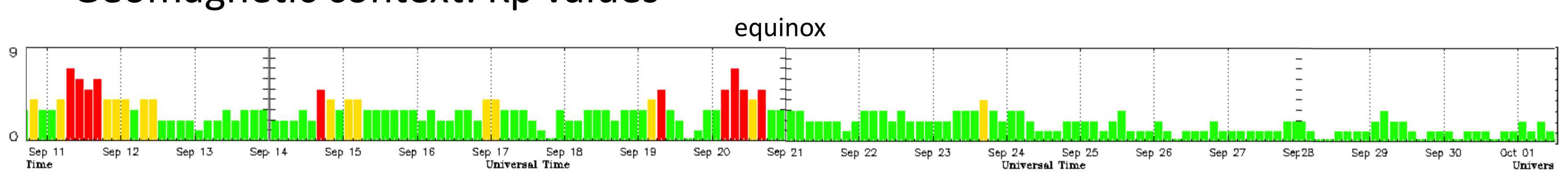

Figure 1: Time series of the geomagnetic index Kp from DOY 255 to 275 in 2015.
Source: Space weather highlights, NOAA (ftp://ftp.swpc/noaa.gov.pub/warehouse)

- RINEX phase anomalies and associated ionospheric activity index

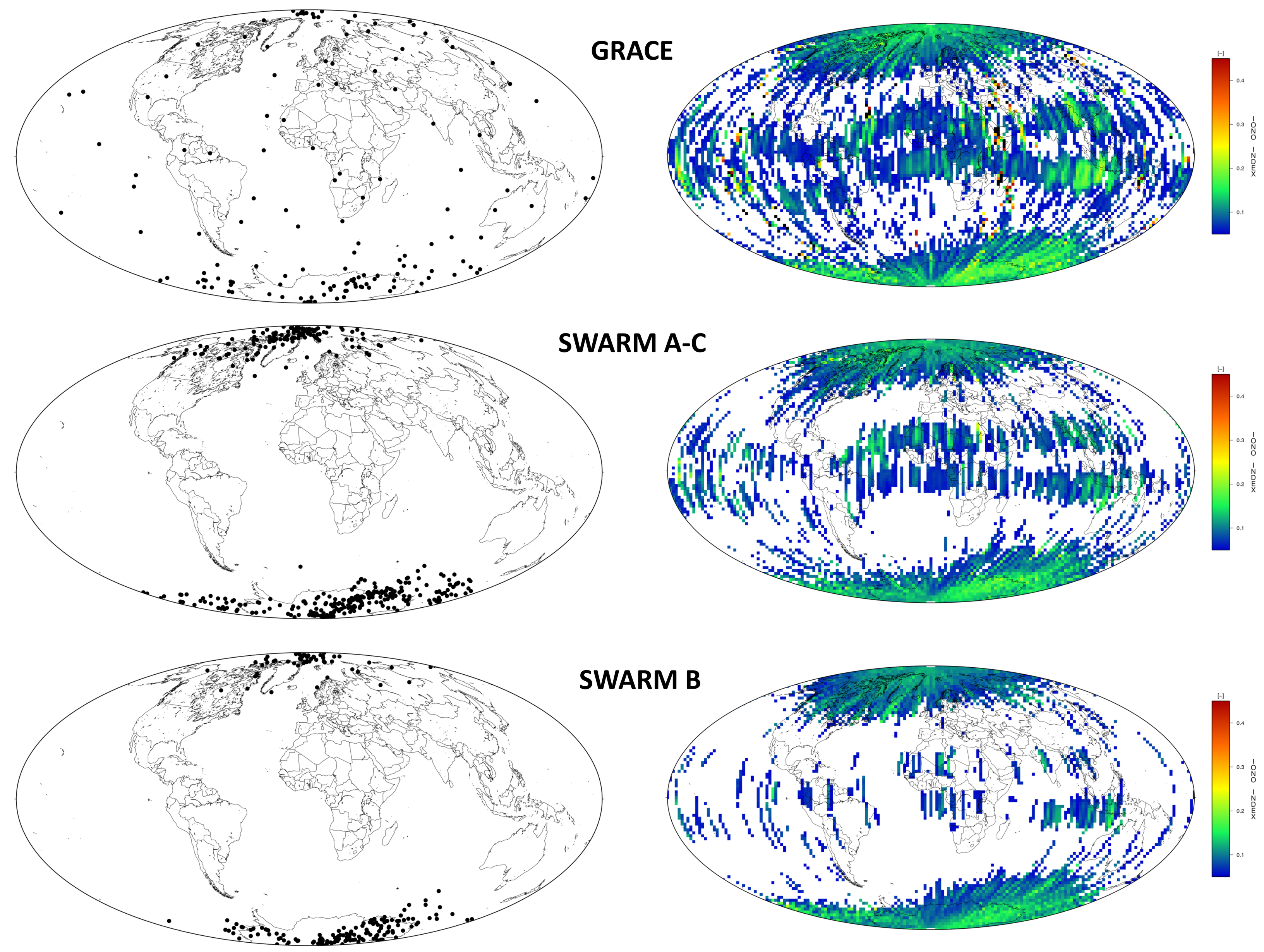

Figure 2: Left : Phase anomalies (cycle slips/data gaps) detected for GRAA, SWAA and SWAB (from top to bottom). Right: high-frequency variability of the TEC derived from GF phase combination for GRAA, SWAA and SWAB (from top to bottom). All graphs are related to both ascending and descending traces (no selection of local time).

- Observations
  - More phase anomalies detected with SWARM than with GRACE; the bulk is observed around polar regions, especially for SWARM for which none of them occurred in the equatorial region.
  - Ionospheric activity index clearly maps the regions where scintillation generally occurs; SWARM-B is the less affected spacecraft due to its higher altitude.
  - Phase anomalies distribution and ionospheric index is approximately similar in the two hemispheres.
  - Very large values (black/red bins) observed with GRACE can be either outliers (missed cycle slips) either strong scintillations due to the 11th or 20th September magnetic storms.

2b. Winter solstice 2015

- Geomagnetic context: Kp values

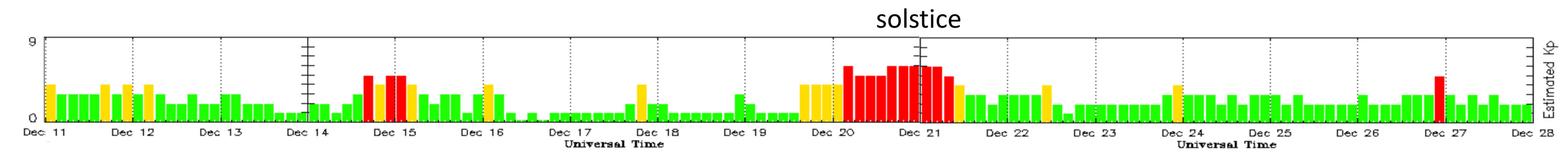

Figure 3: Time series of the geomagnetic index Kp from DOY 345 to 362 in 2015 (no data for DOYs 363 and 364)
Source: Space weather highlights, NOAA (ftp://ftp.swpc/noaa.gov.pub/warehouse)

- RINEX phase anomalies and associated ionospheric activity index

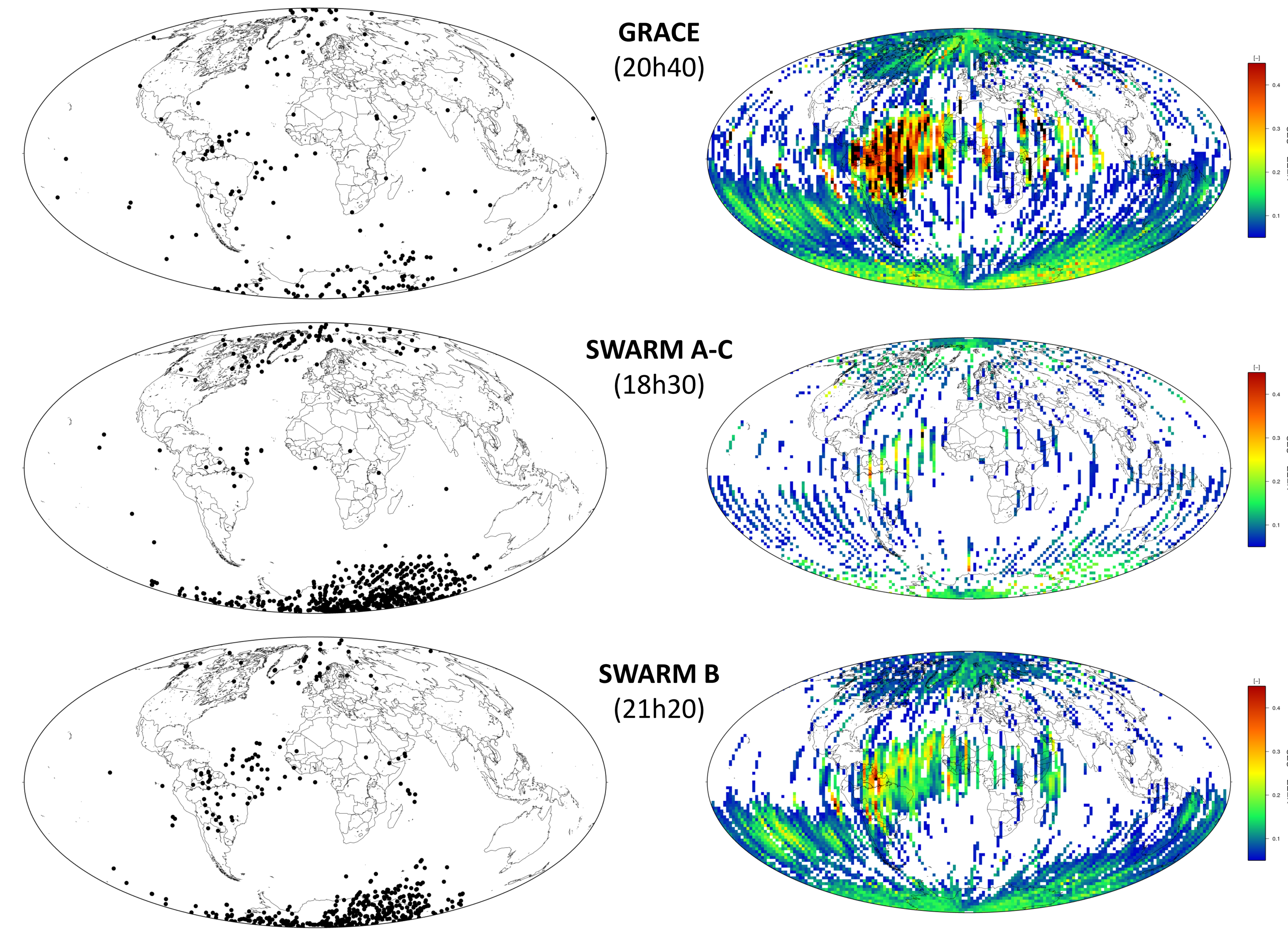

Figure 4: Same than for figure 2, but for ascending traces only → focus on post-sunset enhancement (see local time in Table 1)

- Observations
  - Majority of phase events are still detected over polar regions, but some of them occur when the spacecraft flies over the South Atlantic Anomaly (SAA), especially for GRACE and SWARM-B.
  - Phase anomalies are more numerous over the South pole than over the North pole, which is also observed in the intensity of the ionospheric index: large values occur preferably over Antarctica. This is probably due to seasonal reasons: in December artic regions never see the Sun and ionization is mainly driven by geomagnetic conditions, which were globally quiet during the selected period (*see figure 3*).
  - SSA clearly appears for GRACE and SWARM-B, this is less visible for SWARM-A & C for which local time was before the post-sunset enhancement (around 20h). However, magnetic equator does not appear as clearly as for the equinox. In addition, let us note that the south crest of the equatorial anomaly is markedly highlighted over the Pacific Ocean.
  - Again, some specific large values can be due to geomagnetic effects of the storms occurring on December 15 and 21.

Conclusions and future work

- A good agreement is found between phase anomalies (detected as cycle slips or data gaps) and the ionospheric disturbance index expressing high-frequency changes in the Total Electron Content that scintillations can produce.
- The large number of phase anomalies observed in SWARM data shows that this constellation is more sensitive than GRACE in polar regions, which can suggest different tracking and lock loop configurations. Let us note that there is probably some editing onboard (→before RINEX creation) meaning that data can look "clearer" than they actually are at the receiver level.
- Future work may concern:
  - Processing and analysis of several years
  - The number of observations per epoch can be analyzed to investigate the way that receivers cope with noisy/spurious data (onboard elimination ?)
  - Investigation of the effects of disturbed geomagnetic conditions on the observability of the South Atlantic Anomaly and the equatorial anomaly
  - JASON-2 observations should be added in our analysis. As it flies above the ionosphere (1350km), ionospheric effects are expected to be very attenuated. However, some preliminary studies with JASON-2 have shown that RINEX pre-processing needed very specific settings. The present method missed many cycle slips and outliers, leading to erroneous results in the ionospheric index.
  - Finally, the relationship with PPP kinematic positioning has to be investigated.

Acknowledgments The authors would like to thank the International GNSS Service (IGS), the GRACE and SWARM consortiums for providing GNSS observations and orbits.