Comparison of ground based L-band scintillation with in situ F-region irregularities from Swarm

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Presentation Outline

1. Introduction
1.1 Ionospheric irregularities and scintillations

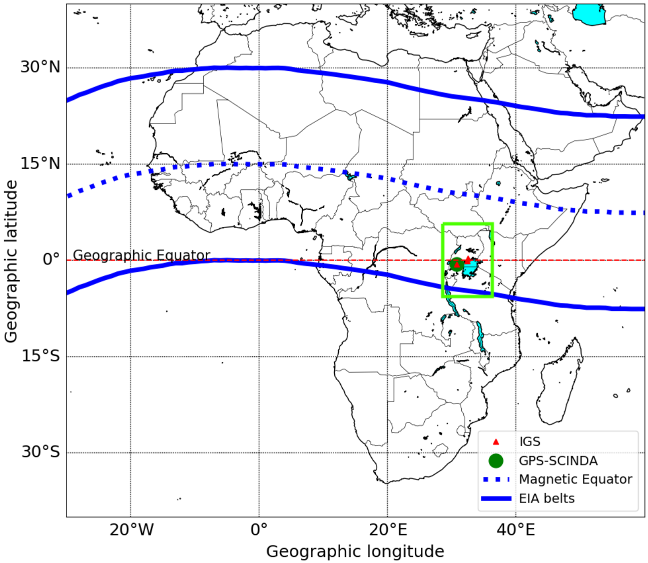
2. Motivation

3. Instruments
3.1 Swarm satellites
3.2 GPS-SCINDA

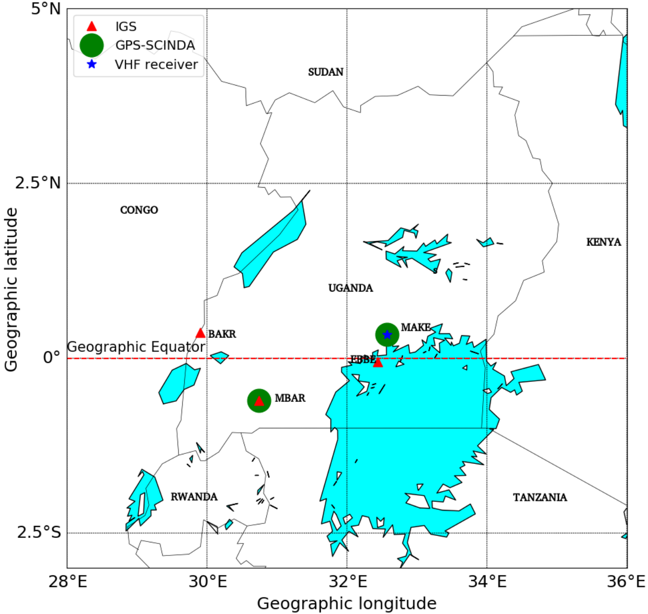
4. Results
4.1 Quantification of ionospheric irregularities
4.2 Correspondence between ionospheric irregularities and scintillations
4.3 Statistical comparison of occurrence of ionospheric irregularities and scintillations
4.4 Derivation of amplitude scintillation from Rino's thin phase screen model

5. Conclusions

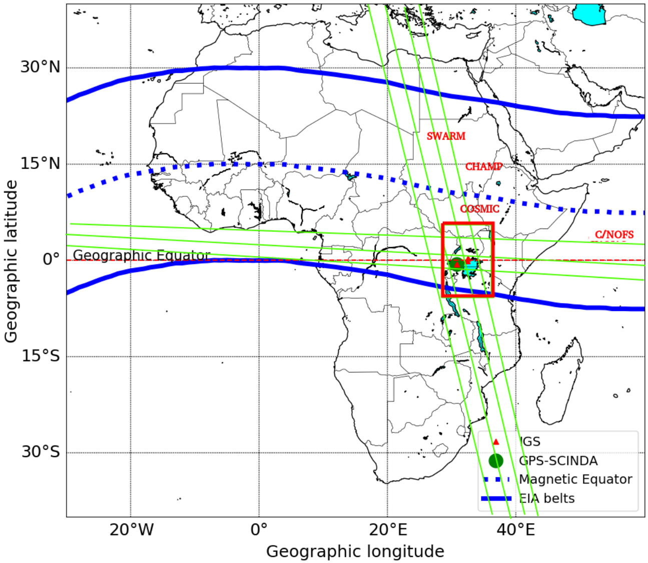
Uganda in Africa



Uganda in Africa



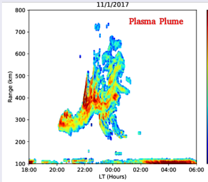
Uganda in Africa

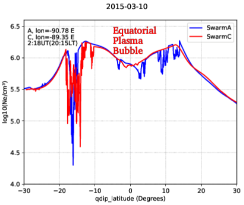


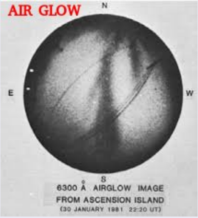
Ionospheric irregularities and scintillations

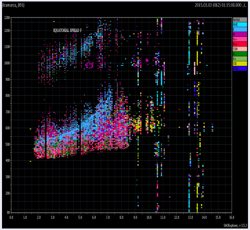
- Ionospheric irregularities are localized plasma density structures in the ionosphere.
- Formation processes: Generalized Rayleigh-Taylor instability (RTI).

Manifestations

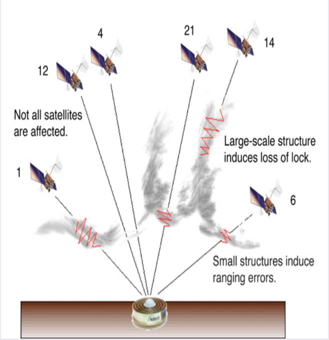








Irregularities ⟶scintillations

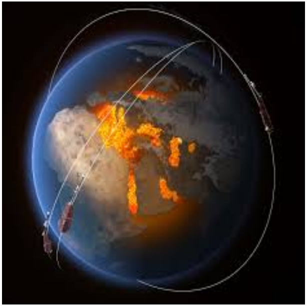


- Occurrence of scintillation may affect the performance of satellite communication and navigation systems e.g, GNSS.

Motivation

- Literature: Basu et al. [1980], Basu and Basu [1976], Basu et al. [2001], Roddy et al. [2010], Sarkar and Gwal [2014], Nishioka et al. [2011]. Theory predicts that the effect of irregularities on radio signals decreases quadratically with their wavelength. Then L-band transmissions used for GNSS operations would be less affected than those at lower VHF and UHF frequencies.
- Achievable accuracy and spatial coverage is still limited by the relatively small number of ground-based GPS receivers over the equatorial African region.
- The Swarm satellite mission offers new opportunities for studying the subject with a better temporal and spatial coverage.
- Alfonsi et al., 2007 recommended Swarm high resolution electron density measurements as input to the Rino's power law phase screen model (Rino, 1979, Rs, 14, 1135-1145) to derive $S4$.

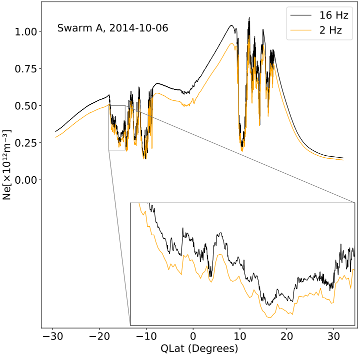
Instruments (1/3)
Swarm satellites



- Mainly a magnetic mission, but the Langmuir Probe (LP) and on-board GPS data are also good for irregularity studies.
- Polar orbits (Swarm A;87.4°, Swarm C;87.5°, Swarm B;88°), so global coverage.
- Two satellites, Swarm A and C, at 440 km altitude, decreasing....; B at 510 km.

- LP density data at 2 Hz (≈3.5 km), in addition 16 Hz (≈ 500 m) from a "faceplate" current (PLP with constant negative bias).
- Swarm A and C are separated by about 150 km (1.4°).

Instruments (2/3)
Swarm faceplate N_e



- The 16 Hz N_e measurements were used to identify irregularity structures.
- Identifying physical processes leading to small scale-size irregularities and improve the modeling of the propagation of radio waves through irregularities.
- The Swarm 16 Hz N_e estimates correspond to a spatial resolution of about 500 m, which is within the range of applicable Fresnel scales, and so theoretically relevant as a cause of L-band scintillations.

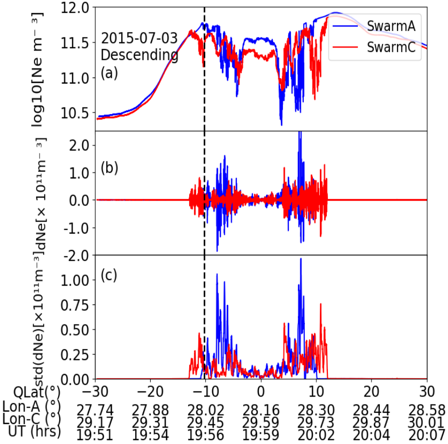
Instruments (3/3)
GPS-SCINDA

- The GPS-SCINDA samples raw data at a frequency of 50 Hz.
- It records the C/No intensity and phase of GPS L1 and L2 signals, as well as the azimuth and elevation of the visible satellites.
- It is a real-time GPS data acquisition and ionospheric analysis system which computes ionospheric parameters amplitude scintillation (S4) and TEC using the full temporal resolution of the receiver.

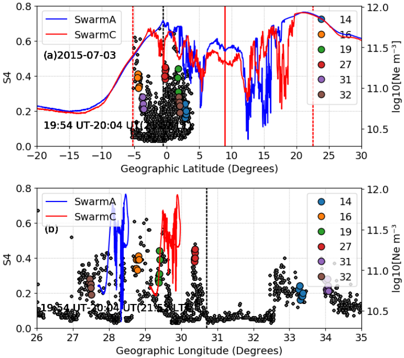
- Amplitude scintillation, $S4^2 = \frac{\langle I^2\rangle - \langle I\rangle^2}{\langle I\rangle^2}$, where I represents the signal intensity.
- The S4 index is defined as the normalized ratio of the standard deviation of signal intensity fluctuations to the mean signal intensity.
- S4 indices are computed by the GPS-SCINDA at 60 s intervals.

Results (1/5)
Quantification of ionospheric irregularities

- $\mathrm{std}(dN_e) = \left[\frac{1}{10} \sum_{i=1}^{i=10} ((N_e)_i - (\overline{N_e}))_i \right]^{\frac{1}{2}}$
- $\mathrm{std}(dN_e) > 1 \times 10^{10}\ \mathrm{m}^{-3}$ were considered to be significantly irregular and selected for additional processing and analysis.
- $S4 > 0.3$ were considered as moderate or strong scintillation (Olwendo et al., 2012).
- Ray path elevations $> 25°$were considered to reduce the multipath effects.
- Study period:2014 – 2017.

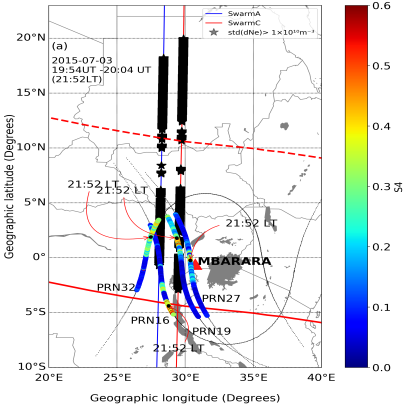


Results (2/5)
Correspondence between ionospheric irregularities and scintillations



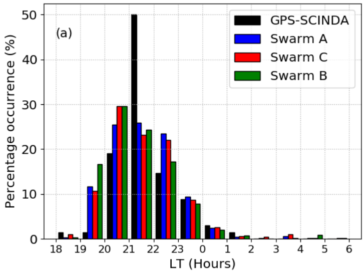
All the four GPS satellites show $S4 > 0.3$ around the same time when density fluctuations are obtained from Swarm A and C.

Swarm A and C ground tracks and the ground tracks of PRN 16, 19, 27, and 32 assuming a piercing height of 460 km.



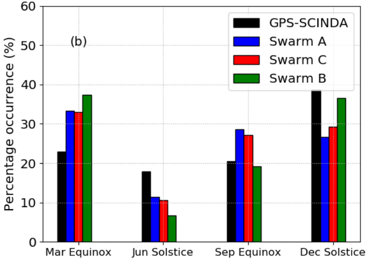
Results (3/5)
Statistical comparison of occurrence of ionospheric irregularities and scintillations

Local time distribution



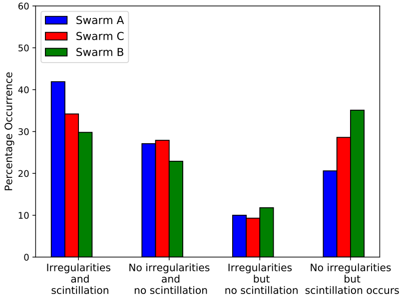
- Percentage occurrence of ionospheric irregularities and scintillations increases between 18:00 LT and 20:00 LT and is highest between 20:00 LT and 22:00 LT. A decrease is detected after 22:00 LT until 06:00 LT.

Seasonal distribution



- Overall, the seasonal dependence of the occurrence of ionospheric irregularities observed by Swarm is very similar to that of amplitude scintillation over Mbarara.

Results (3/5)
Statistical comparison of occurrence of ionospheric irregularities and scintillations



- The outputs of the summary plots could be categorized into four cases considering the presence (or not) of irregularities and scintillation.

- For a large number of passes, amplitude scintillations were enhanced when the LPs also recorded density perturbations.

- Counter examples, i.e. irregularities but no scintillations, or vise versa, showed that mismatches between observed irregularity structures and scintillations can occur over a few minutes and within distances of a few tens of kilometers.

Derivation of amplitude scintillation from Rino's thin phase screen model

- The 16 Hz N_e data were first split into 8-s long segments.
- For each segment, a detrended electron density represented by dN_e was determined by subtracting the mean from the instantaneous values of electron density.
- Spectral analysis was then carried out using the Fast Fourier Transform algorithm.

$$S4^2 = (r_e\lambda)^2 L \sec\theta\, C_s Z^{\nu-0.5}\left\{\frac{\Gamma[(2.5-\nu)/2]}{2\pi^{0.5}\Gamma[(\nu+0.5)/2](\nu-0.5)}\right\}F \qquad (1)$$

[Rino, 1979]:
Turbulence strength, $C_s = 8\pi^{3/2}\langle\Delta N_e^2\rangle q_o^{2\nu-2}\Gamma(\nu+0.5)/\Gamma(\nu-0.5)$
Fresnel zone parameter $Z = \lambda Z_R \sec\theta/4\pi$, $Z_R = zz_s/z + z_s$

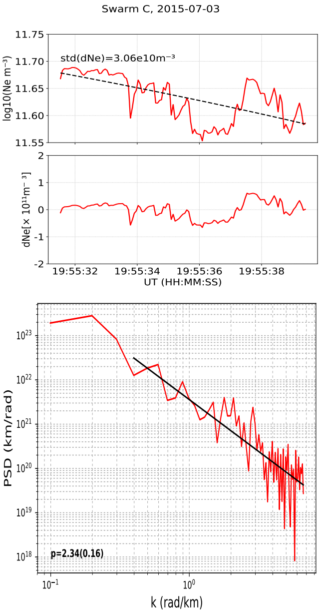
Parameters:
$r_e = 2.8\times10^{-15}$ m
Irregularity layer thickness $L = 200$ km
Outer scale cut-off number, $q_o = 2\pi/L_o$, L_o=L o $= 175$ km [e.g, Patel et al., 2011].
With phase screen at 460 km, z =460 km, z_s=19,740 km

$p = 2\nu - 1$

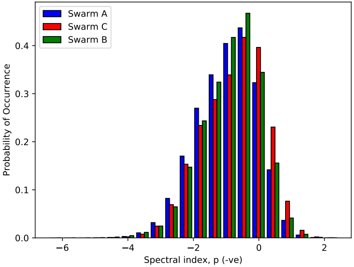
F is the geometry-dependent Fresnel filter factor.

λ is the wavelength.

Results (4/5)



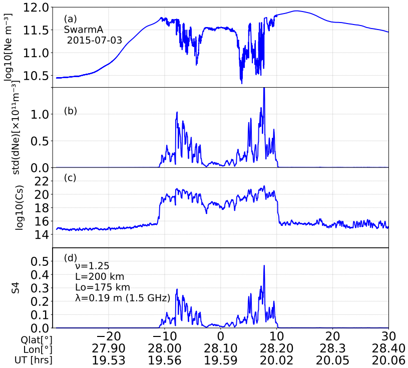
- Regions in the spectra tend to follow a power law i.e, $P(k) \propto k^{-p}$.

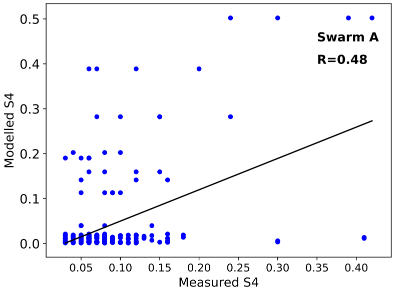


- Highest occurrence of spectral index is between -1.8 and -2.2.

Results (5/5)

- The calculated $S4$ for Swarm A demonstrates good agreement between the increase in the level of $S4$ for GPS satellite of prn 16, 19, 27 and 32.





- The $S4$ index frequently varies from about 0 to about 0.5 for Swarm A satellite pass on 2015-07-03.

- Generally, the results show a weak positive correlation between the observed and modeled S4 for Swarm A.
- This could be because of the "negative" detections summarized previously.

Conclusions

- Measurements of N_e variations by Swarm were compared with S4 at the ground taking into account in some detail the relative positions in space and time of Swarm and PRN piercing points.
- Applying the 1-D phase screen model, we also estimated the S4 index from the hight resolution in situ data.
- For selected events, the observed irregularities along Swarm tracks could be identified with moderate increases in $S4$ ($S4 > 0.3$) at the ground.
- In some cases, irregularities could not be associated with significant scintillations, or these were seen without Swarm recording sufficient density variations.
- Statistically and not surprisingly there is at satellite passes a reasonable correspondence between in situ measured irregularities and L-band scintillations. The distributions of irregularities and scintillations over both LT and seasons show similar patterns.
- Swarm A and C high resolution in-situ N_e data may allow the modeling of scintillations in the L band at low latitudes. Our results may be seen as a first step to verify this.

Grazie per l'attenzione