Ionospheric characterisation of the South Atlantic Magnetic Anomaly using a mobile ship-based dual-frequency GPS Ionospheric Scintillation and Total Electron Content Monitor

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Abstract. This project proposes the novel use of a mobile geodetic-grade dual-frequency GPS Ionospheric Scintillation and Total Electron Content Monitor (GISTM), located on board the polar research vessel SA Agulhas II, to characterise the ionosphere over the South Atlantic Magnetic Anomaly (SAMA) during voyages through this area of the South Atlantic Ocean. It is shown that a 10° elevation cut-off is sufficient to tolerate ship roll angles of up to 20° to avoid multipath from the ocean surface. Preliminary ship-based scintillation results show increased S_4 counts, as well as extremely high σ_ϕ counts, compared to a stationary GISTM at Hermanus, South Africa.

1. Ionospheric Scintillation

Ionospheric Scintillations are rapid fluctuations in both the phase and amplitude of trans-ionospheric radio signals resulting from variations in electron density along the ray path [1]. Scintillation measurements are traditionally done using dedicated dual-frequency GPS receivers at static locations. Ionospheric scintillation affects GPS signals in two ways: Amplitude scintillation presents as an abrupt severe fade in signal strength while phase scintillation is characterised by rapid changes in the carrier wave phase; both of these can lead to loss of lock, increase in position errors and GPS outage [2].

SANSA operates several of these specialised receivers throughout Southern Africa as well as at Marion Island, Gough Island, and in Antarctica at the SANAE IV research station. The SAMA is a region of the Earth where the magnetic field is up to 60% weaker than at comparable latitudes [3]. It is of interest due to increased levels of precipitation of high energy particles into the ionosphere over this region during geomagnetic storms. However, the majority of the SAMA lies beyond the reach of these fixed land-based sensors [4]. The geographical extent of the South Atlantic Magnetic Anomaly is shown in Figure 1. The approximate coverage that these (and other) static stations provide of the Southern Oceans can be seen in Figure 2.

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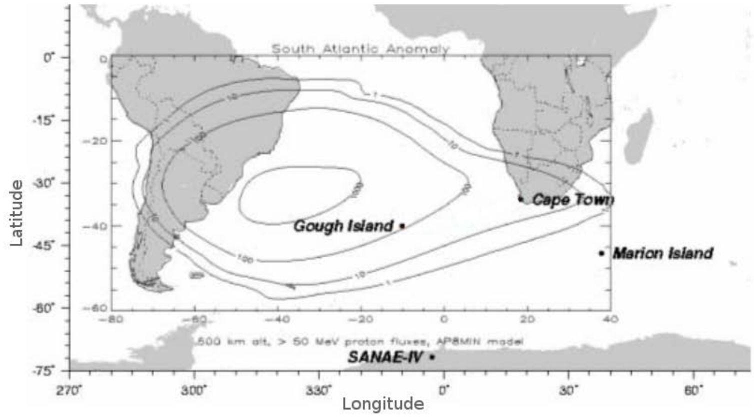

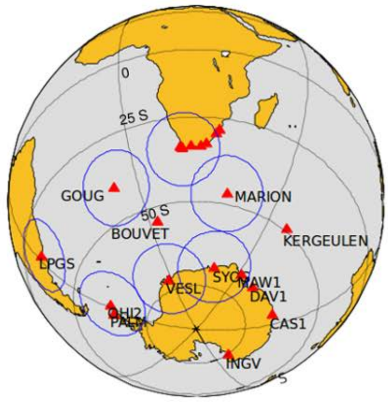

Figure 1: (Left) The South Atlantic Magnetic Anomaly as defined in terms of the $\geq$ 50 MeV proton flux particles at 500km altitude during a geomagnetic storm [5].

Figure 2: (Right) Approximate coverage of existing fixed GISTM stations. These are calculated using a 350km ionospheric pierce point (IPP) height and an elevation of 10° [5].

2. The SA Agulhas II route and GISTM

The SA Agulhas II ice-breaking polar research vessel sails from Cape Town to Antarctica/South Georgia in December−February, Marion Island in April−May, and Gough Island/Tristan da Cunha in August−October. A plot of the typical locations of the SA Agulhas II at various times of the year is shown in Figure 3.

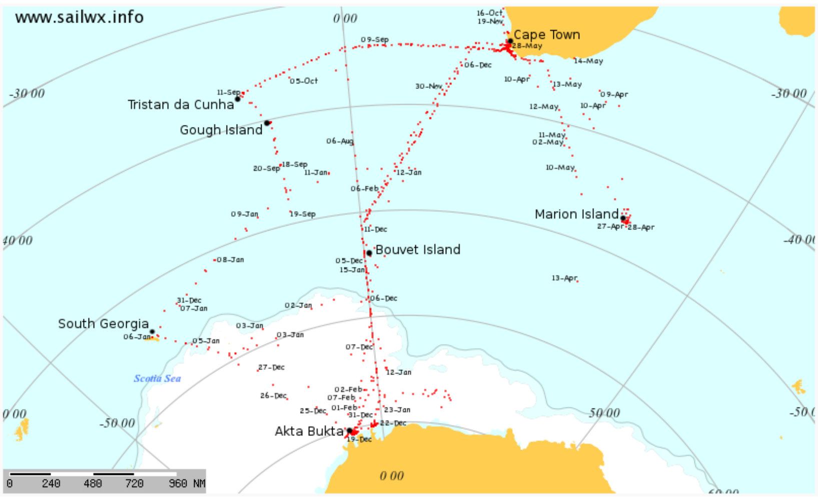

Figure 3: The various routes of the SA Agulhas II between May 2013 and Feb 2016.[6]

The multi-frequency multi-constellation NovAtel GISTM unit was installed on board the SA Agulhas II in 2012 (see Figure 4). It has enabled the first terrestrial measurements of scintillation from new locations within the SAMA region [3],[5]. In this research, the amplitude (S_4) and phase scintillation (σ_ϕ) indices from L1 signals recorded at 50 Hz during the SA Agulhas II voyages in the periods 28 June 2014 − 13 October 2014 and 18 December 2014 − 10 February 2016 will be analysed for the first time. Only GPS satellites (PRN $\leq$ 32) will be used.

Figure 4: The SA Agulhas II polar research vessel, pictured at Akta Bukta in Antarctica in February of 2015, is equipped with a NovAtel GISMT receiver in the Crow's Nest. The grey dome antenna is located at the very top of the mast, providing an unobstructed view of the sky.

3. Negative Horizon and Ship Roll Tolerances

The open ocean has no urban canyons or environmental obstructions which may cause multipath. The only potential source of multipath GPS signals is the ocean surface itself. A hard-coded limitation in the GISTM receiver software resulted in only data for ray paths with elevations $\geq 10°$ being recorded. The 37.8 m height of the GISTM antenna (above mean sea level) and taking the radius of the Earth at 6378 km produces a negative horizon elevation angle of 0.2° as seen in Figure 5. The antenna to horizon distance is 22.219 km.

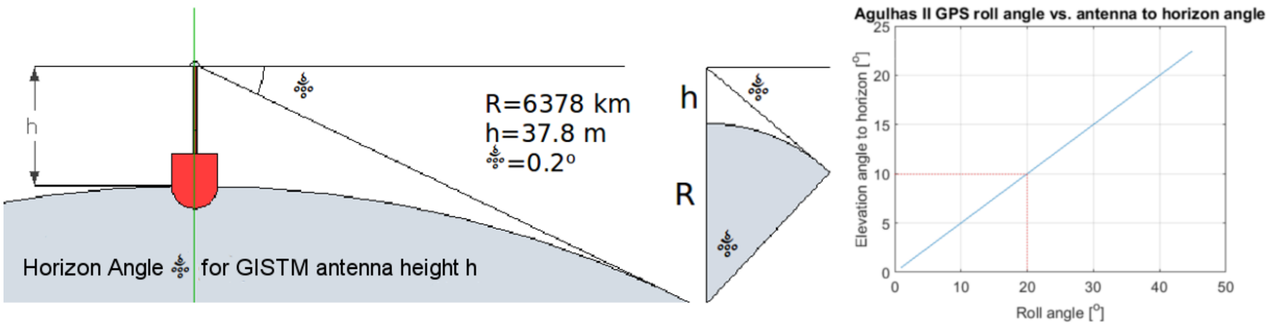

Figure 5: The relation between the roll angle and the elevation angle of the horizon for the SA Agulhas II.

The motion of the vessel includes translation (point A to B), vibration and the 3 axial movements (roll, pitch and yaw). The roll motion is most likely to incur occasional multipath if the roll angle is large enough. Roll angles of up to 20° off vertical can be tolerated by the 10° GISTM cut-off without incurring multipath (see Figure 5). It is rare for the SA Agulhas to experience rolling beyond this limit. The motion effect on the scintillation data due to waves and vibration will be studied in future work.

4. Preliminary Results

The thresholds for significant scintillation can be expressed in terms of the amplitude (S_4) and phase (σ_ϕ) scintillation indices, or the number of scintillation events above a given threshold in a given time. The levels of ionospheric scintillation which may give rise to GPS navigation errors and outages have been reported in several studies ([2],[7],[8],[9]). The benchmark levels for significant scintillation have been shown to be dependent on the particular receiver technologies

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[10]. In high-latitude regions phase scintillation is more frequent and intense than amplitude scintillation [9]. In most cases scintillation levels of $S_4 \leq 0.2$ and $\sigma_\phi \leq 0.2$ are considered to be insignificant in terms of impact on GPS navigation [8]. In this study, scintillation is quantified in terms of the number of S_4 and σ_ϕ-events with intensity above 0.2 in a 10-minute period. This allows a clear distinction between background noise levels and significant increases in scintillation counts. S_4 and σ_ϕ values $\geq$1 are suppressed to remove outliers.

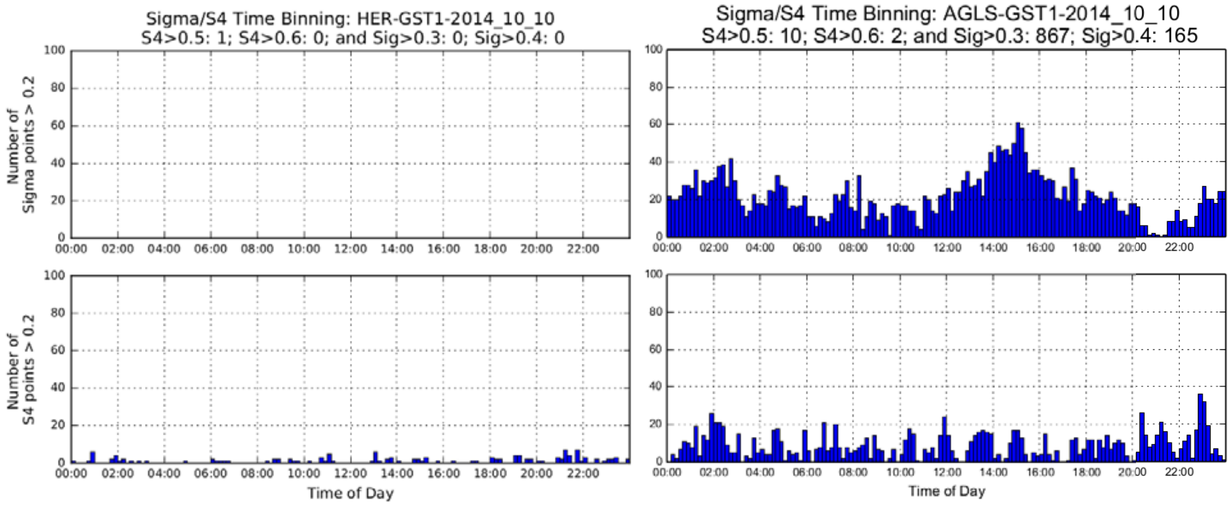

Figure 6: Histogram of S_4 and $\sigma_\phi \geq 0.2$ counts recorded on 10 October 2014 at Hermanus (left) and on board the SA Agulhas II (right). Time is in UT.

Figure 6 shows a comparison of S_4 and σ_ϕ values ≥ 0.2 counts recorded on 10 October 2014 on board the SA Agulhas II with similar counts recorded in Hermanus on the same date. The SA Agulhas II results clearly show the high background level of scintillation above the threshold of 0.2. The higher background levels may be a result of the motion of the SA Agulhas II affecting the scintillation observations.

A significant increase in the σ_ϕ (phase) ≥ 0.2 counts is visible in the SA Agulhas II data during the period 14:00-16:00 UT, while there was no change at Hermanus. This indicates that the likely cause of the increase may be a precipitation event over the SAMA which was not observed from Hermanus.

An increase in the σ_ϕ without a concurrent increase in S_4 is in line with typical results for high latitude regions.[9]

5. Conclusions

A 10° elevation cut-off on the GISTM is shown to be sufficient to prevent multipath from the horizon up to roll angles of 20° while the ship is in the open ocean. Preliminary results indicate that the motion of the ship may be responsible for higher background level of phase scintillation. The increase in σ_ϕ during the period 14:00-16:00 UT on 10 October 2014 may indicate a precipitation event over the SAMA.

This work is in the early phase. Future work will include investigating the extent of the ship's motion effect on scintillation data, as well as attempting to identify scintillation events in the SAMA region by comparing the SA Agulhas II data to the stationary receiver on Gough Island.

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