Sensing the Ionosphere with the Scintillation Auroral GPS Array and Validation Using ESA's Swarm Satellite System

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Objective

Objective 1: Detect scintillation and characterize ionosphere using Scintillation Auroral GPS Array (SAGA)

Objective 2: Validate results from SAGA using Swarm

Background (SAGA)

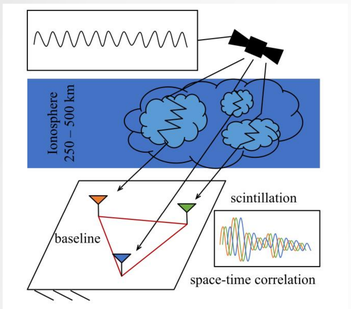


Fig 1.) Image describing scintillation Ref. [1]

- SAGA is located at Poker Flat Research Range; Alaska and is used to characterize irregularities in the ionosphere
- SAGA provides low and high-rate data
- Low-rate scintillation indices are used to detect scintillation
  - Scintillation indices are a measure of signal variation
  - If scintillation indices are above a threshold value for a continuous time period, scintillation is detected

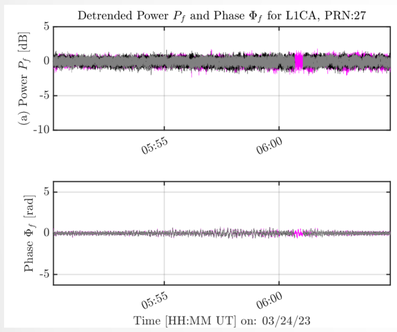


Fig 2.) High-rate data used to find velocity of the irregularity

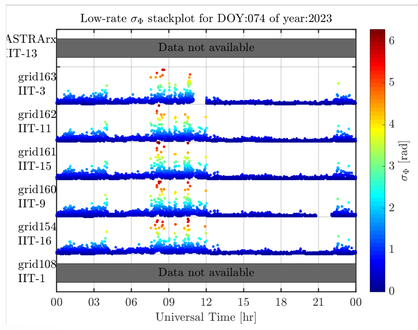


Fig 3.) Low-rate phase scintillation indices for each receiver at Poker Flat

Spaced-receiver method to calculate irregularity drift velocity [1]

- SAGA uses high rate (100 Hz) power and phase data to determine plasma drift velocity
- Drift motion of irregularities can be observed on the ground using correlations of received signals separated by a distance

Spaced-receiver method [1]

- SAGA receives $S_i(t)$,$S_j(t)$ scintillating signals for receivers i and j
- Using an auto-correlation and cross-correlation function, a time delay τ between observations can be found
- Using the x_{ij}, y_{ij} (2D distances between receiver pair i and j) and the time delay between signal detection, the ion velocity is found

Parameters SAGA can measure

- Characteristic velocity (Vc) – measures internal turbulent motion
- "Frozen-in Velocity" (V) - bulk movement of irregularity
- Theta – angle irregularity moves with respect to ground
- Assumption: V>Vc for SAGA to predict a "good" velocity measurement

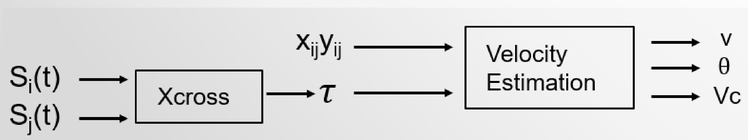


Fig 4.) Diagram of steps taken to find the velocity using SAGA

Background (Swarm)

- ESA's Swarm constellation consists of 3 satellites: Swarm A, Swarm B, and Swarm C
  - Swarm A, C altitude = 460 km
  - Swarm B altitude = 510 km
- Swarm A and B are used for validating SAGA
- Swarm carries 2 Thermal Ion Imagers (TII's)
  - Ion drift velocity is determined from kinetic energy and position of the o^+ signal on a CCD sensor
- Swarm provides satellite velocity (NEC Frame) and ion velocities w.r.t. ground in 3 directions
  - cross-track, along-track, z direction
  - Only ion cross-track velocities are used for comparison to SAGA

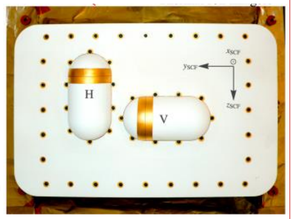


Fig 5.) TII sensor orientation on Swarm. One sensor is orientated in a horizontal direction and one in a vertical direction. Cross-track velocities obtained from only the horizontal sensor [3]

Method

- ESA/Swarm campaign Feb.-Mar. 2023 where Swarm specifically flew over Poker Flat
- 4 step process to validate velocity estimation from SAGA

Step 1.) Find and filter scintillation events

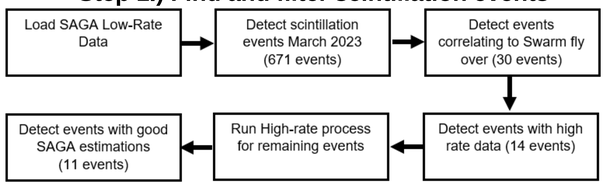


Fig 6.) Event filter logic is finding scintillation events and filtering these events leaving only 11 to be used in comparing SAGA velocity estimations to Swarm

Step 2.) Extract Swarm Data corresponding to 11 events

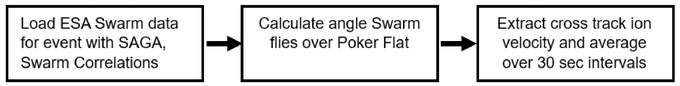


Fig 7.) Extraction of Swarm data logic. Data provided by ESA.

Step 3.) Average Swarm Data over 30 sec. intervals

- Average shown for case study:
  - Scintillation detected March 24th (DOY 83) for PRN 27 from 5:50-6:05 UTC

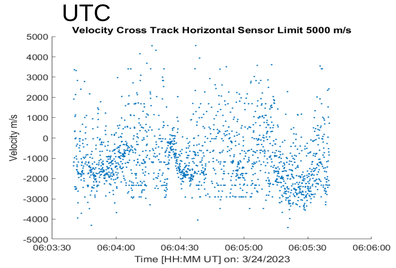


Fig 8.) Raw Swarm data for 2-minute flyover over SAGA

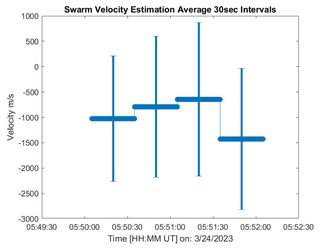
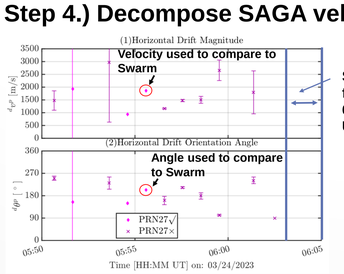


Fig 9.) Average raw Swarm data for 30 second interval. Error is a one sigma value.

Step 4.) Decompose SAGA velocity to align to Swarm cross-track velocity



Swarm flyover time 6:3:40-6:5:40 UT

Fig 10.) Velocity/Theta outputs from SAGA. Use the estimate corresponding to 5:55:05 UT to compare to Swarm

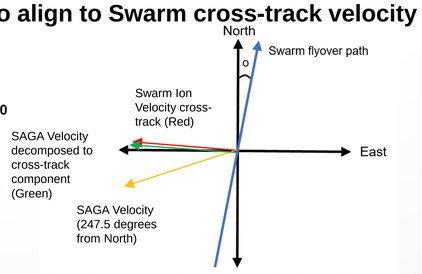


Fig 11.) Decomposing SAGA velocity to line up with Swarm velocity. Positive Velocity means Eastward

Results

Comparison of SAGA to Swarm

- Case Study: SAGA detects scintillation March 24th (DOY 83) for PRN 27 from 5:50-6:05 UTC

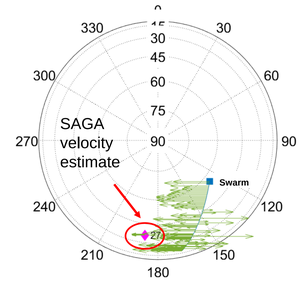


Fig 12.) Decomposition of velocities into cross-track direction shown on a sky plot

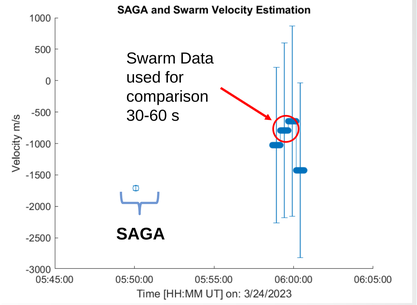


Fig 13.) Velocity cross-track from both SAGA and Swarm. Swarm estimate used when SAGA and Swarm are close to each other

- Use predicted velocity from SAGA at 6:01:40 UT

Method	V (m/s)	Angle (deg)	V Cross (m/s)	V Cross 1 σ (m/s)
SAGA	1852.4	247.5	-1711.64	37.88
Swarm	-1026.08	N/A	-1026.08	1239.51

Fig 14.) Table comparing the cross-track velocity of the case study

- From the table above, the velocity cross-track from Swarm and SAGA both face the same direction, and the velocity of SAGA is within the error bars of Swarm. Thus, verifying SAGA velocity estimations are correct.

Comparison of all 11 event's velocities and directions

Comparing Results	Saga velocity within Swarm Error bars	SAGA and Swarm pointing in same direction
YES	8 (72.7%)	8 (72.7%)
NO	3 (27.3%)	3 (27.3%)

Fig 15.) Table comparing the cross-track velocities of the 11 scintillation events found

Conclusion

- Found correlations of SAGA and Swarm and compared 11 events for verifying SAGA
- SAGA and Swarm cross-track velocities agree a majority of the time in both speed and direction. Thus, there is a strong case that SAGA velocity predictions are correct
- **Future Work: Find more Swarm and SAGA correlations in past years**

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References

[1] Su, Y., S. Datta-Barua, G. S. Bust, and K. B. Deshpande (2017), Distributed sensing of ionospheric irregularities with a GNSS receiver array, Radio Sci., 52, 988–1003, doi:10.1002/2017RS006331.

[2] Burchill, J.K., Knudsen, D.J. Swarm Thermal Ion Imager measurement performance. *Earth Planets Space* **74**, 181 (2022). https://doi.org/10.1186/s40623-022-01736-w

[3] Knudsen, D. J., J. K. Burchill, S. C. Buchert, A. I. Eriksson, R. Gill, J.-E. Wahlund, L. Åhlen, M. Smith, and B. Moffat (2017), Thermal ion imagers and Langmuir probes in the Swarm electric field instruments, J. Geophys. Res. Space Physics, 122, 2655–2673, doi:10.1002/2016JA022571.

[4] S. Datta-Barua, P. Llado, and D. L. Hampton (2021), Multiyear detection, classification and hypothesis of ionospheric layer causing GNSS scintillation, Radio Science.

[5] Sreenivash, V., Su, Y., & Datta-Barua, S. (2020). Automated ionospheric scattering layer hypothesis generation for detected and classified auroral GPS scintillation events. *Radio Science,* 55, e2018RS006779. https://doi.org/ 10.1029/2018RS006779

Scintillation data for SAGA can be found at: http://apollo.tbc.iit.edu/~spaceweather/live/?q=SAGA