Monitoring Space Weather with Space-Based GNSS Observations

Keith Groves, Charles Carrano, William McNeil

Institute for Scientific Research, Boston College

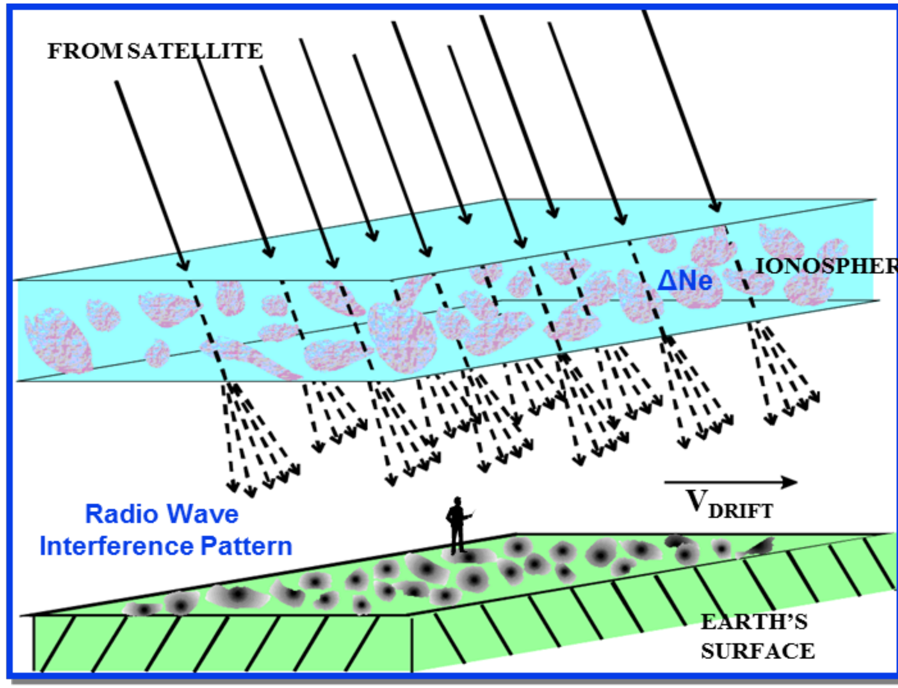
15th meeting of the International Committee on Global Navigation Satellite Systems (ICG-15), 27 September - 1 October 2021, Vienna

Scintillation Physics: A Simple Picture

$$\tau_d = R/c + \frac{r_e c}{2\pi}\frac{N_{tot}}{f^2}$$

$$\delta\varphi = 2\pi f R/c - r_e c \frac{N_{tot}}{f}$$

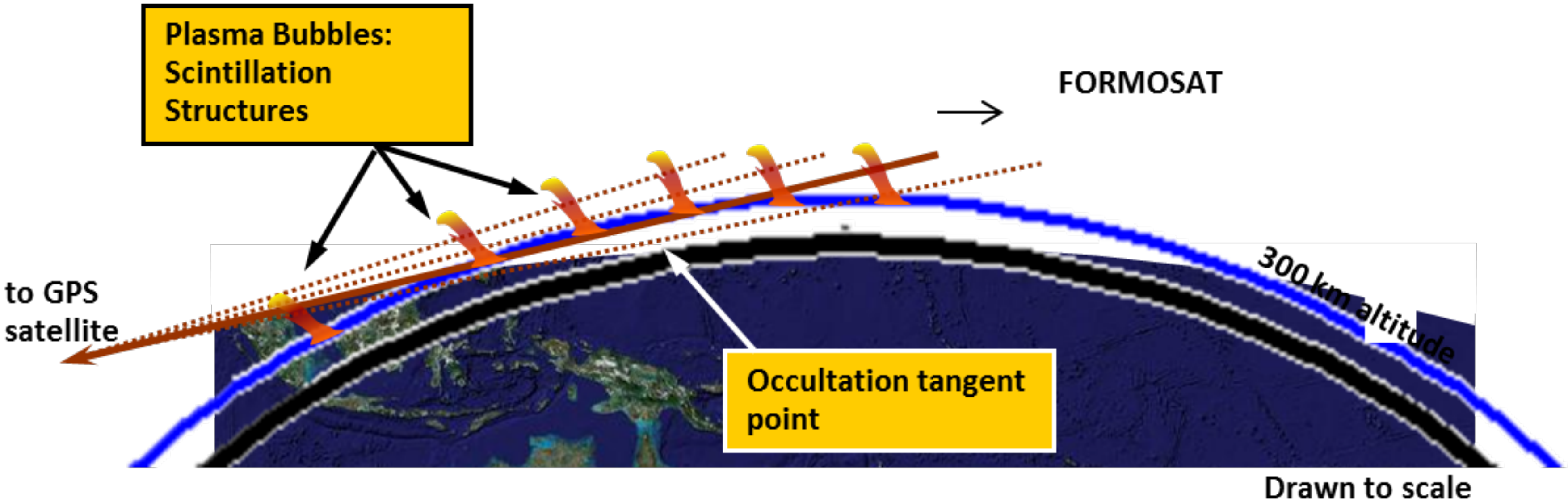
$$N_{tot} = \int N_e(z)dz$$



- Phase variations on wavefront from satellite cause diffraction pattern on ground
- Interference pattern changes in time and space
- User observes rapid fluctuations of signal amplitude and phase

Scintillation Monitoring from Space via Radio Occultations

- Observed signal is integrated over long slant paths. Scintillation can be generated by irregularities located anywhere along the path (in principle).
- Quantitative use of data requires geolocation: determination of the location and spatial extent of the irregularities from the scintillations they produce.
- Potential for interaction with multiple turbulent plasma structures makes it challenging to constrain the inversion problem
- Other sources of information (PLP, ground sites) are useful (and available)



Irregularity Geolocation

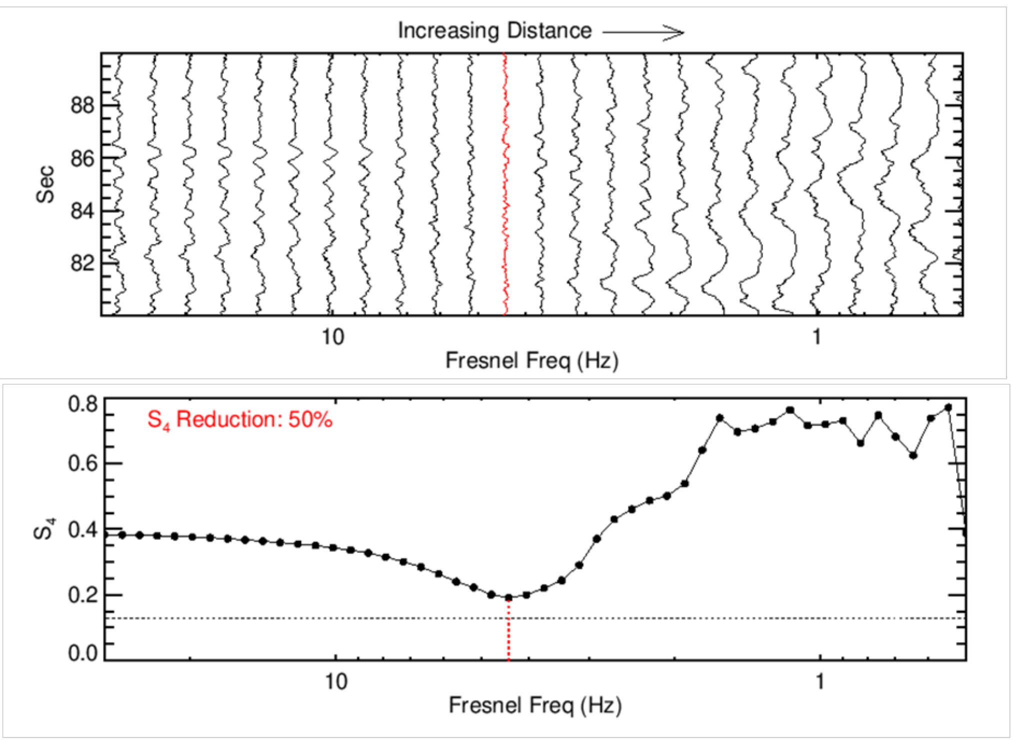
- BC has developed a Bubble Geolocation Product for the TGRS instrument that uses 5 different methods to identify the location of scintillation producing irregularities along RO raypaths:
  - *RF back-propagation – uses high rate intensity and phase (50-100 Hz samples)*
  - *Irregularity Parameter Estimation (IPE) – uses high rate intensity only (50-100 Hz samples)*
  - *S4 and SIGMA-PHI – uses the ratio of these metrics only*
  - *S4 and ROTI – uses the ratio of these metrics only*
  - *Tangent Point – assumes irregularities are located at the tangent point of each ray*
- We recently completed a validation of the back-propagation results using UV images from GOLD and ground-based UHF receivers, so we focus on this technique here.

Geolocation via Back-Propagation

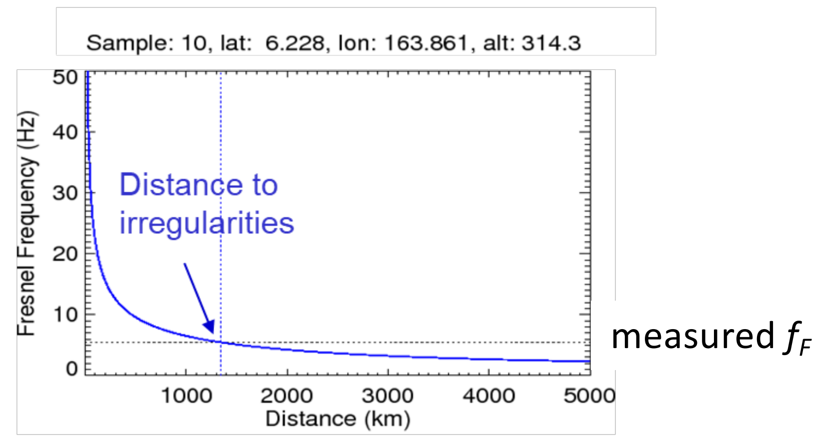
Unlike traditional BP algorithms, we perform back-propagation in the time domain, with Fresnel frequency as the independent variable to be measured. We use the Rino scintillation model (1979), generalized to the RO geometry, to relate Fresnel frequency to Fresnel scale, and then to distance along the ray-path to the irregularity region.

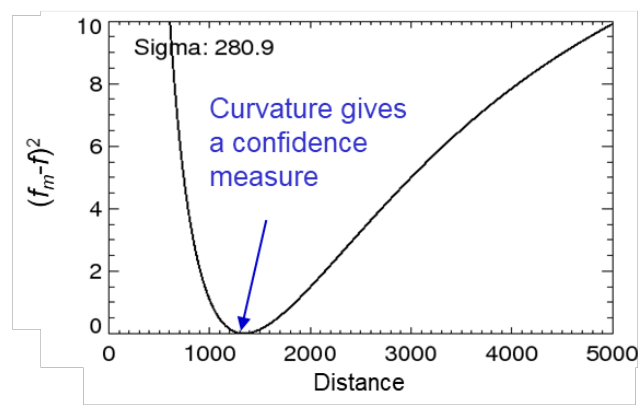
$$U_s(t) = F^{-1}\left\{\exp\left[-\tfrac{1}{2}i(2\pi f / f_F)^2\right] F\left[U_{RX}(t)\right](f)\right\}$$

1. Back-propagate complex signal in 10-sec segments to measure Fresnel frequency of the scattering.



2. Geometric model provides Fresnel frequency vs distance. Intersection with measurement gives distance to irregularities.

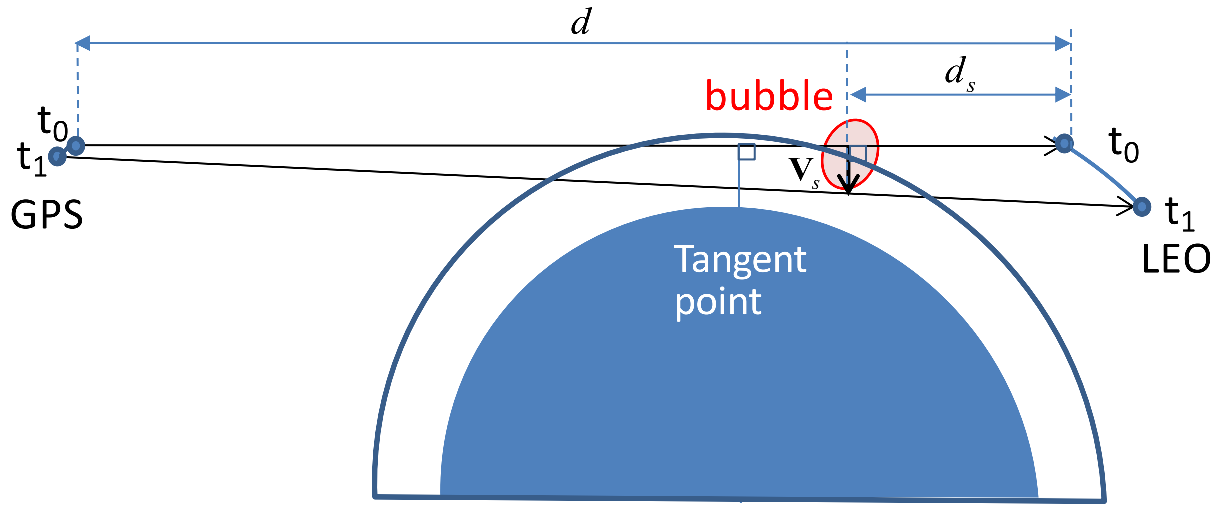




Mapping Fresnel Frequency to Irregularity Location

- Scan velocity is proportional to distance (d_s) from the irregularities causing the scintillation

$$\mathbf{V}_s(d_s) = \mathbf{V}^{\mathrm{LEO}} + (d_s/d)\left[\mathbf{V}^{\mathrm{GPS}} - \mathbf{V}^{\mathrm{LEO}}\right]$$



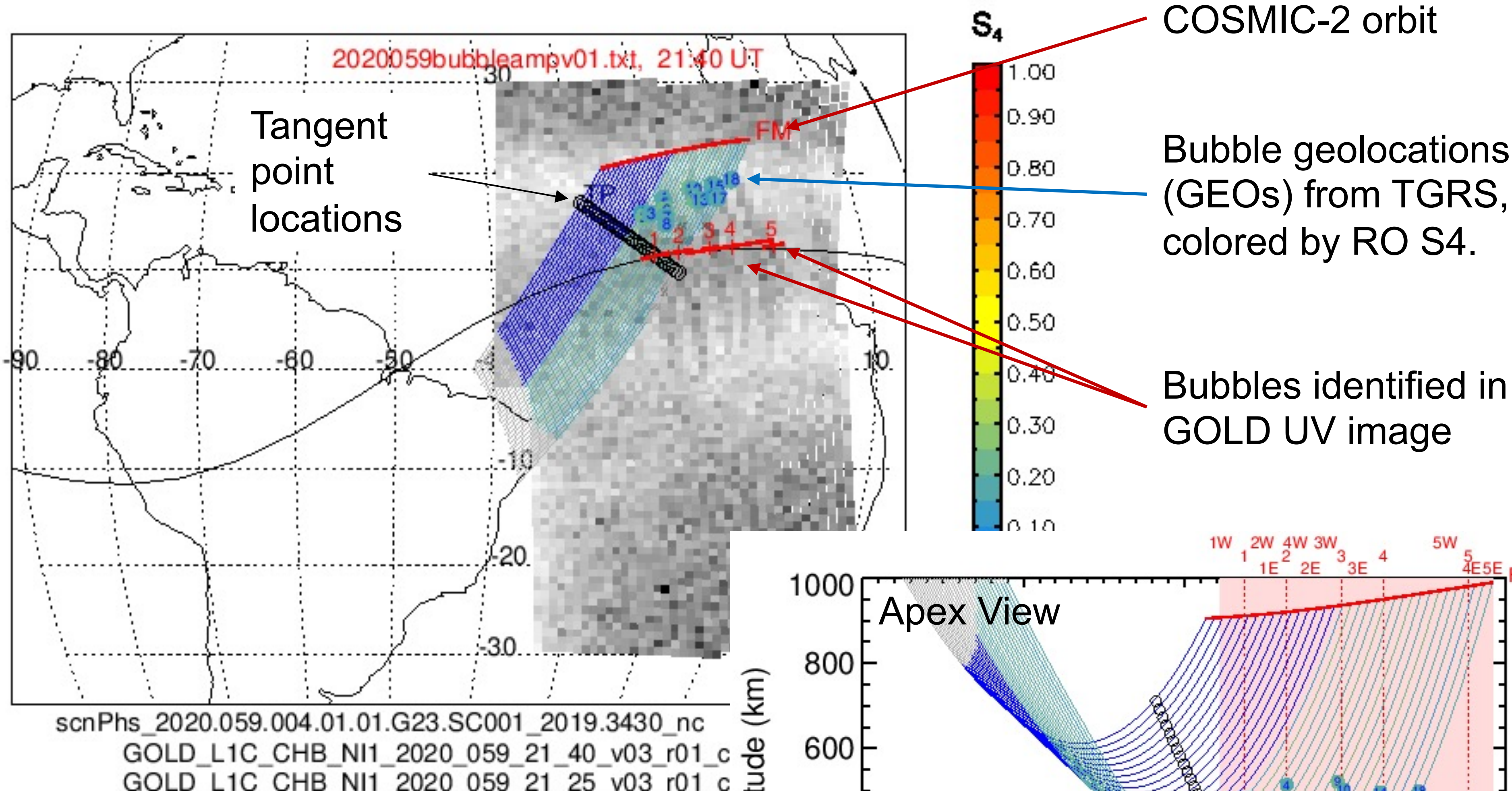
- For anisotropic field-aligned irregularities we must use an effective scan velocity, V_{eff}
- Effective scan velocity: $V_{eff}(d_s) = \left[\dfrac{CV_{sx}^2 - BV_{sx}V_{sy} + AV_{sy}^2}{AC - B^2/4}\right]^{1/2}$

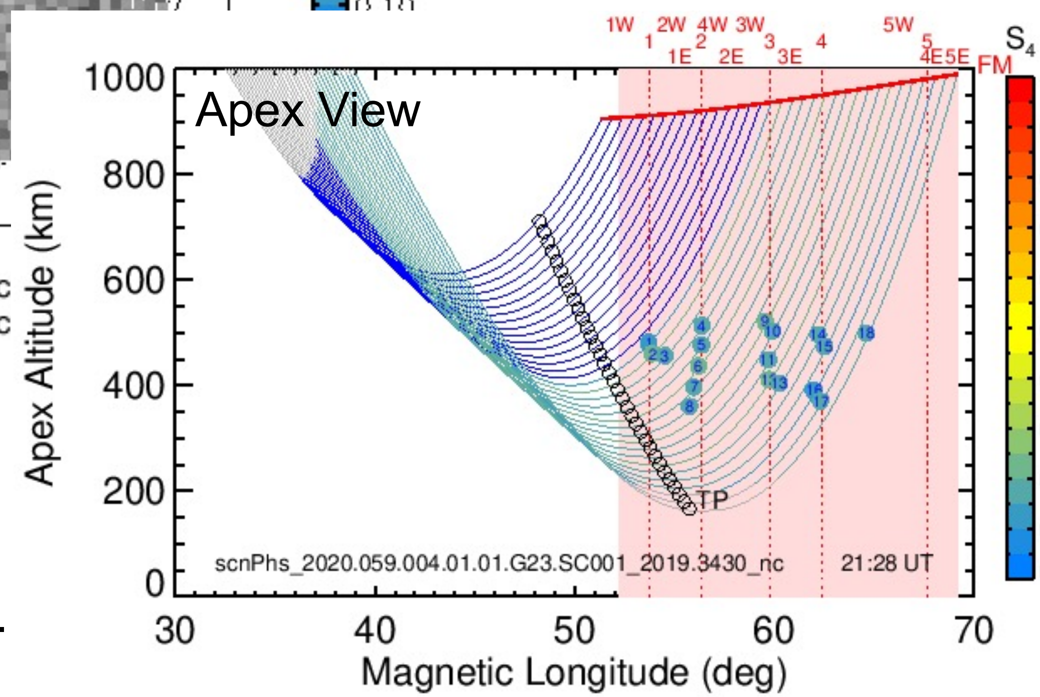
  V_{sx}, V_{sy} are components of V_s in plane $\perp$ to ray-path

- Fresnel frequency: $f_F(d_s) = V_{eff} / \rho_F(d_s)$

Once $f_F(d_s)$ has been measured, e.g. via back-propagation, this purely geometric model can be inverted to find d_s

TGRS Geolocations with Confirmation from GOLD

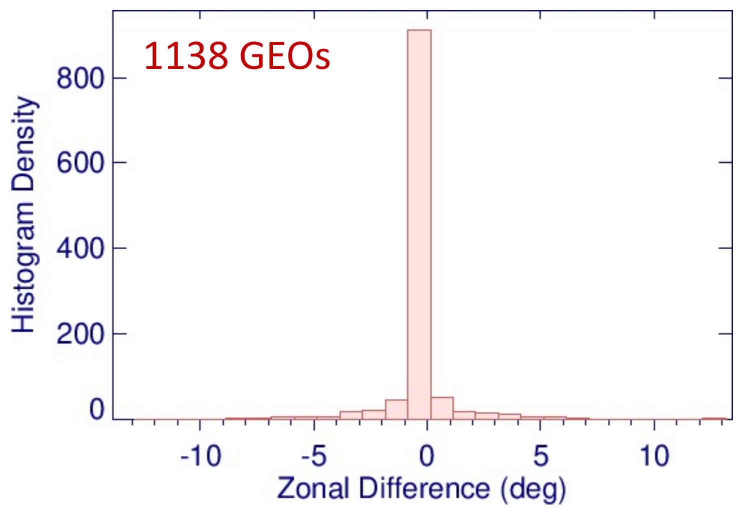




TGRS does not detect all bubbles, just those intersected by the RO ray-paths at F-region altitudes, and those for which RO S4 triggers download of high-rate data.

Validation of the TGRS Geolocation Product

- Validation of more than 1100 TGRS geolocations using GOLD UV images over South America & Atlantic suggest 90% of TGRS GEOs are accurate to 2 degrees or better.



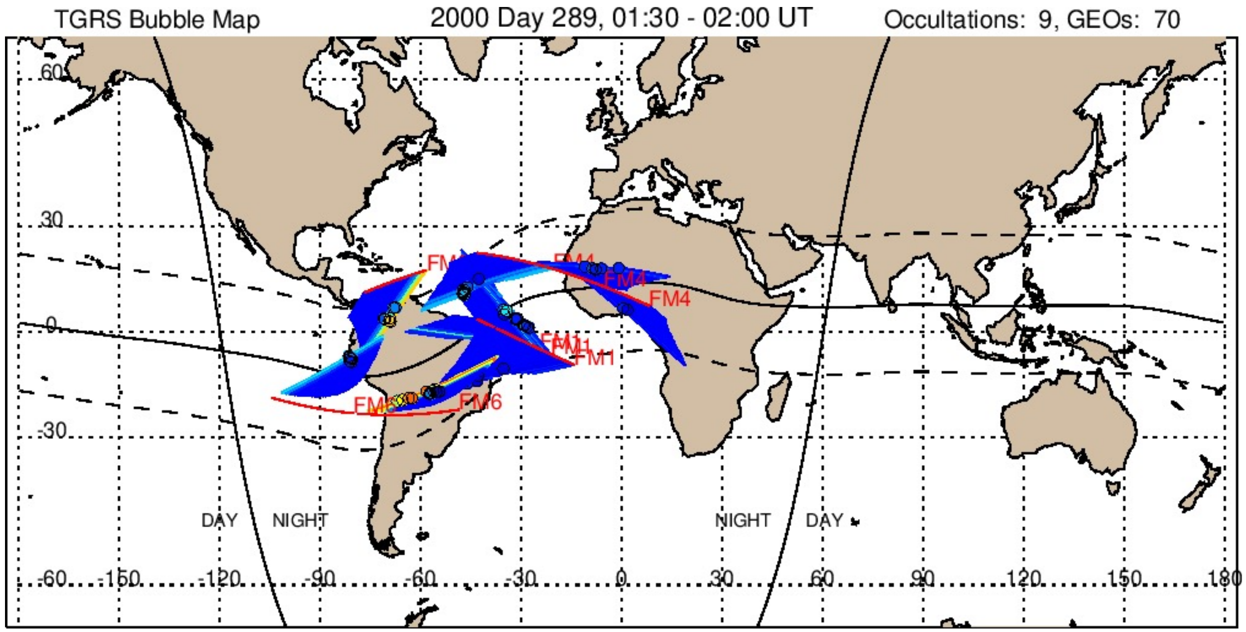
Error (deg)	Samples	%
All	1138	100
< 5	1105	97
< 2	1030	91
< 1	968	85
0	817	71

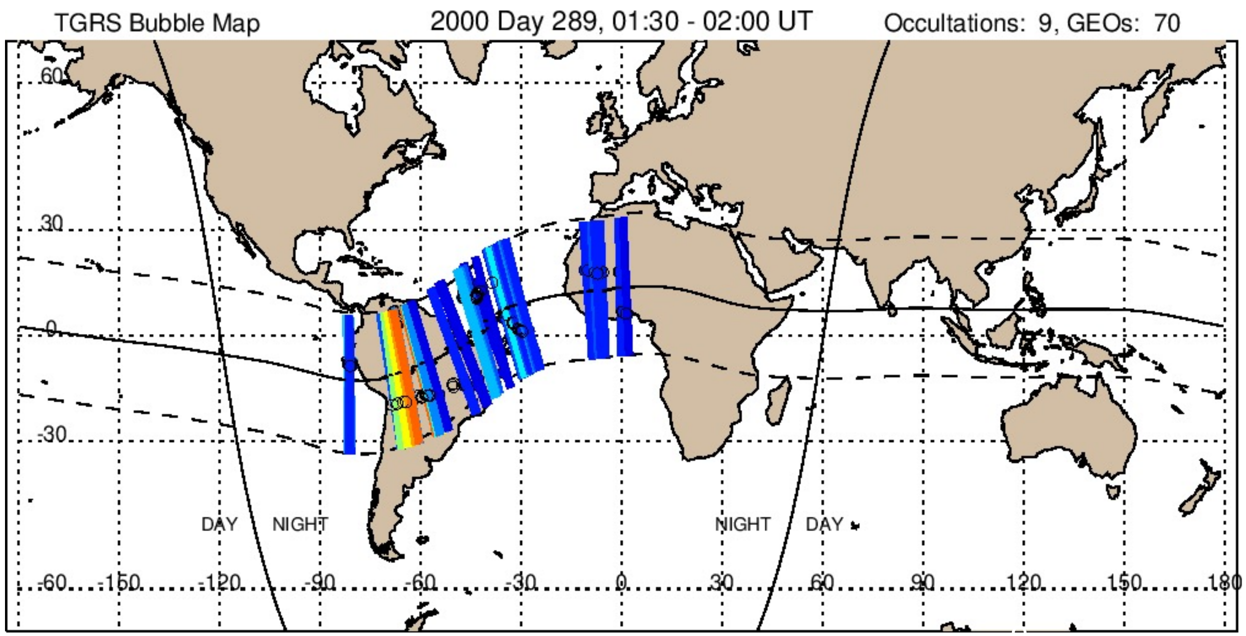
- Validation of > 3000 TGRS geolocations using SCINDA VHF measurements produced rms errors of less than 1° in longitude (~100 km) at each site.

Errors in Geolocation from VHF/ROTI Validation										
	Sao Luis		Singapore		Bangkok		Kwajalein		Addis Ababa	
Total GEOs	1777	100%	496	100%	387	100%	335	100%	296	100%
Errors < 2-deg	1755	98.8%	484	97.6%	367	94.8%	308	91.9%	290	98.0%
Errors < 1-deg	1714	96.4%	464	93.6%	341	88.1%	282	84.2%	279	94.2%
RMS Error	0.41-deg		0.58-deg		0.81-deg		0.99-deg		0.56-deg	

TGRS Bubble Geolocation Maps

- We are currently developing tools to visualize the global distribution of TGRS bubble geolocations.
- A separate limb-to-disk model extracts quantitative estimates of CkL from the RO S4, and then predicts scintillation for other frequencies and geometries.
- This RO data can be fused with ground-based scintillation data to provide next-generation scintillation nowcast/forecast products.





Concluding Remarks

- We are entering a golden age of plentiful data from space-based radio occultation observations from multiple satellite constellations (government and commercial).
- Recently developed theoretical results facilitate new ways to exploit space-to-space GNSS links for space-weather monitoring.
- This offers unprecedented opportunities for continuous monitoring of scintillation activity on a global basis (in particular, over ocean regions where observations have been lacking).
- The inclusion of measurements from additional constellations will expand coverage dramatically assuming technology is able to support the increased data throughput requirements.
- Real-time, global monitoring appears to be right around the corner.