Ionospheric Sensing with Radio Occultations: COSMIC-2

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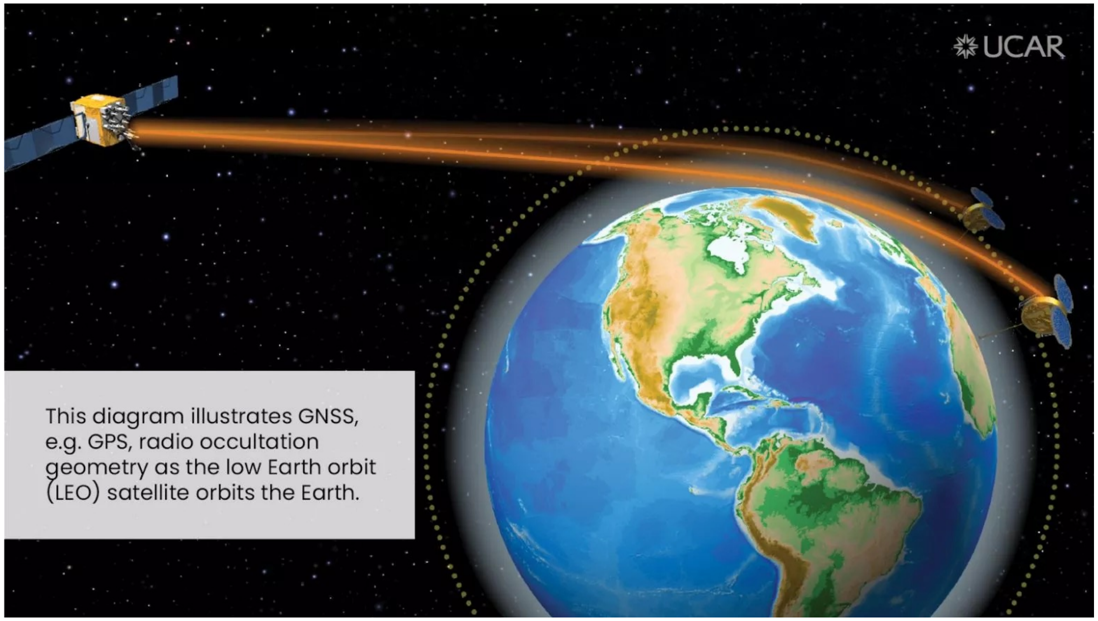
Overview

- "Radio occultation" (RO) refers to the reception of GNSS signals from a satellite in low-earth orbit; as the LEO satellite travels over the horizon from the GNSS source the signal scans down through the earth's atmosphere until it is eventually blocked by the surface ("occulted")

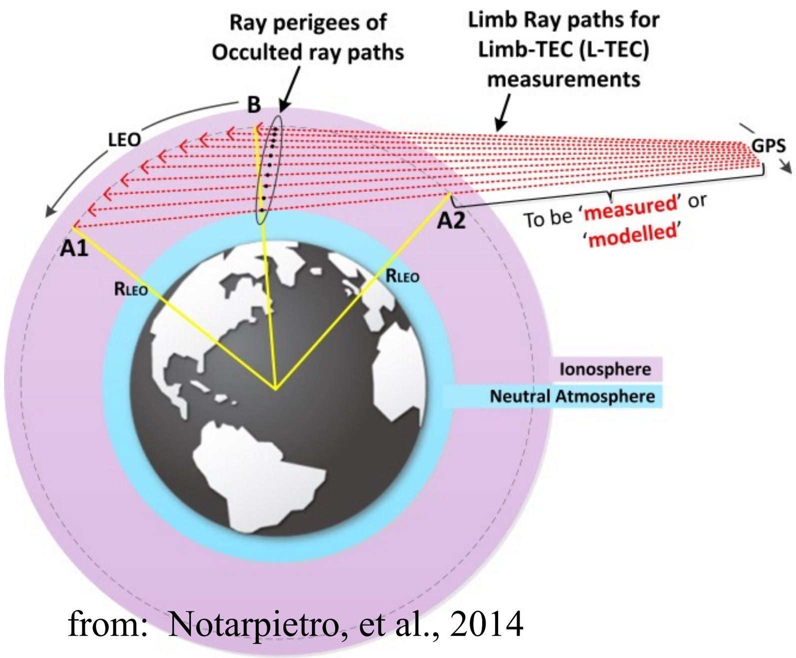
- The primary mission for RO data are tracking the temperature and water vapor content of the lower atmosphere, but the index of refraction change caused by the ionosphere can also be measured to infer a vertical electron density profile

- Irregularities can cause scintillation on the links as well and here we focus on inferring the location and strength of those irregularities with RO data from the GNSS sensor on-board COSMIC-2 satellites

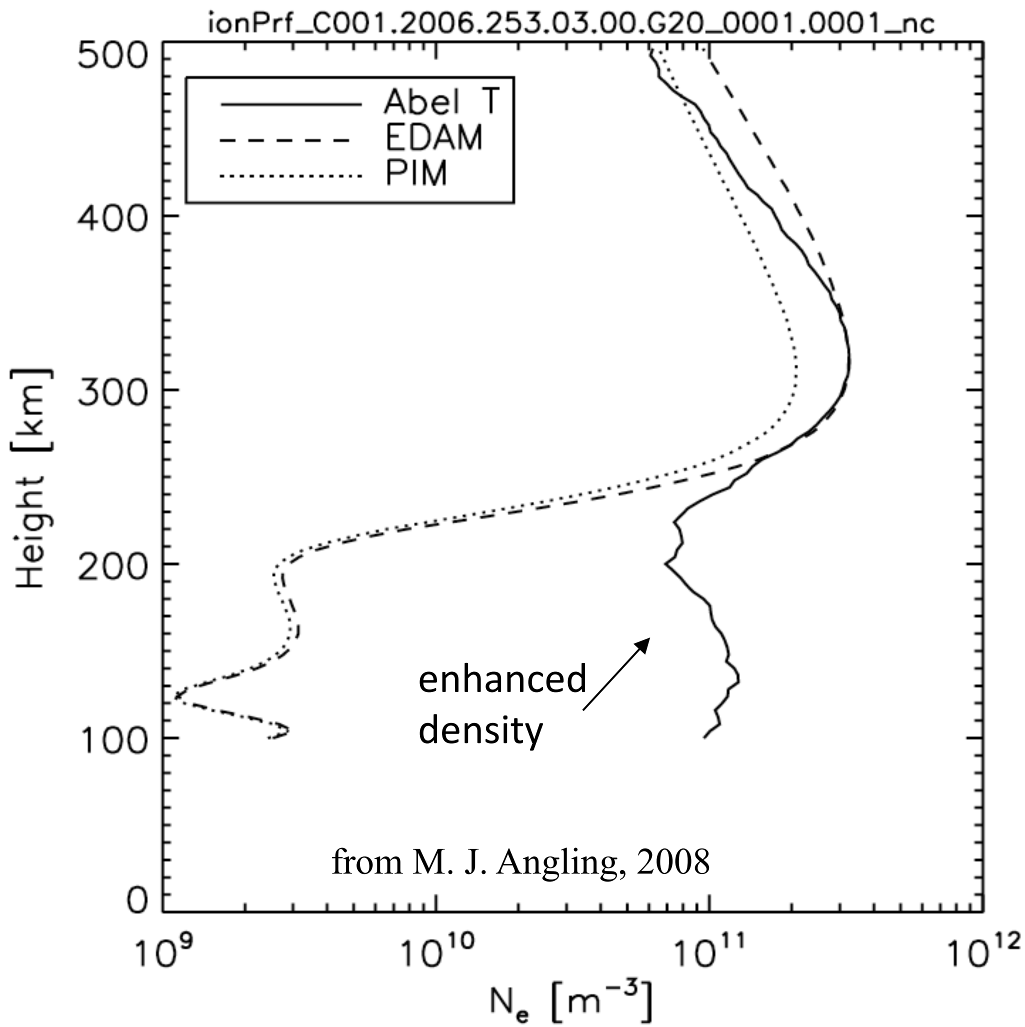


Electron Density Profile (EDP) from COSMIC

- EDPs were among the first space weather parameters to be extracted from RO data
- The plot to the right shows EDPs from two different models and a 3rd derived via the "Abel Transform" applied to COSMIC RO data (solid trace)
- This approach has had limited success, but other methods, including direct assimilation of the slant TEC, have shown promise for improving ionospheric specification
- Notice the much greater density present in the bottomside of the RO EDP



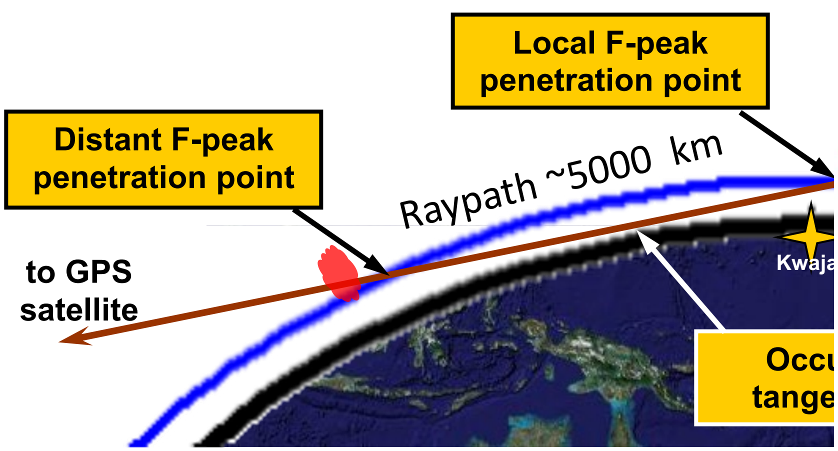
from: Notarpietro, et al., 2014

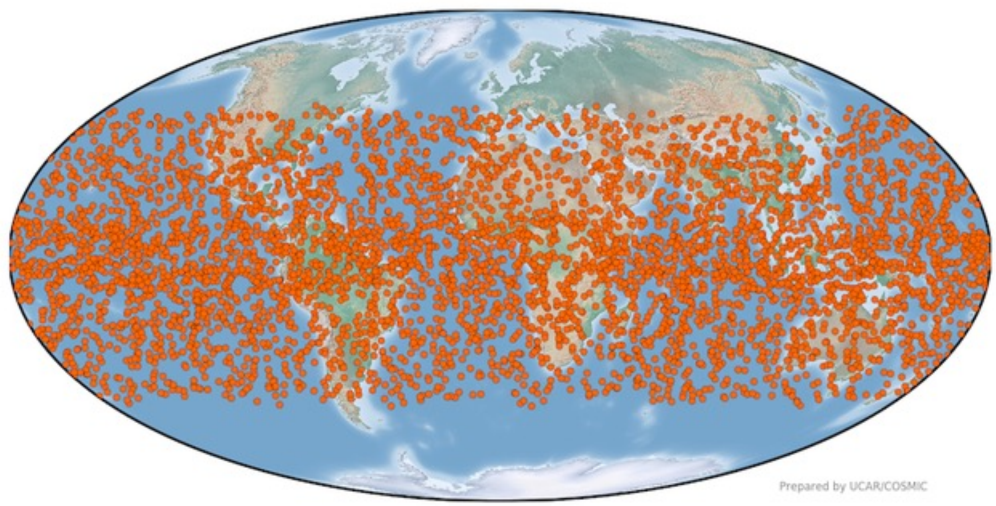


from M. J. Angling, 2008

What About Characterizing Irregularities with RO?

- Observed signal is integrated over long slant paths (1000-5000 km). 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.
- COSMIC-2 consists of 6 satellites flying at about 550 km altitude with an inclination of 24° ; the constellation generates about 5,000 occultations per day covering mid- to low latitudes.





Forward Propagating Waves in a Random Medium

In the Helmholtz equation for the scalar electric field, *U*, $\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial z^2}+k^2 n^2\right)U=0$

the random terms *n* and *U* appear as a product (they are coupled). We use the split-step technique to uncouple them.

For propagation in free space (n=1), can be factored into the product of two operators:

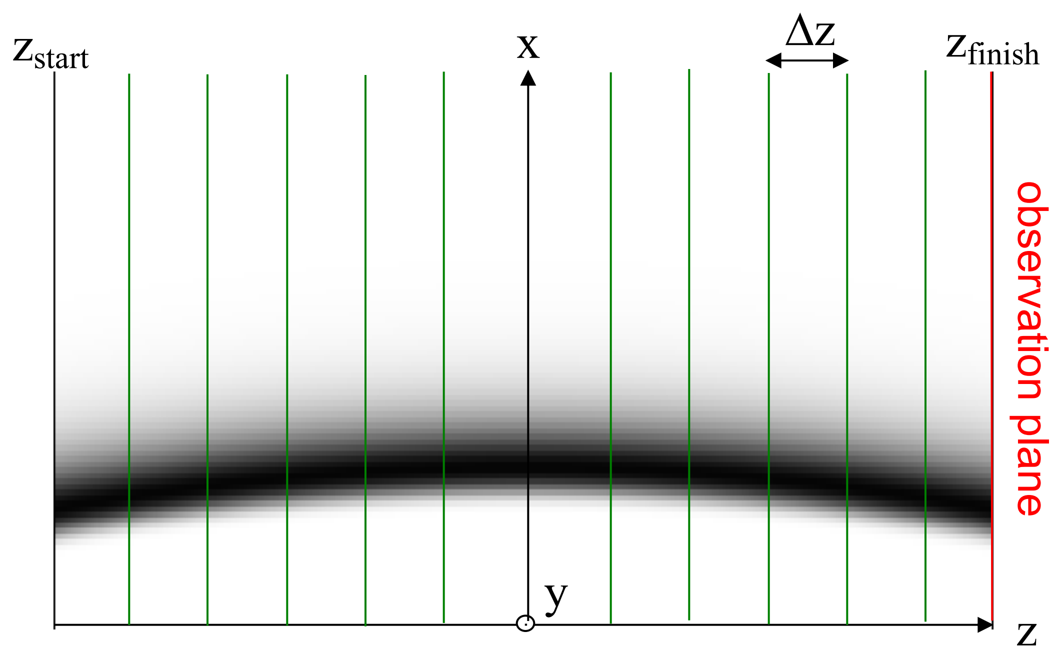
$$\underbrace{\left[\frac{\partial}{\partial x}+i\sqrt{k^2+\frac{\partial^2}{\partial z^2}}\right]}_{\text{Backward propagating waves}}\underbrace{\left[\frac{\partial}{\partial x}-i\sqrt{k^2+\frac{\partial^2}{\partial z^2}}\right]}_{\text{Forward propagating waves}}U=0$$

Neglecting backscattered waves, solution is: $U(x,z)=\exp\left[iz\sqrt{k^2+\frac{\partial^2}{\partial z^2}}\right]U(x,0)$

This operator is much simpler to apply in Fourier space: $\hat{U}(K,z)=\underbrace{e^{iz\sqrt{k^2-K^2}}}_{\text{Free-space propagator}}\hat{U}(K,0)$

Applying inverse transform gives solution: $U(x,z)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty}\hat{U}(K,0)\,e^{iz\sqrt{k^2-K^2}}e^{iKx}dK$

The Multiple Phase Screen (MPS) Method



After Knepp (1983)

<u>Equatorial plane</u>

y-axis is along magnetic field

z-axis is tangent to Earth

x-axis completes orthogonal system

Suitable for weak and strong scatter through weakly inhomogeneous random fields

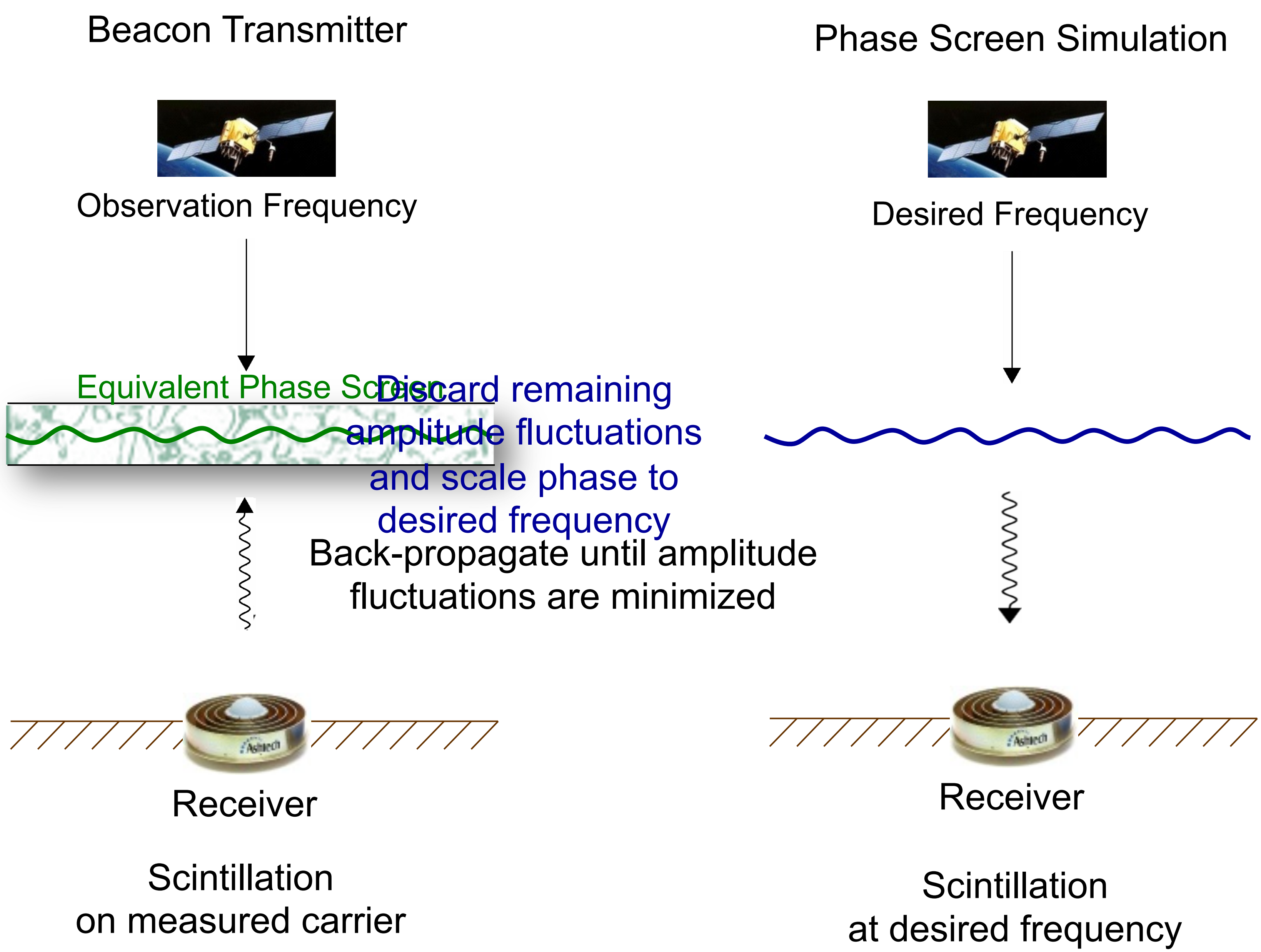
Steps of the MPS Algorithm

1)	Initial condition (plane wave):	$U\left(x, z_{start}^{-}\right) = U_0$
2)	Impose accumulated phase change due to N_e fluctuations between screens	$U\left(x, z_n^{+}\right) = U\left(x, z_n^{-}\right) \exp\left[i \int_{z_n}^{z_{n+1}} \lambda r_e \Delta N_e\left(x, \xi\right) d\xi\right]$
3)	Propagate in free-space to the j+1th screen	$\hat{U}\left(K, z_{n+1}^{-}\right) = \hat{U}\left(K, z_n^{+}\right) \exp\left[i(k^2 - K^2)^{1/2} \Delta z\right]$
4)	Repeat until the wave reaches the observation plane	$U(x) = \frac{1}{2\pi} \int_{-\infty}^{-\infty} \hat{U}\left(K, z_{finish}^{+}\right) e^{iKx}\, dx$

FFT

FFT

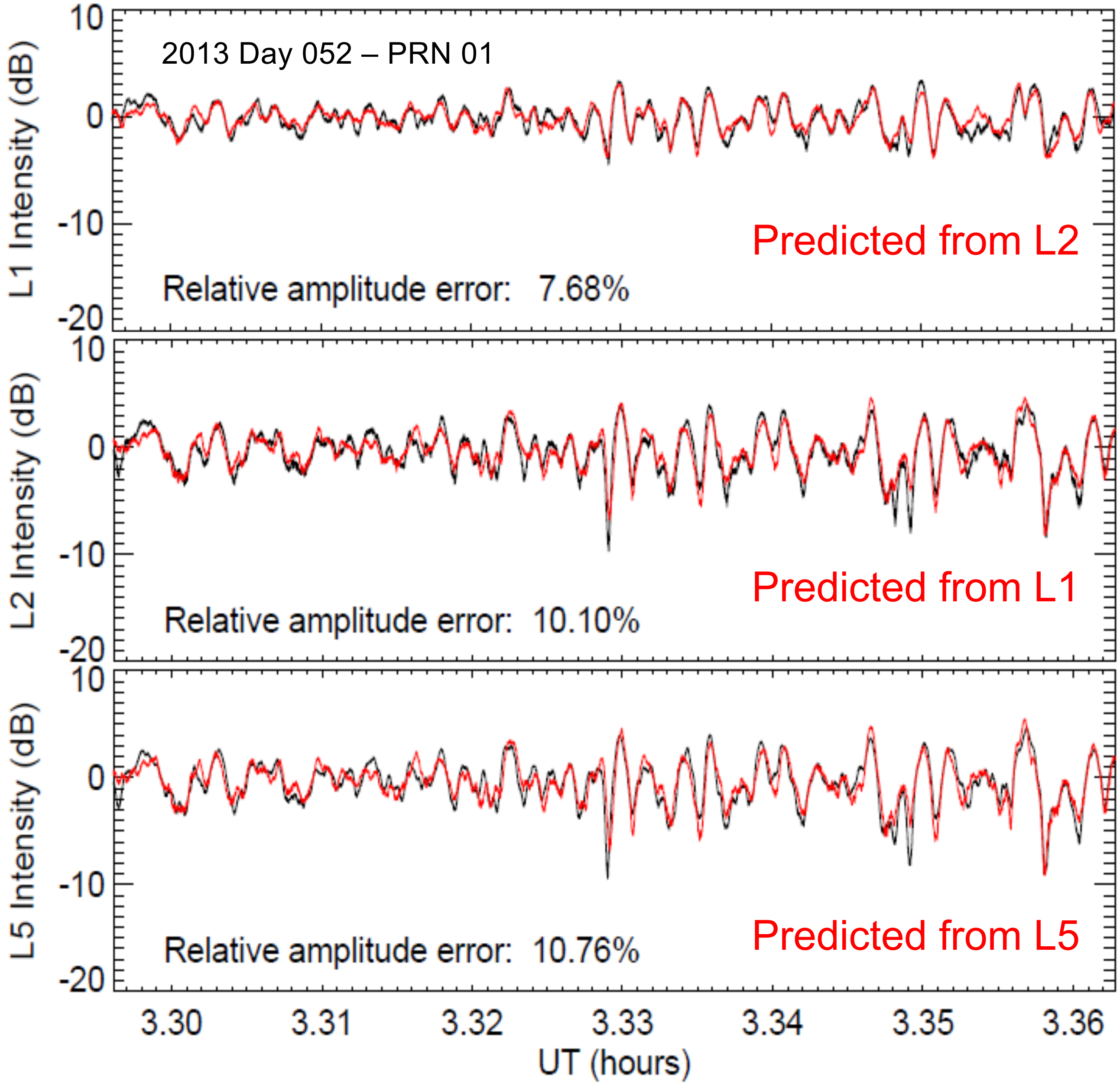
Inverse Diffraction Method
(Mapping from One Frequency to Another)



How Well Does Back Propagation Work?

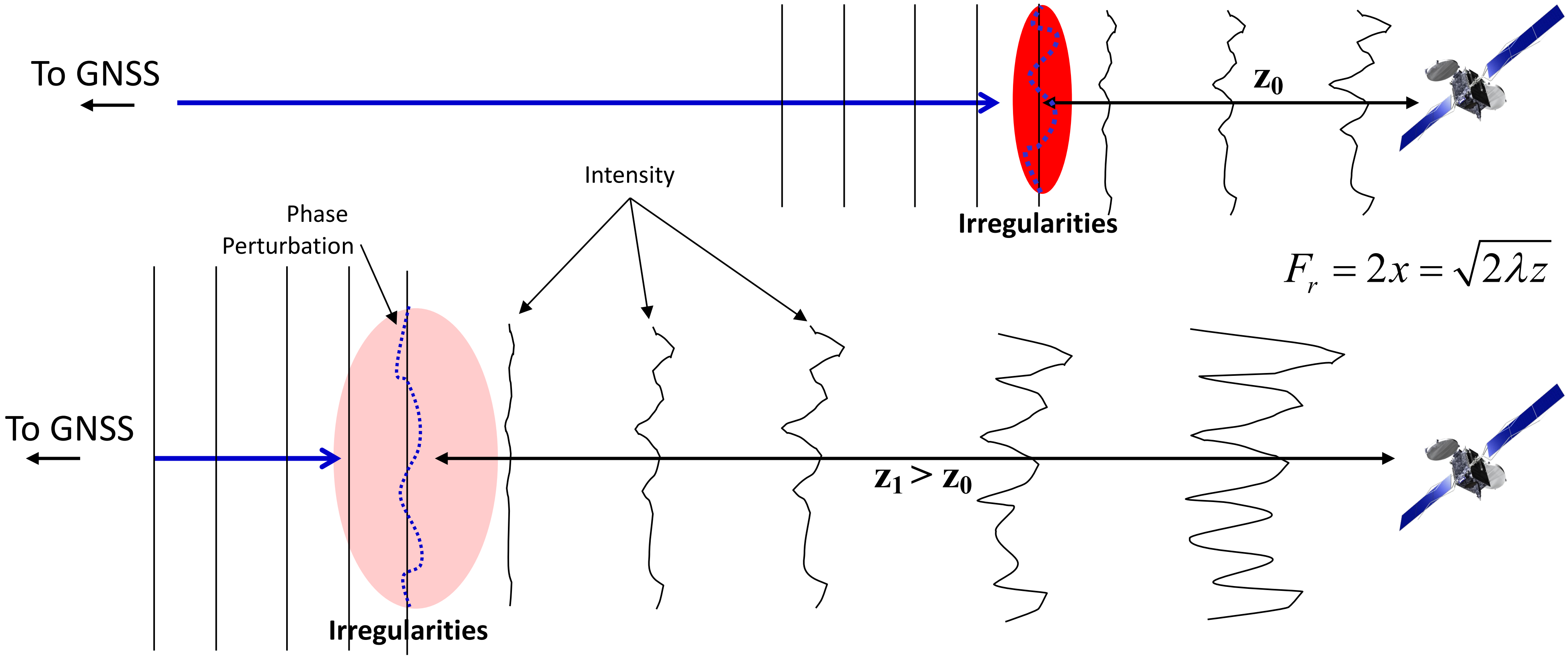
Results from real GPS data

Black – measured, Red - Predicted



What Happens When the Location of the Irregularities is Unknown?

Distance and Scintillation Strength are Coupled



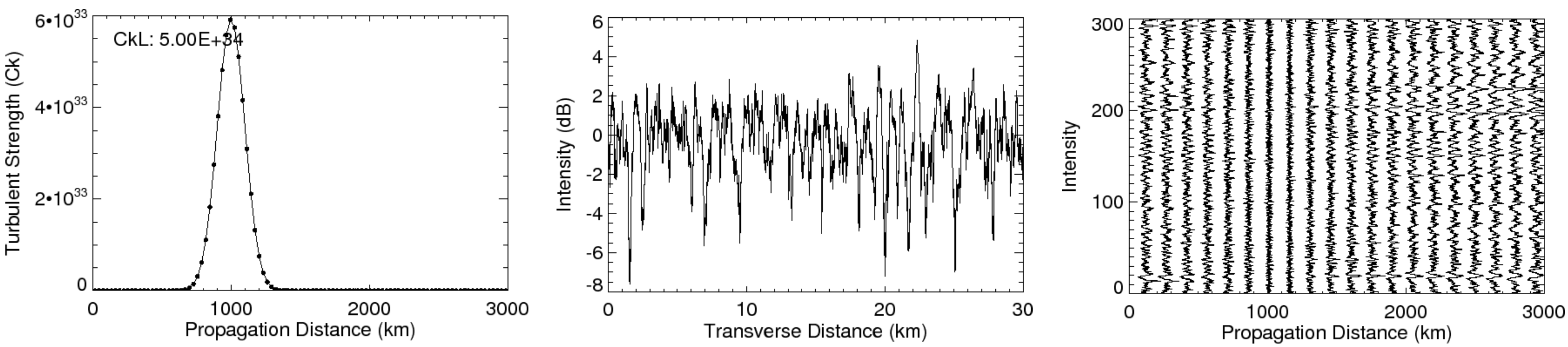
- Weak irregularities far away from the receiver can cause stronger intensity scintillation than strong irregularities close to the receiver
  - The diffractive interference effects increase as the wave propagates along
  - Also, the Fresnel scale is larger for distant irregularities and the amplitude of irregularities increases rapidly with increasing scale size (power law); larger scales can contribute as the distance to the source increases

Back-Propagation Method for Locating Irregularities

- Back-propagation of the received wave (as a function of spatial coordinates):

$$U_s(\rho) = F^{-1}\left\{\exp\left[-\tfrac{1}{2} i\kappa^2 \rho_F^2\right] F\left[U_{RX}(\rho)\right](\kappa)\right\}$$

Fresnel scale: $\rho_F = \sqrt{d_s / k}$



- Back-propagation of a *time-series* provides the Fresnel frequency, $f_F = V_{eff} / \rho_F$, not distance to the scattering region.

change of variable $\rho \to V_{eff} t, \quad \kappa \to 2\pi f / V_{eff}$

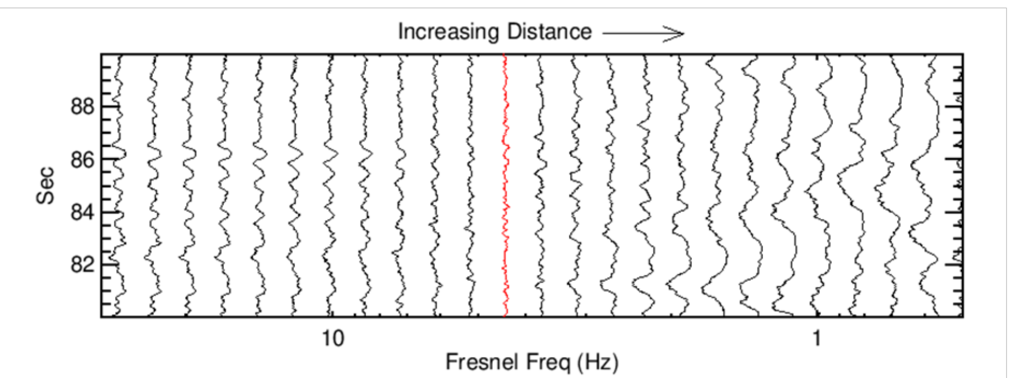
Temporal form: $U_s(t) = F^{-1}\left\{\exp\left[-\tfrac{1}{2} i(2\pi f / f_F)^2\right] F\left[U_{RX}(t)\right](f)\right\}$

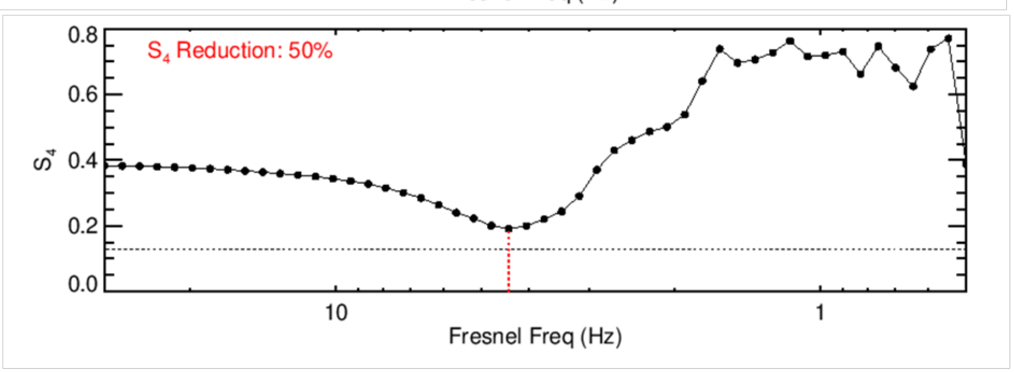
Bubble Geolocation via Back-Propagation

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.

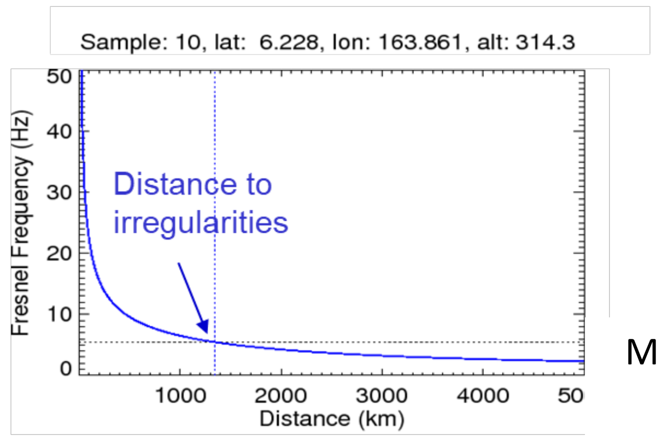
$$U_s(t) = F^{-1}\left\{\exp\left[-\tfrac{1}{2} i (2\pi f / f_F)^2\right] F\left[U_{RX}(t)\right](f)\right\}$$

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

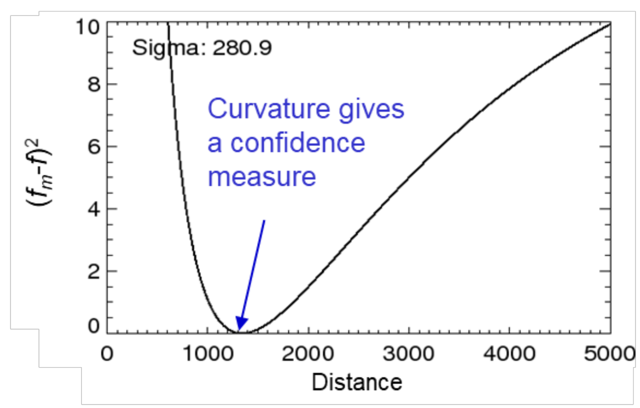




2. Geometric model provides Fresnel frequency vs distance. Intersection with measurement gives distance to irregularities.



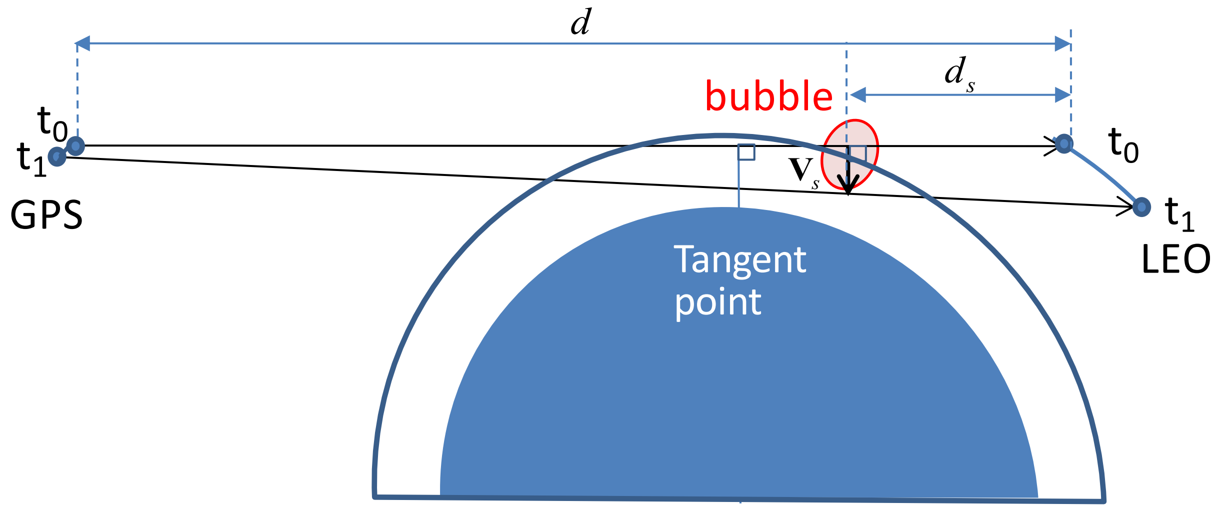
Measured f_F



Mapping Fresnel Frequency to Irregularity Location

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

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



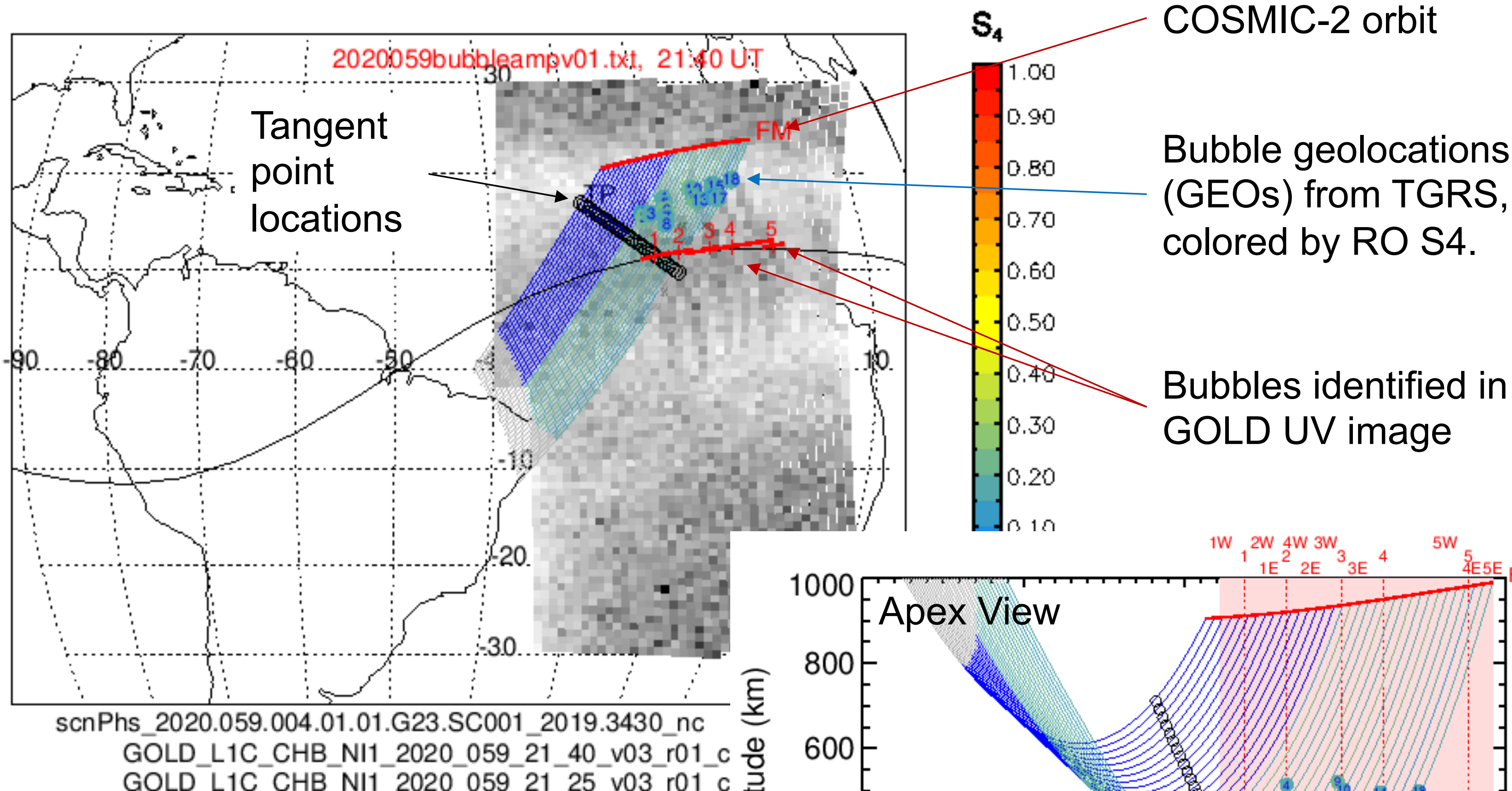
- For anisotropic field-aligned irregularities we must use an effective scan velocity, V_{eff}
- Effective scan velocity: $V_{eff}(d_s) = \left[\dfrac{CV_{sx}^2 - BV_{sx}V_{sy} + AV_{sy}^2}{AC - B^2/4}\right]^{1/2}$

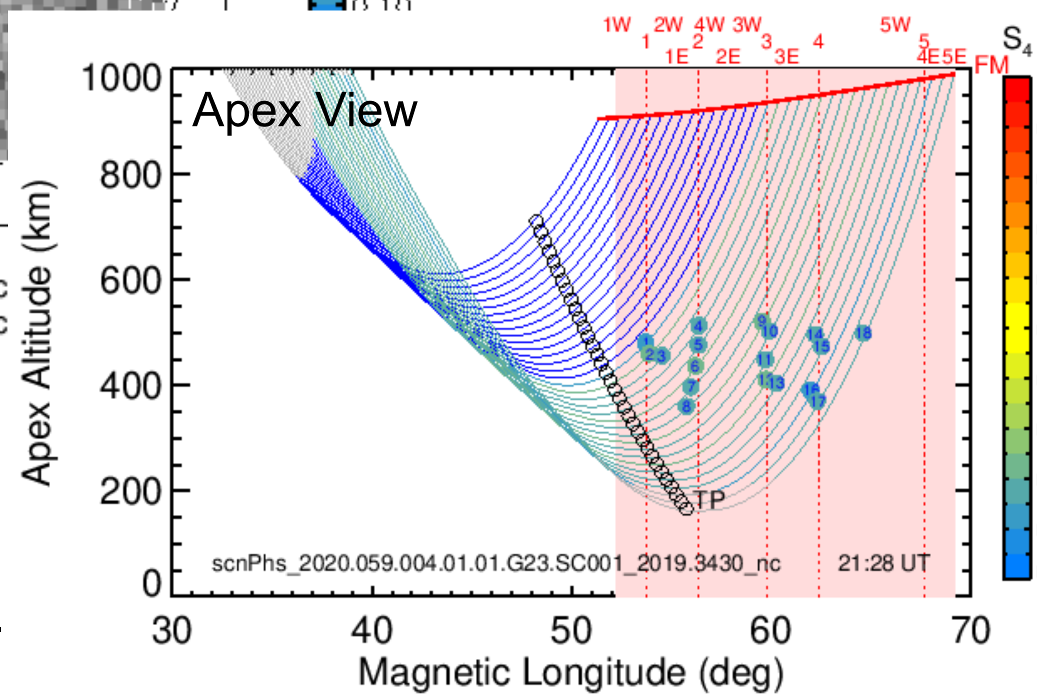
  V_{sx}, V_{sy} are components of V_s in plane $\perp$ to ray-path

- 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 UV imagery

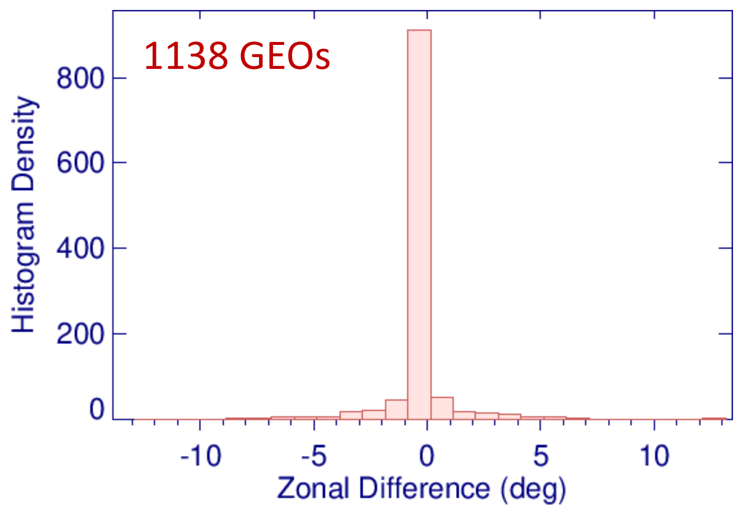




TGRS does not detect all bubbles, just those intersected by the RO ray-paths at F-region altitudes, and those for which RO S4 triggers download of high-rate data.

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.



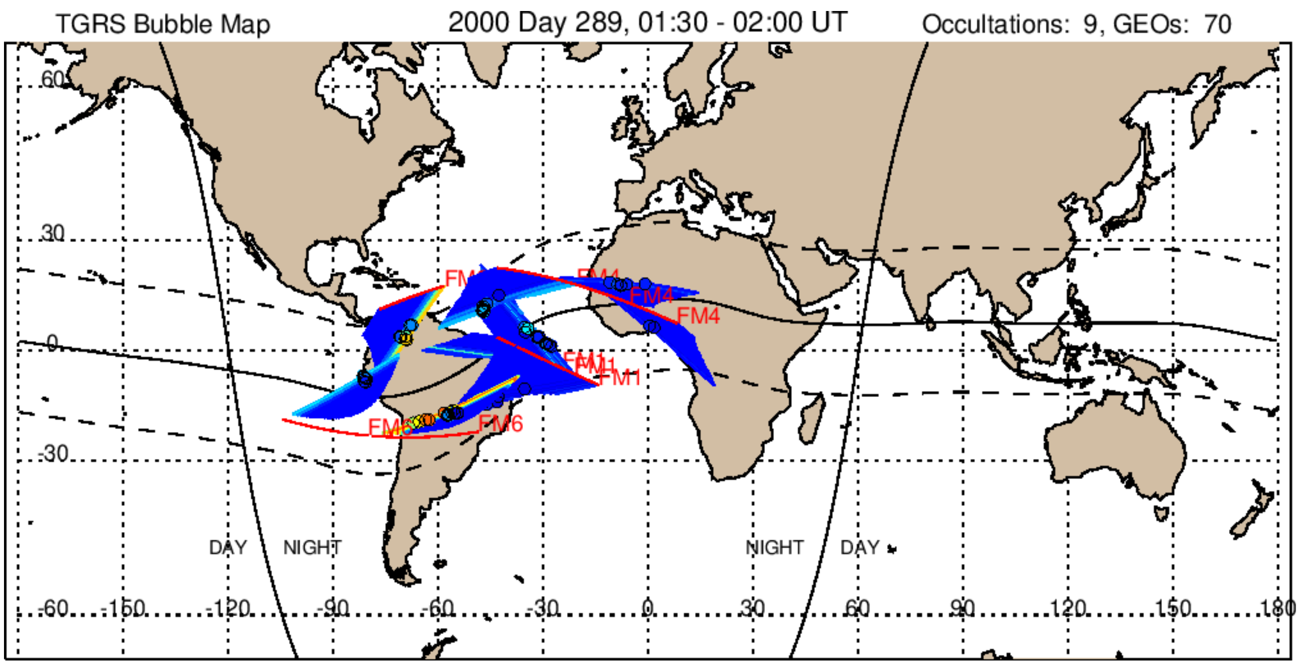
Error (deg)	Samples	%
All	1138	100
< 5	1105	97
< 2	1030	91
< 1	968	85
0	817	71

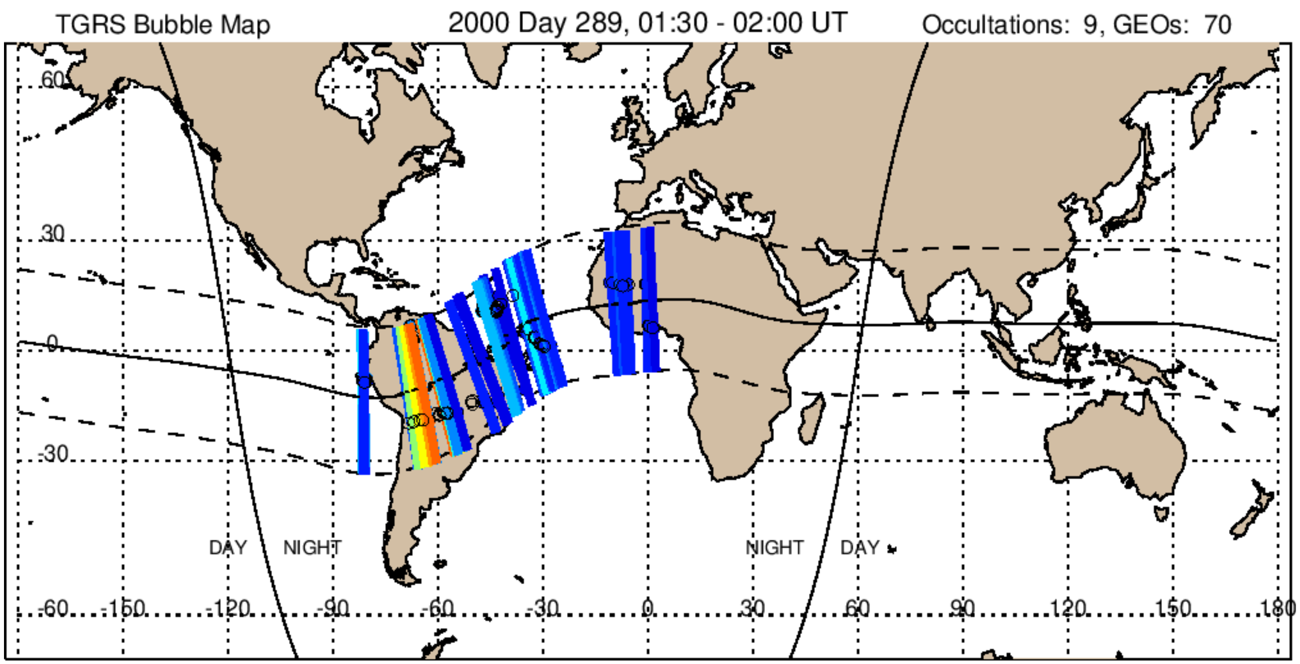
- Validation of > 3000 TGRS geolocations using SCINDA VHF measurements produced rms errors of less than 1° in longitude (~100 km) at each site.

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

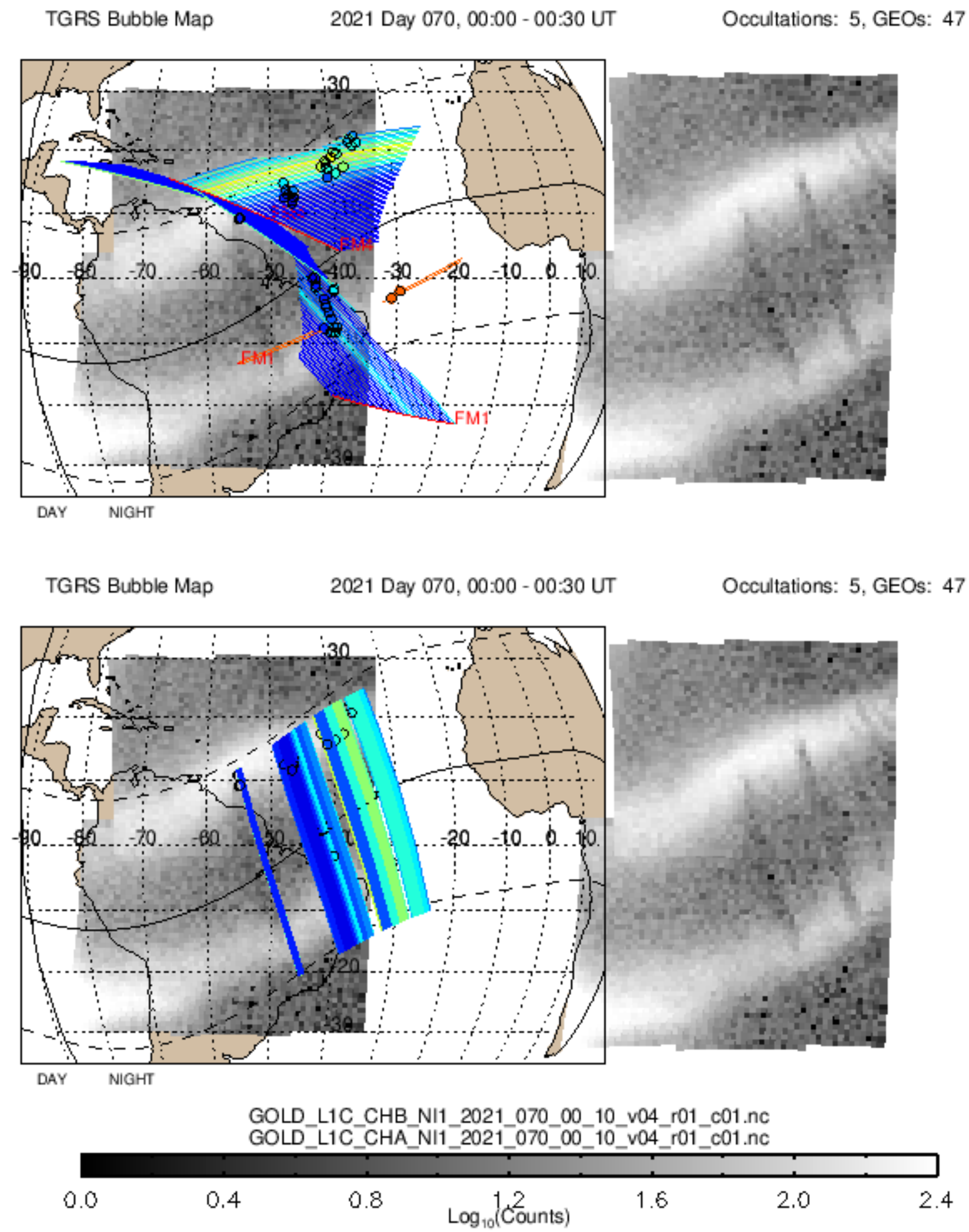
- We are currently developing tools to visualize the global distribution of TGRS bubble geolocations.
- A separate "limb-to-disk" model extracts quantitative estimates of CkL from the RO S4, and then predicts S4 at other frequencies.
- COSMIC-2 provides coverage over land and sea; as we refine the methods and RO satellites increase in number this technique will enable continuous global monitoring of low latitude irregularity formation and associated scintillation activity





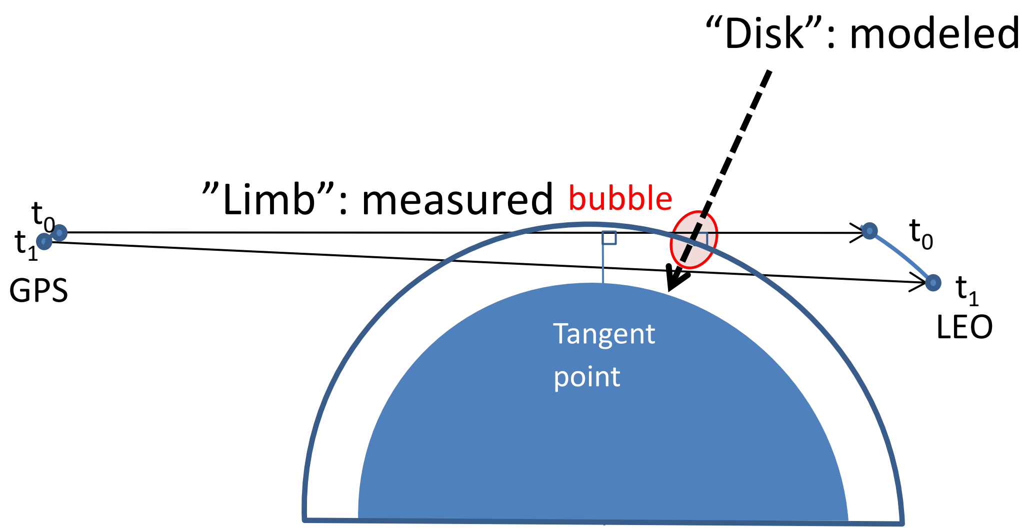
Validating Bubble Maps with GOLD UV Imagery

- Gold imagery to the right with bubbles inferred from RO data
- Three clear depletions (bubbles) visible in the GOLD image
- The RO observations tagged each bubble, but many details are difficult to infer (e.g., width, meridional extent, strength of irregularities)
- Hundreds of such images have been manually reviewed to validate the algorithm

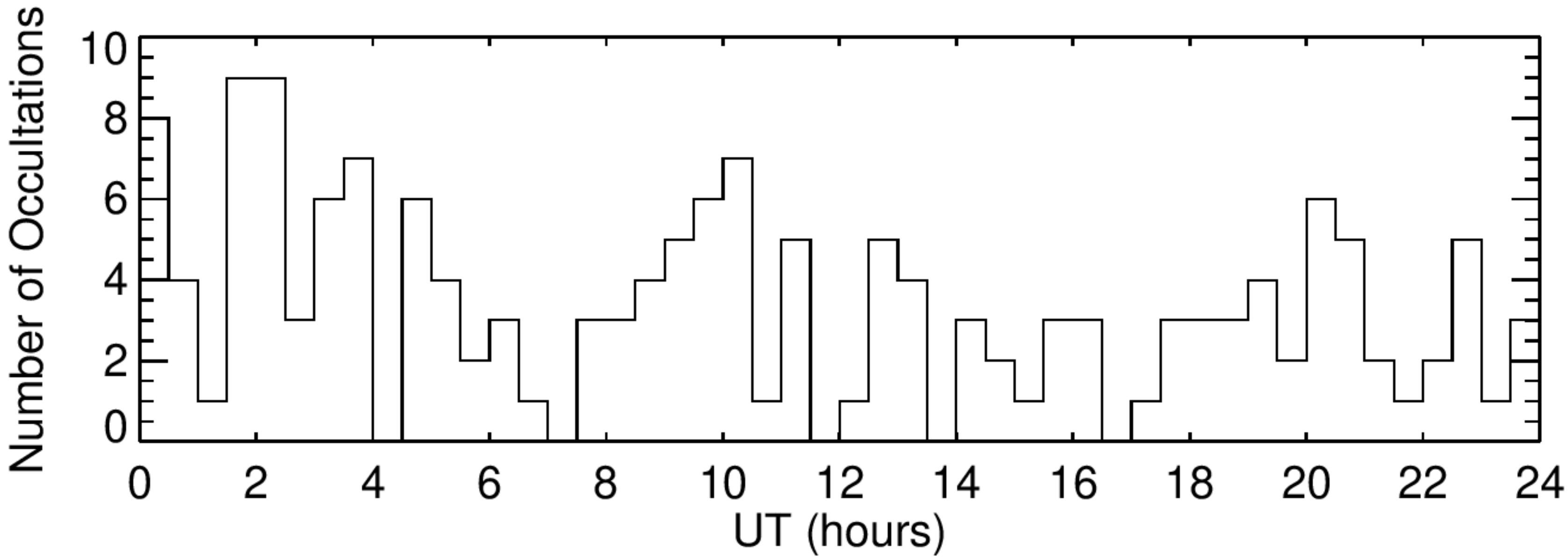


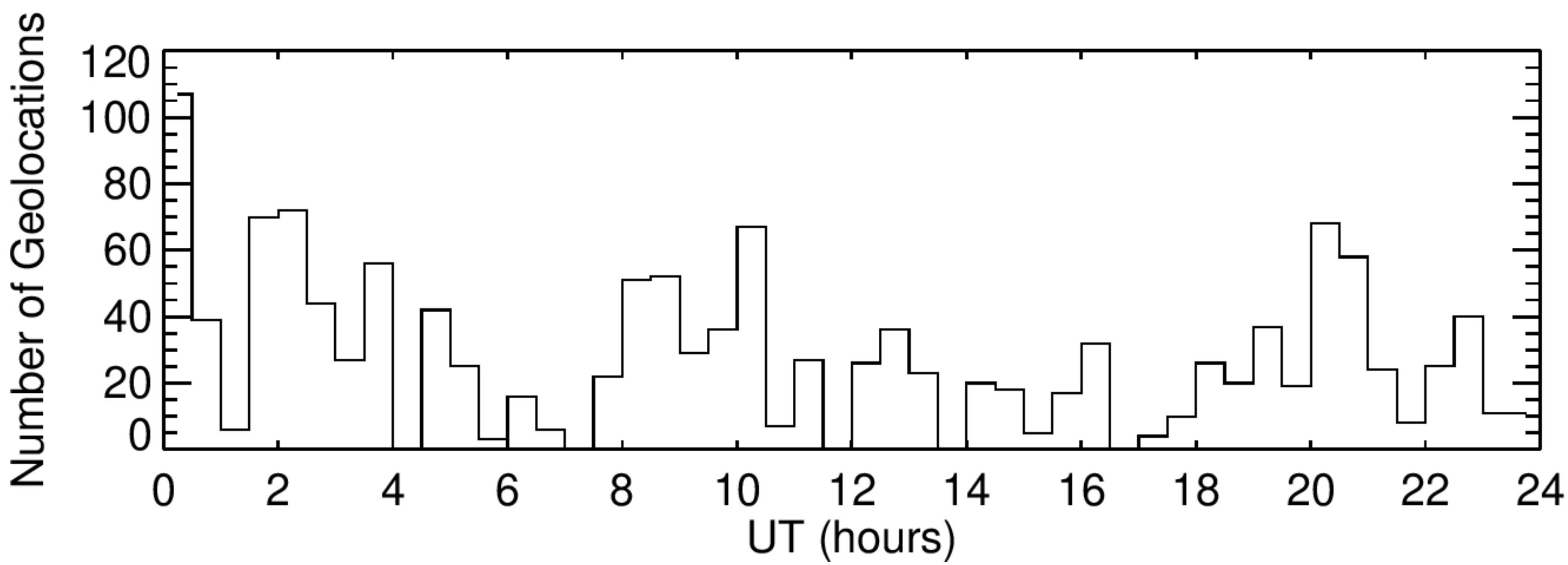
Estimating Irregularity Strength

- Now that we know where the irregularities are located, we would like to estimate their strength so we can model propagation effects from an overhead geometry relevant to GNSS users on the earth's surface.
- We call this the "limb-to-disk" (L2D)problem; we measure in the limb geometry but need to specify the disk geometry to provide relevant information to users
- The total irregularity strength is measured on the horizontal limb geometry, but that does not specify what a signal from overhead will encounter
- Parameters like the width of the bubble and the vertical structure of the irregularities are unknown; the problem is severely underconstrained and the requisite information cannot be wholly inferred from RO data alone
- This is a topic of active research and we are currently exploring a number of options to address the problem, including attempts to estimate bubble width from RO data



COSMIC-2 Coverage on a Typical Day





Summary

- Radio occultations provide a potentially powerful capability to monitor ionospheric irregularities globally over land and sea
- The geolocation of the irregularities requires relatively high rate data (~50 Hz or greater) to apply complex propagation theory to localize the source region
- This technique has been demonstrated successfully with real RO data from COSMIC-2
- GOLD comparisons with more than 1000 geolocations indicate that 90% of the locations are accurate to within 2° longitude (~200 km); considering path lengths of 3500-5000 km, this is an achievement
- The problem of specifying scintillation values for an overhead geometry (L2D) remains under investigation; longer slant paths for RO geometries enhance scintillation effects relative to overhead propagation through a thin ionospheric slab (~ 100 km)
- The expectation of an increasing number of RO satellites suggest that the future for this concept is bright, with continuous real-time data streams providing continuous coverage over the entire planet

References

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