The Use of GNSS-Aircraft Links to Detect/Diagnose Atmospheric Turbulence

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The Motivation

- Turbulence is the main cause of in-flight injuries – for both passengers and flight attendants.
- After a severe encounter, the airline has to perform a structural check on the aircraft.
- Pilots will try to re-route around an area if there have been reports of moderate or greater turbulence.

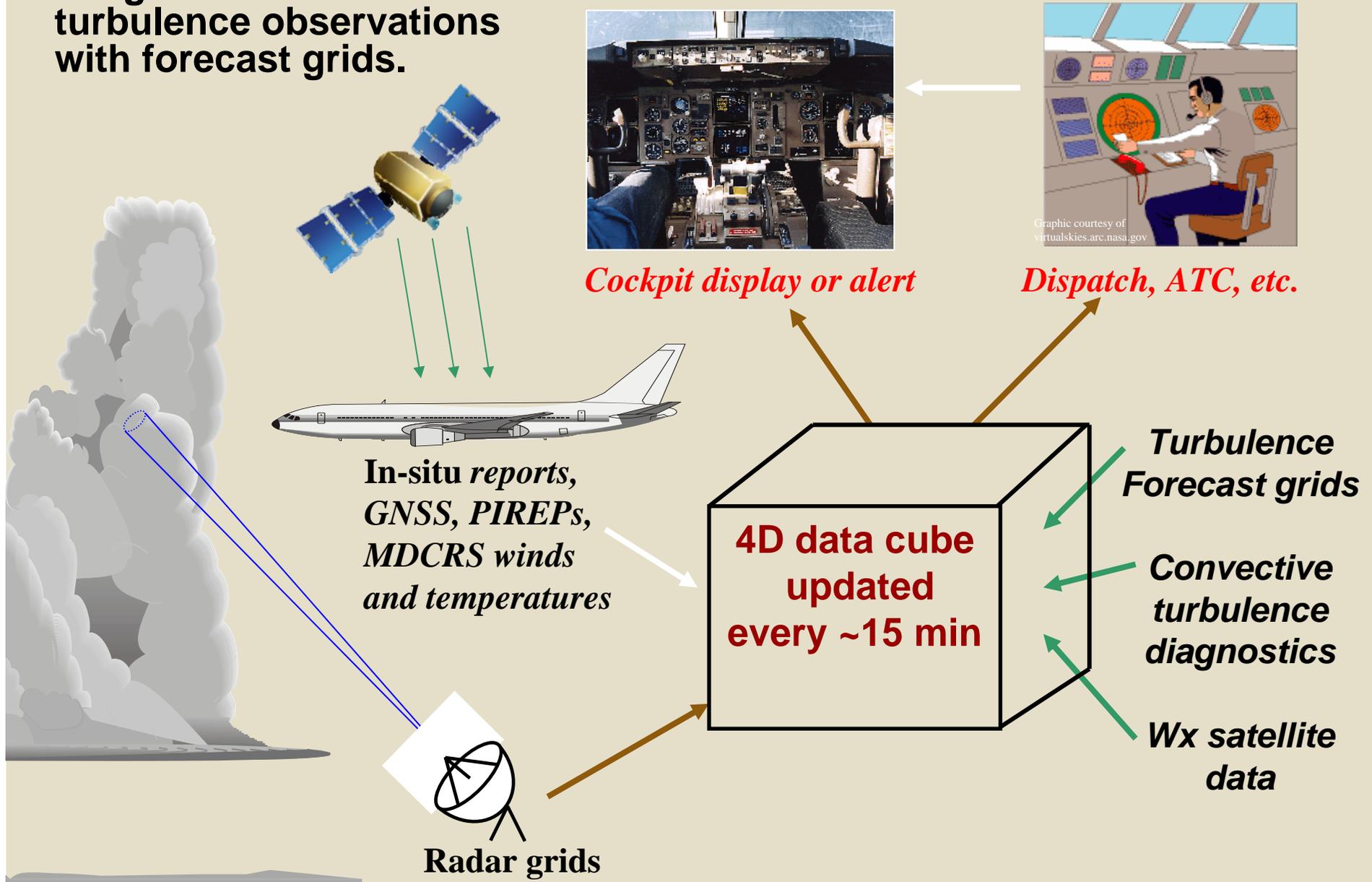Bottom-line: Turbulence is a safety problem as well as having a large financial impact on the airlines.
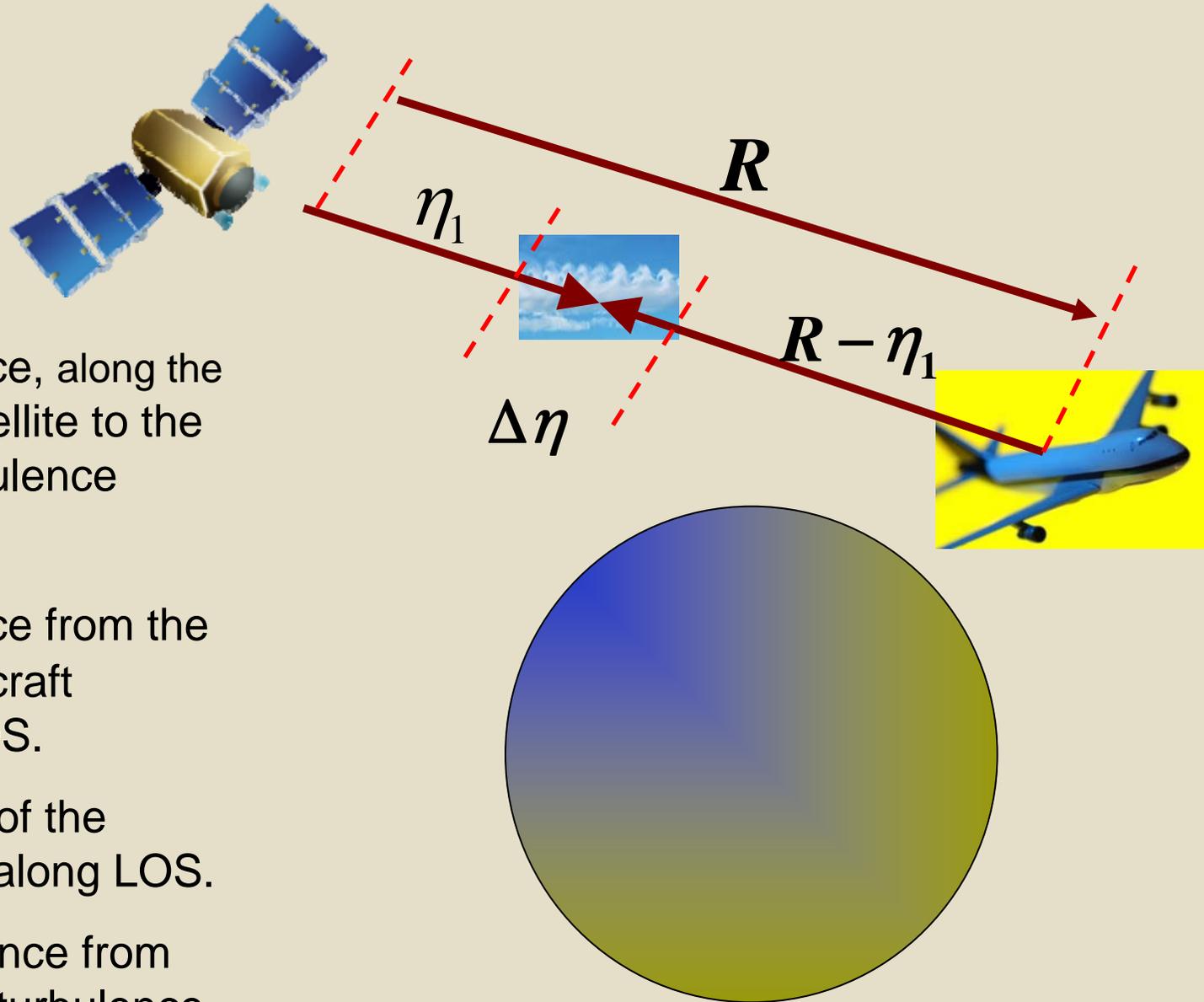
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The Concept

- Airborne receivers would be a platform of opportunity to collect occultations in the cruise regime of commercial aviation, e.g., 20-40 kft. AGL.

- The turbulence measurements from these occultations would probably not be used as stand-alone information, but integrated into operational nowcast/forecast products.

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Turbulence Nowcasting/Forecasting System:

Merges all current turbulence observations with forecast grids.

Cockpit display or alert

Graphic courtesy of
virtualskies.arc.nasa.gov

Dispatch, ATC, etc.

In-situ *reports, GNSS, PIREPs, MDCRS winds and temperatures*

4D data cube updated every ~15 min

Turbulence Forecast grids

Convective turbulence diagnostics

Wx satellite data

Radar grids

Geometry of the Problem

η_1 is the distance, along the LOS, from the satellite to the center of the turbulence patch.

R is the distance from the satellite to the aircraft receiver along LOS.

$\Delta\eta$ is the width of the turbulence patch along LOS.

$R - \eta_1$ is the distance from the aircraft to the turbulence patch.

R

η_1

$R - \eta_1$

$\Delta\eta$

Theory (Condensed Version)

- Use standard weak scattering wave propagation theory - modified to accommodate moving transmitter and receiver, and localized turbulence patch.

- Log-amplitude frequency spectrum for a turbulence patch in the neutral atmosphere at η_1 and width $\Delta\eta$ is functionally given by:

$$\Phi_\chi(f) = C \int_{\eta_1-\Delta\eta/2}^{\eta_1+\Delta\eta/2} F\left[C_n^2(\eta), V_{eff}(\eta), L_0, R, k, f; \eta\right] d\eta$$

- Where k is the transmitter wavenumber, L_0 is the turbulence length scale, $C_n^2(\eta)$ is the turbulence intensity, and $V_{eff}(\eta)$ is an effective velocity.

Analysis

- The objective is to determine where the turbulence is along the LOS, η_1 , and what the intensity $C_n^2(\eta_1)$, is at that location.

- Note that the comparable expression for turbulence in the ionosphere is given by a different constant and a change in the wavenumber functionality k^2 to k^{-2}.

In the following, a mid-point approximation to the integral was used.
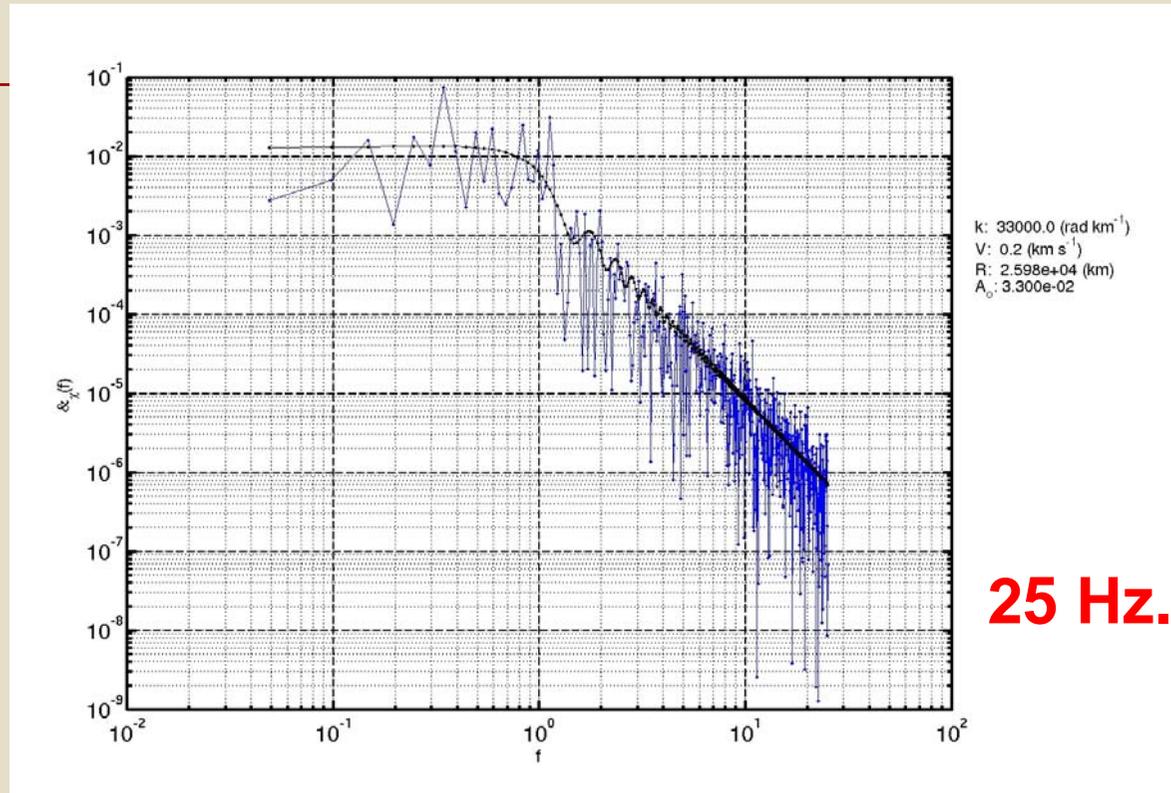
Example Spectra (constant intensity)
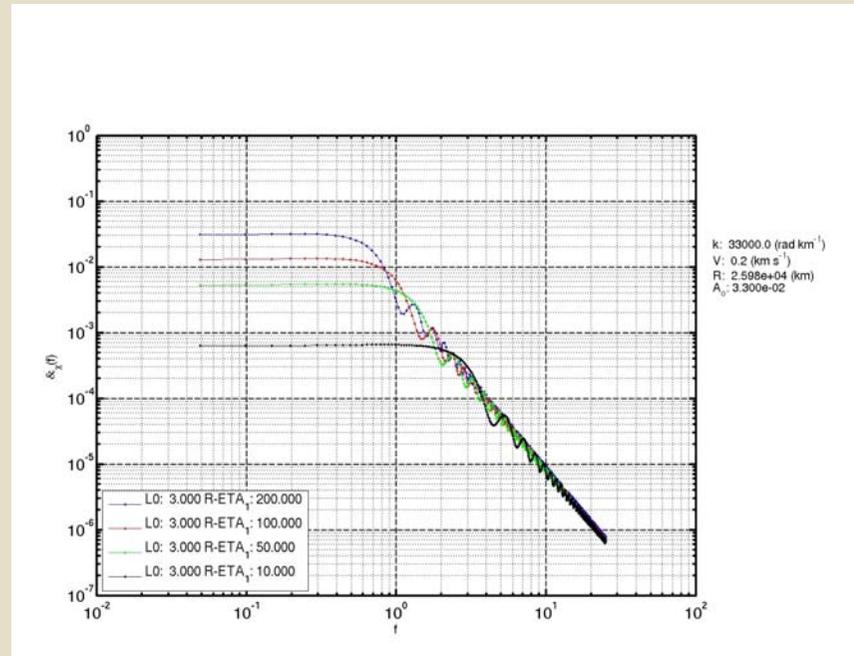
Holding $L_0 = 3\,km$ fixed and varying $R - \eta_1$.
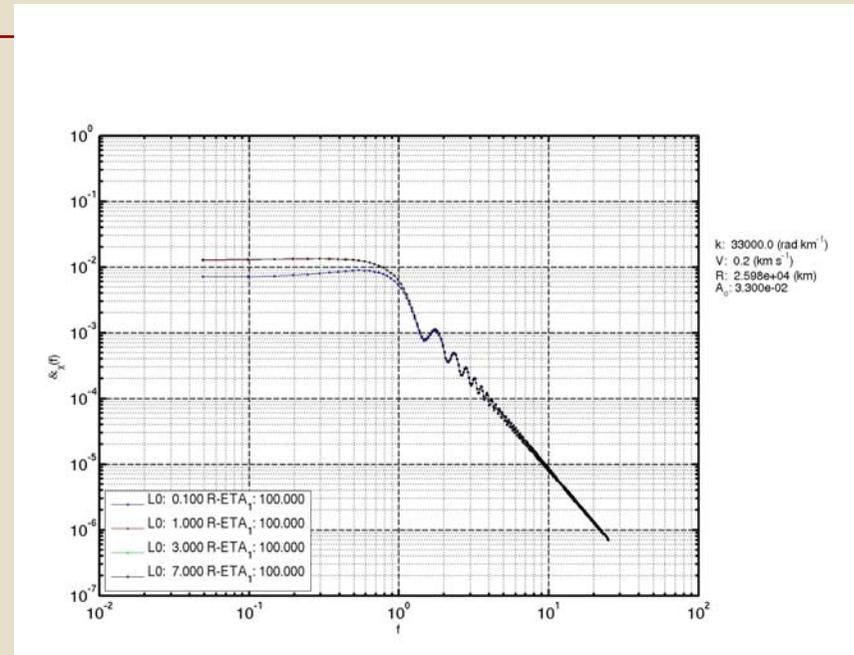
Holding $R - \eta_1 = 100\,km$ fixed and varying L_0 .
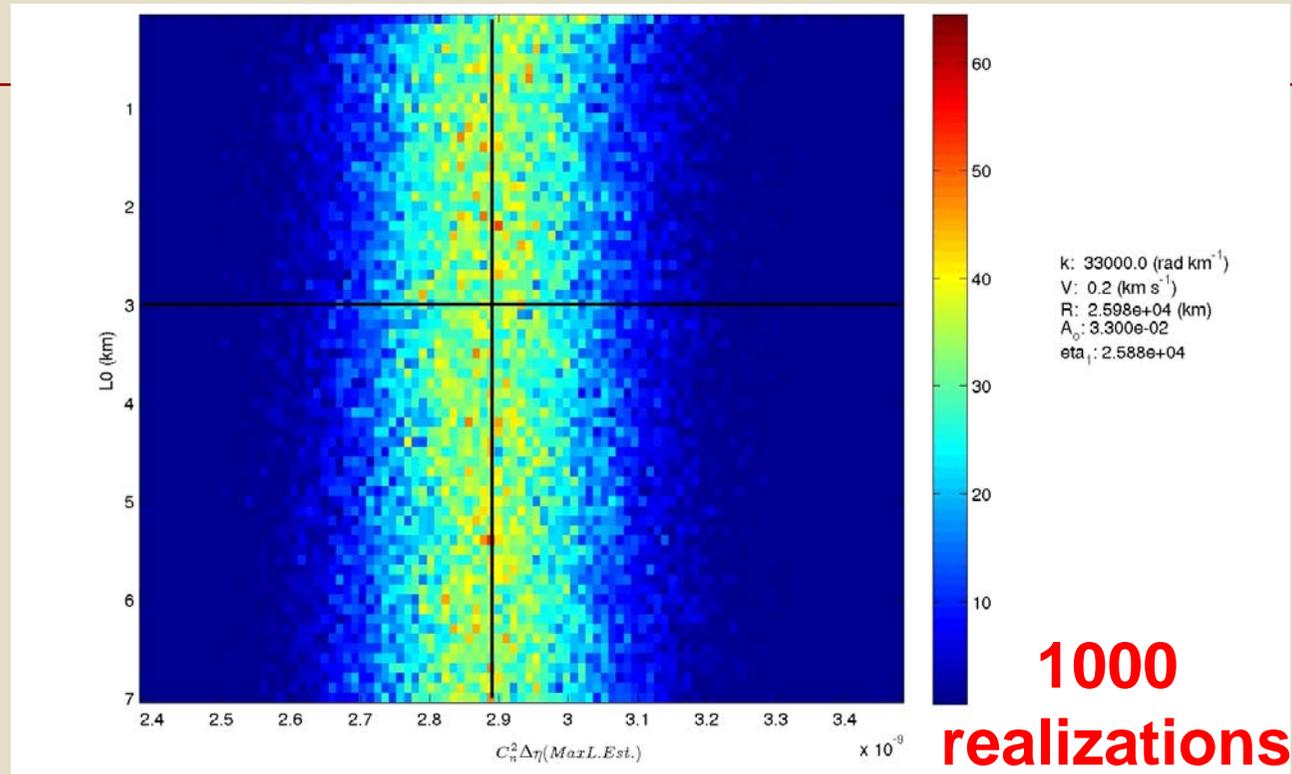
Note strong functionality on $R - \eta_1$ and weak on L_0 .

Spectral Simulation

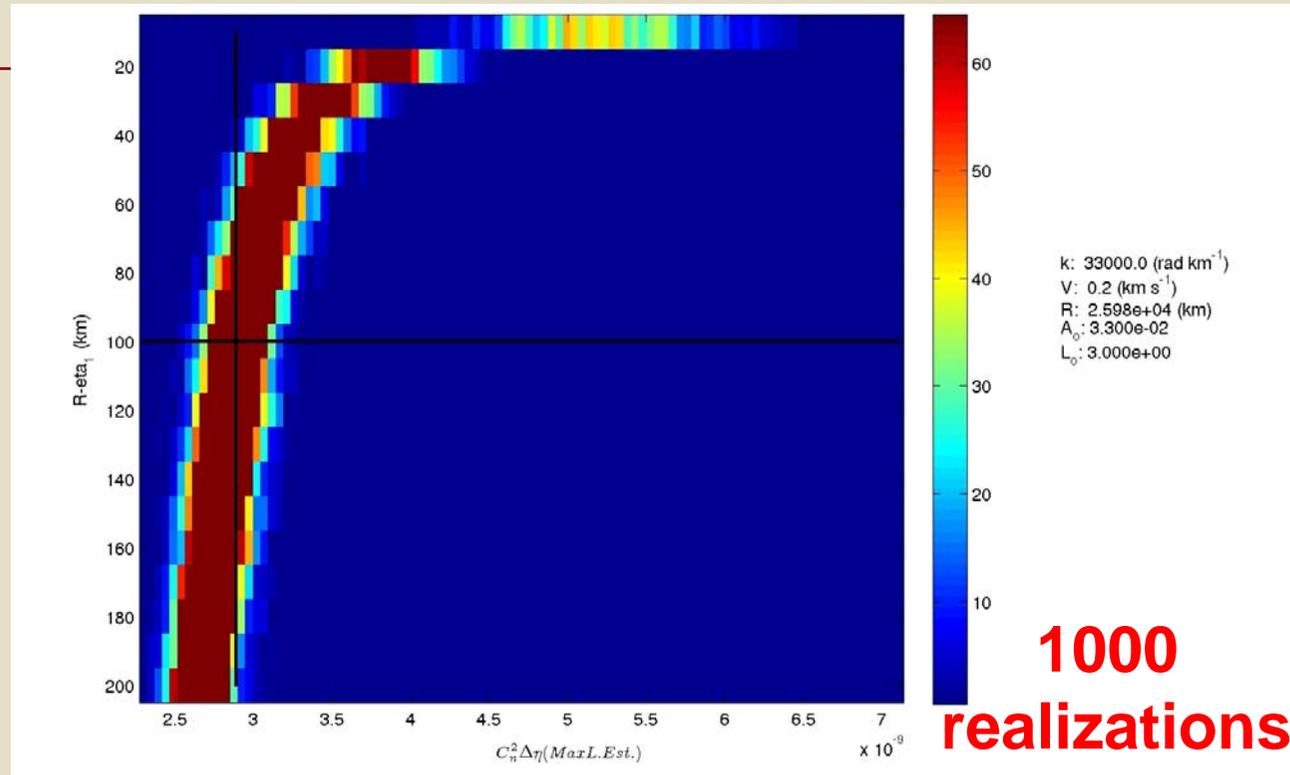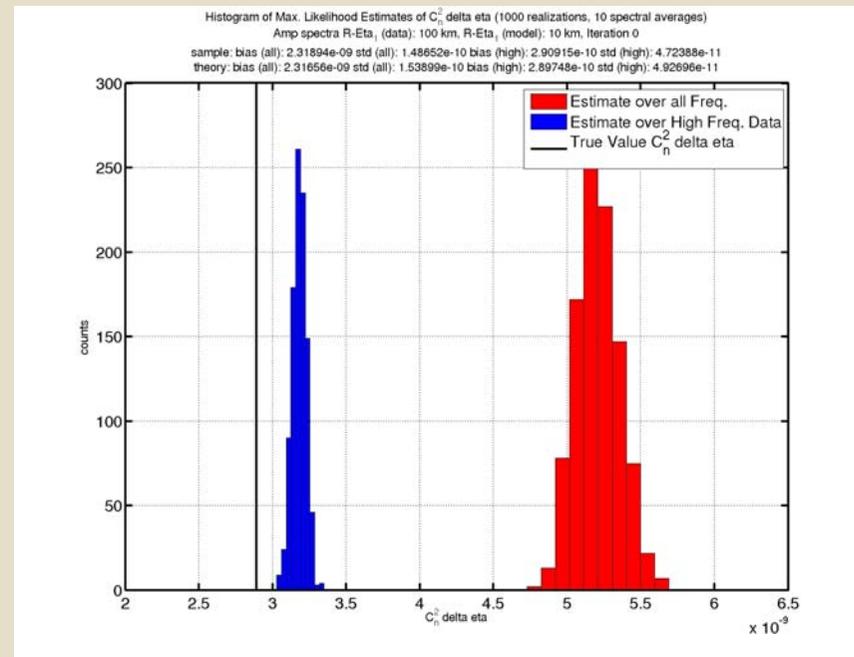**Log-Amplitude Spectrum: theory and simulated.**
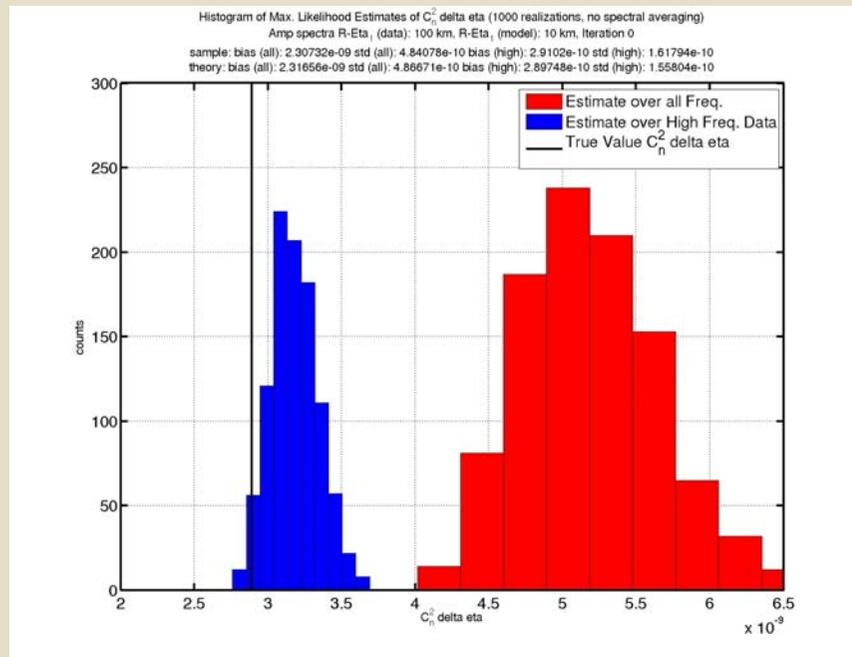
Parameter Estimation

1000 realizations

Maximum Likelihood (ML) estimation of intensity with fixed $R - \eta_1 = 100\,km$ while varying L_0. Horizontal and vertical lines are simulated (i.e., "true") values.
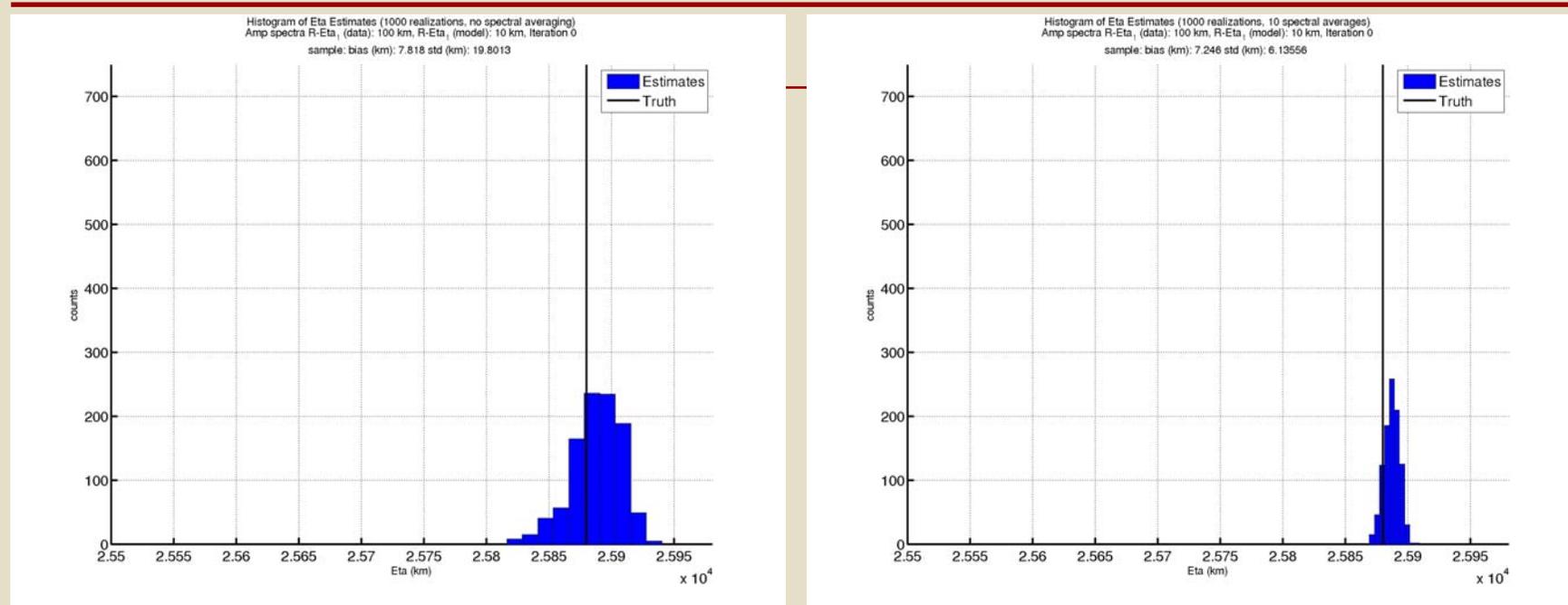
Parameter Estimation (cont'd)

ML estimation of intensity with fixed $L_0 = 3\,km$
**while varying** $R - \eta_1$.

- **ML estimation of intensity for un-averaged spectra (left) and 10 spectral averages (right).**

- **Solid vertical line is true value.**

- **Blue values are from using the high-frequency portion of the spectrum, red values use all the spectral points.**

- **Simulated $R - \eta_1$ value is 100 km, "guess" is 10 km - i.e., _underestimate_.**

Iterative Parameter Estimation

Estimation of η_1 by minimization method. Un-averaged spectra (left) and 10 spectral averages (right).

Iterative Parameter Estimation
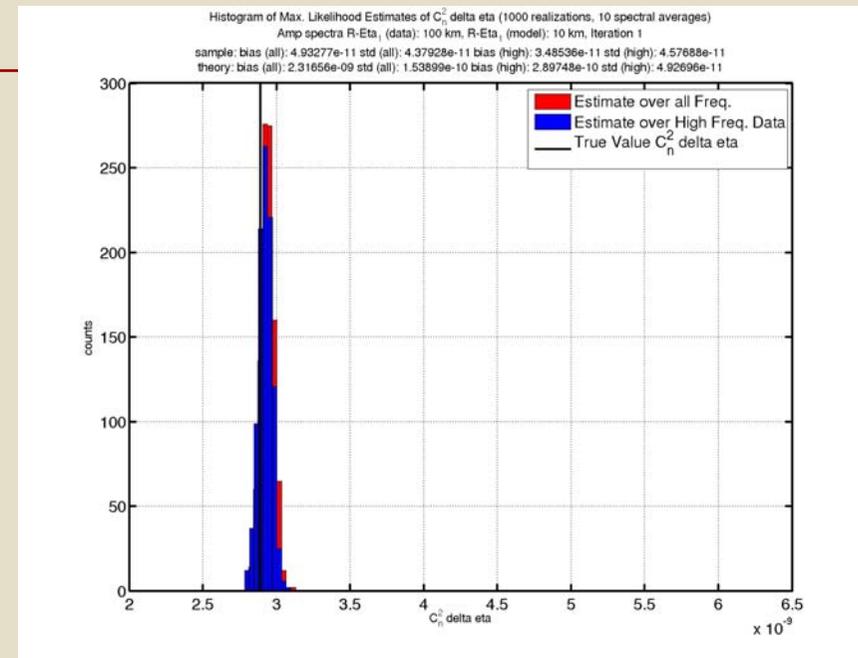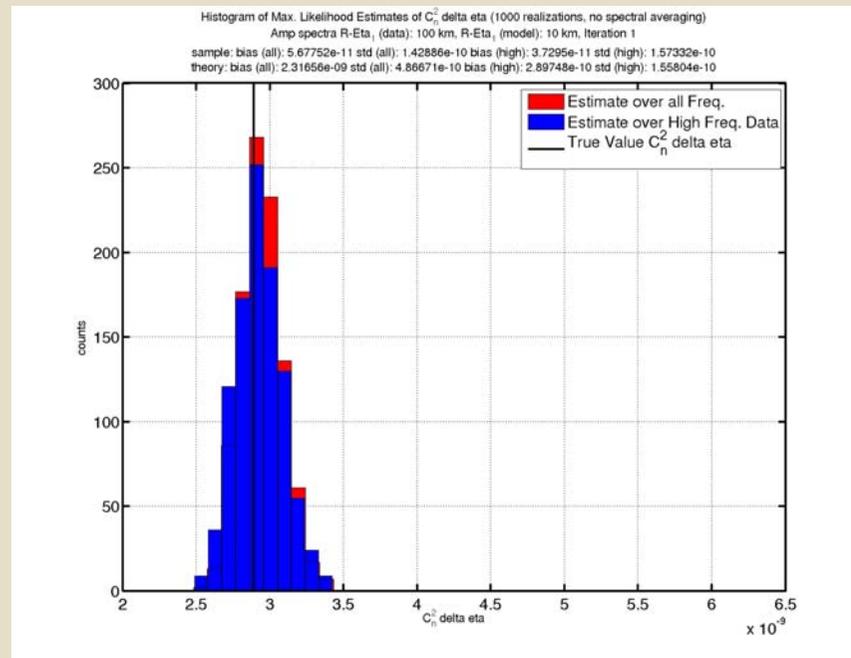
ML estimation of intensity after using η_1 estimates. Un-averaged spectra (left) and 10 spectral averages (right).

Conclusion

- Wave propagation theory, adapted to this problem, has been developed.

- These techniques can be used for any moving transmitter/receiver pair (e.g. LEO-LEO), as well as for the neutral atmosphere and the ionosphere.

- For mid-point approximation, it has been shown that estimates of turbulence intensity and patch location can be made.

Future Work

- Mid-point approximation may not be accurate at higher frequencies.

- Break up integral into intervals small enough so that the mid-point approximation is valid.

- Use 1-D (or maybe 2-D) tomography to estimate turbulence position and intensity.

- Analyze multiple patches along the LOS.

- Analyze real data.