Effects of Tropospheric Spatio-Temporal Correlated Errors on the Analysis of Space Geodetic Data

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March 6, 2012

Motivation

- VLBI error budget (becoming less Gaussian dominated).
- Reduction of thermal errors will require modeling of correlated noise sources.
- Troposphere errors have correlations in both space and time.
  - Kolmogorov frozen flow model.
  - Modeling delay errors Treuhaft & Lanyi (Radio Sci. 1987)
  - Water vapor radiometer (WVR) measurements.
- Instrumental errors introduce station specific temporal correlations.

Thermal Errors

Recording Rate	Improve	
128 Mb/sec	-	Last 10 years
256 Mb/sec	1.4	Recent RDV runs
512 Mb/sec	2	VLBA continuum
2 Gb/sec	4	Mark 5C (R&D fringes)
4 Gb/sec	5.7	Mark 5C dual bank
16-32 Gb/sec	11.3-16	Haystack Mark 6

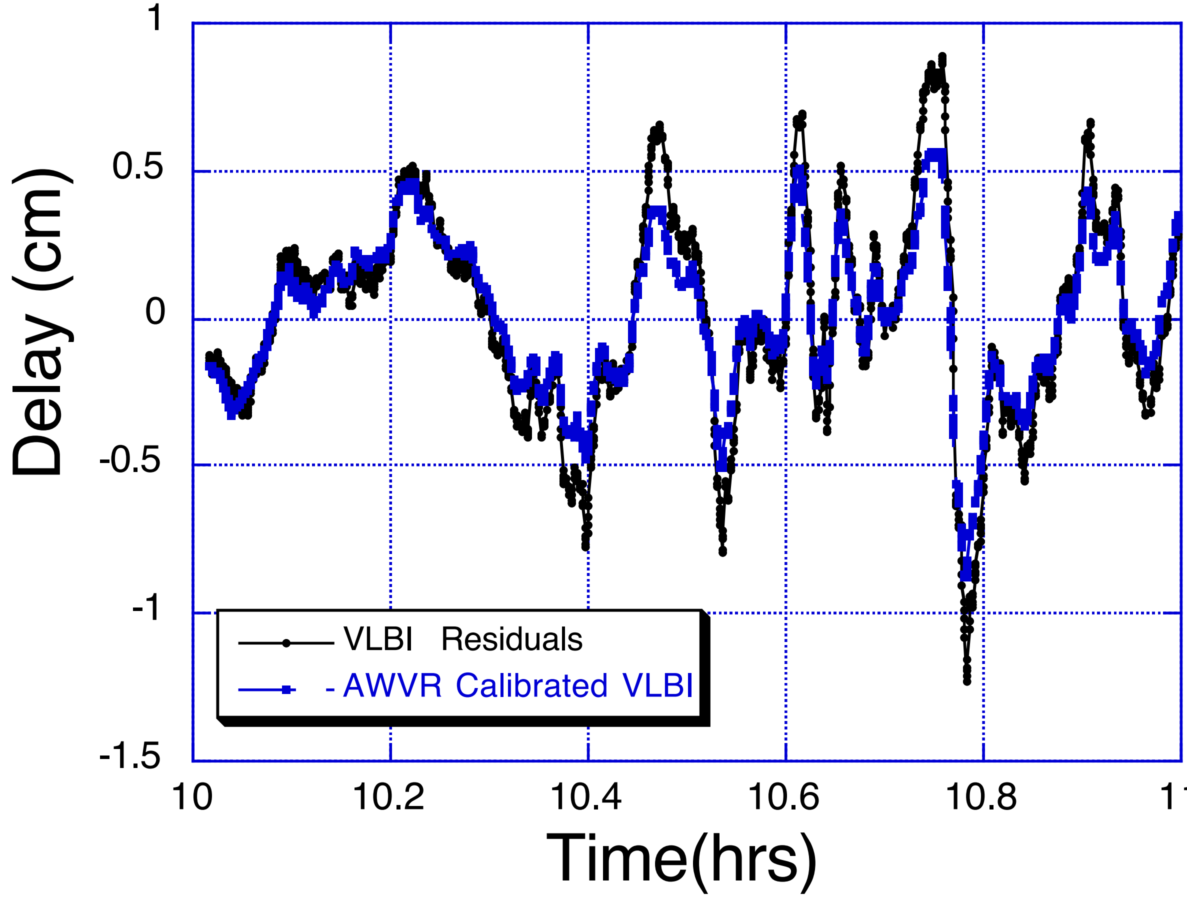
Data rates are sky-rocketing.
Factors of 10 improvement in the near future.

Future: Trop. Turbulence Dominates

- Monitor 22 GHz/1.3cm water (rotational) line brightness temperature along line-of-sight.
- 3mm scatter reduced to 1mm Goldstone-Madrid 8000 km baseline using X/Ka phase delays.
- As thermal errors average down, the troposphere fluctuations dominate the residuals.

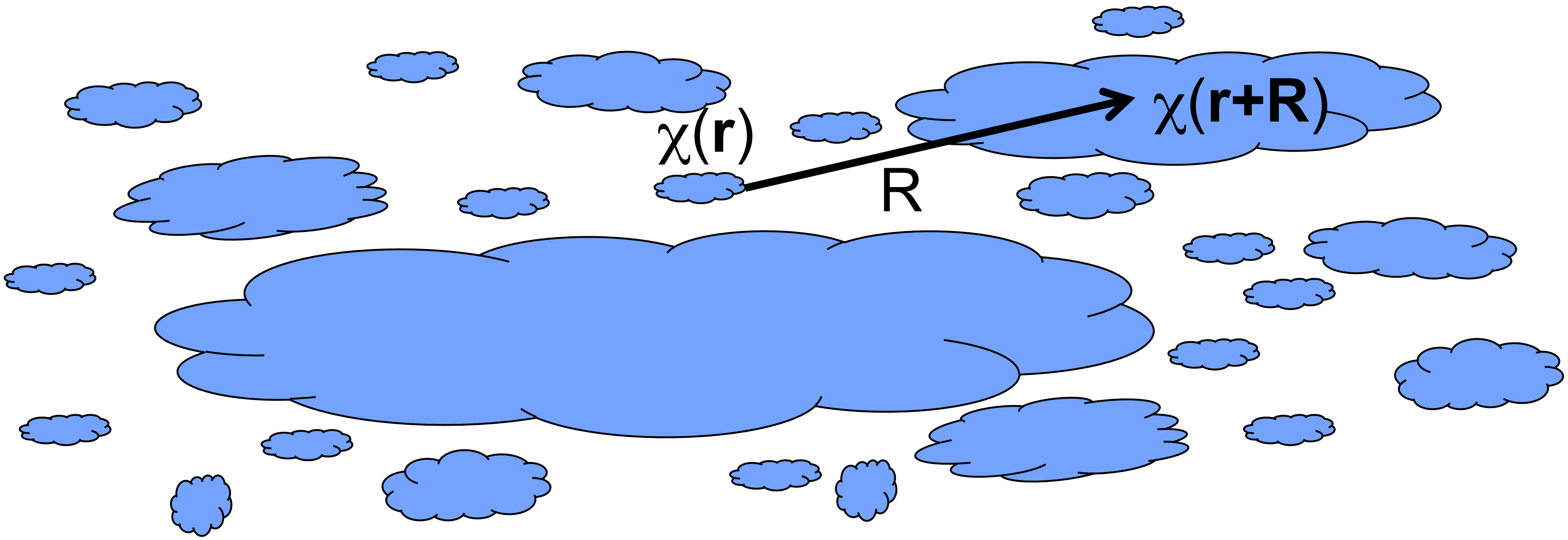
Measured with the JPL Advanced Water Vapor Radiometer

VLBI Delay Residuals DOY 200
Ka-Band DSS26-DSS55



Jacobs et al, AAS Winter 2005.
Bar Sever et al , IEEE, 2007.

Kolmogorov Theory of Turbulence



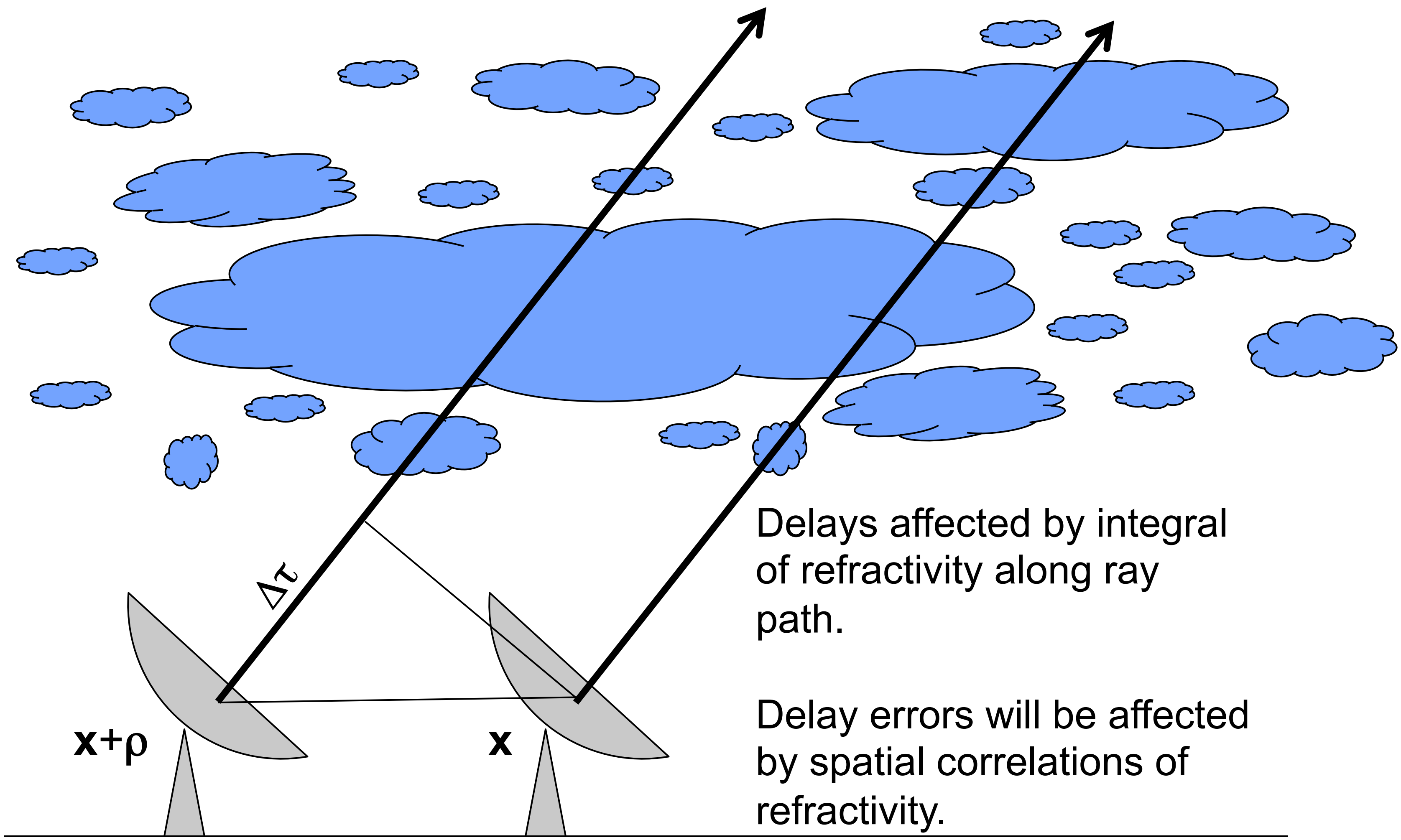
Structure function of refractivity (Tatarskii,1961)
Based on Kolmogorov turbulence.

$$D_{\chi}(R) = C^2 R^{2/3}$$

Structure function contains information statistical scatter and covariance.

Constant related to rate of energy dissipation and viscosity.

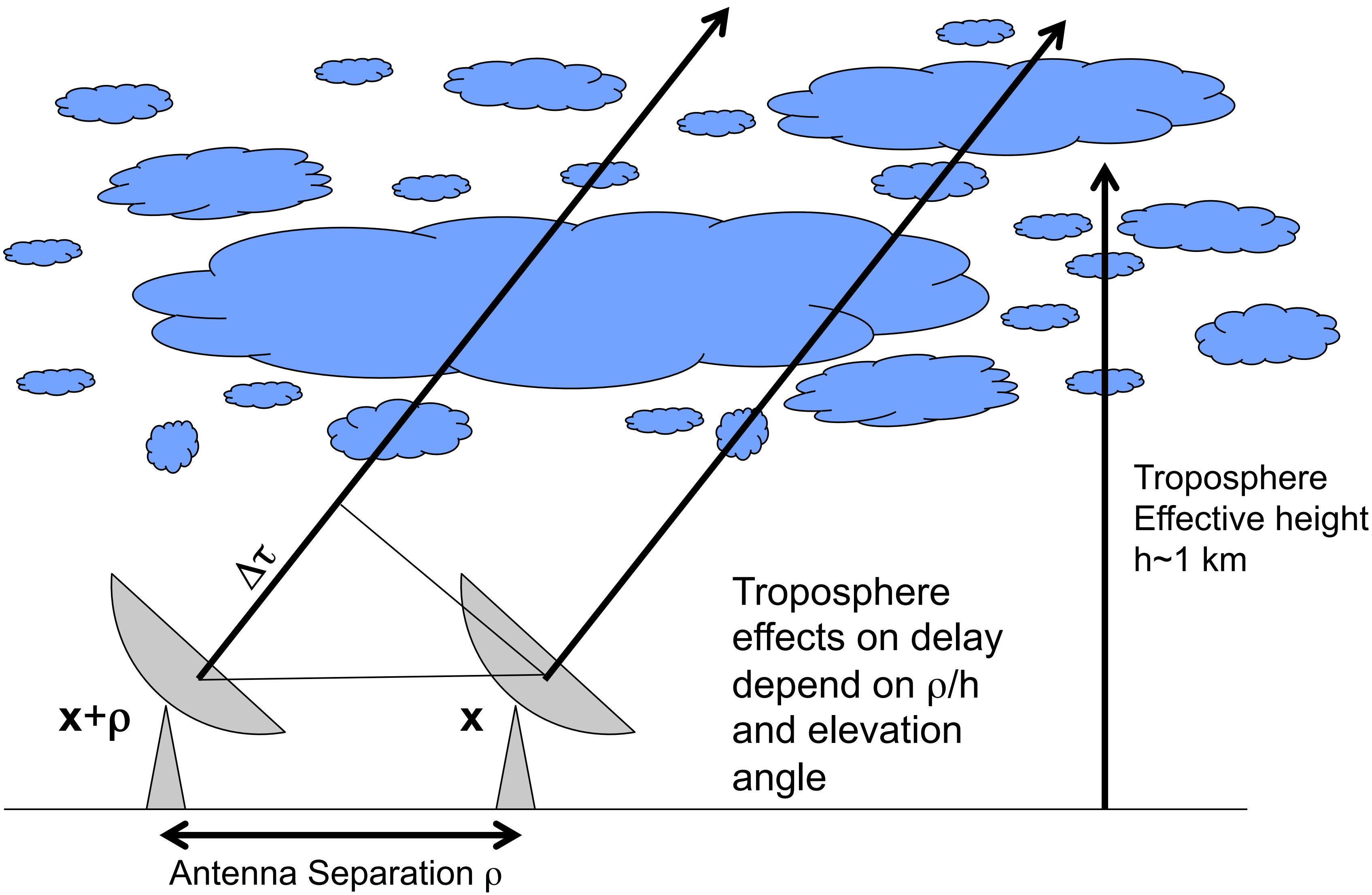
Spatial Correlations on Delay Errors



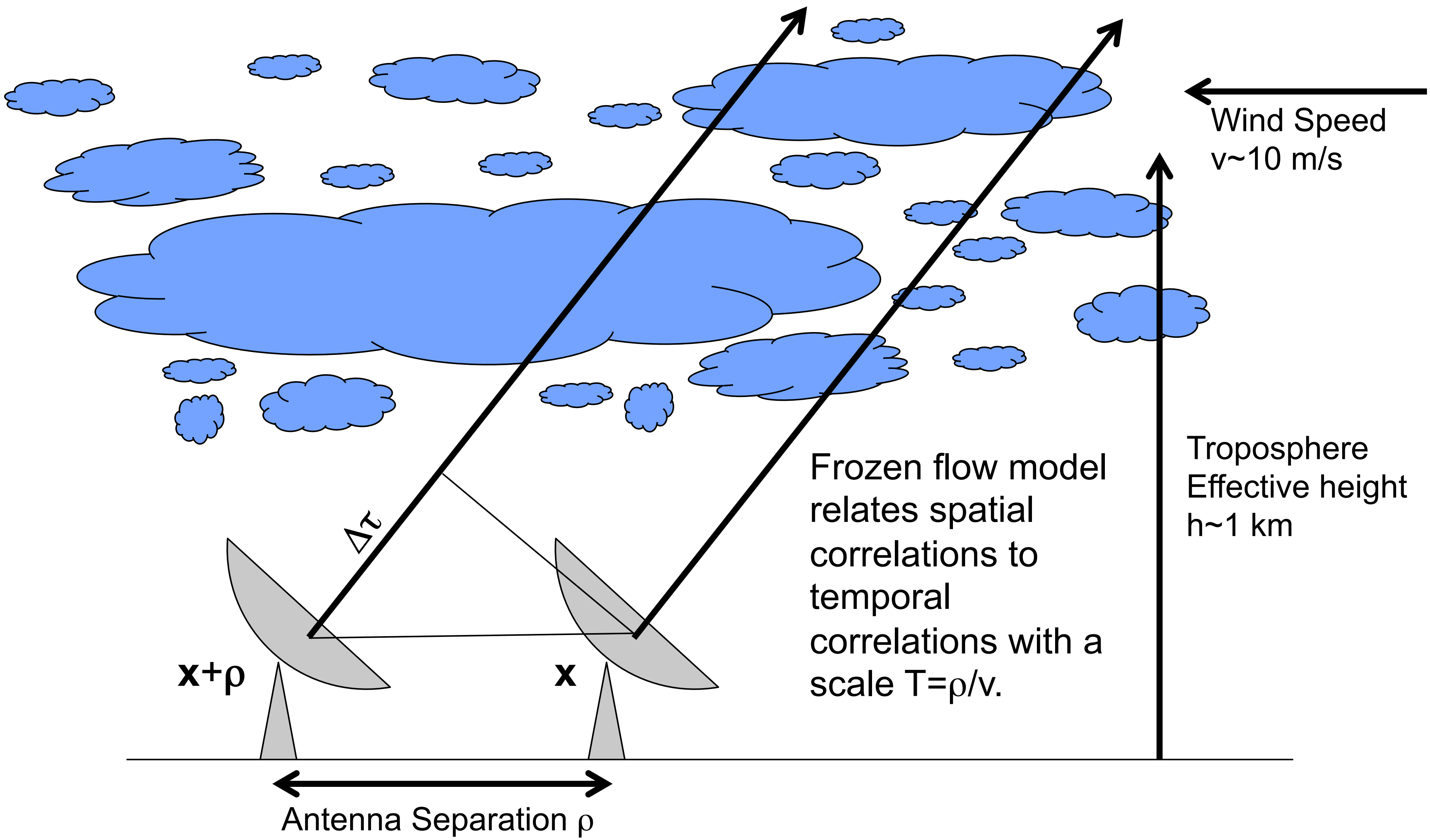
Delays affected by integral of refractivity along ray path.

Delay errors will be affected by spatial correlations of refractivity.

Tropospheric Effects on Delays



Temporal Correlations on Delay



Frozen flow model relates spatial correlations to temporal correlations with a scale T=ρ/v.

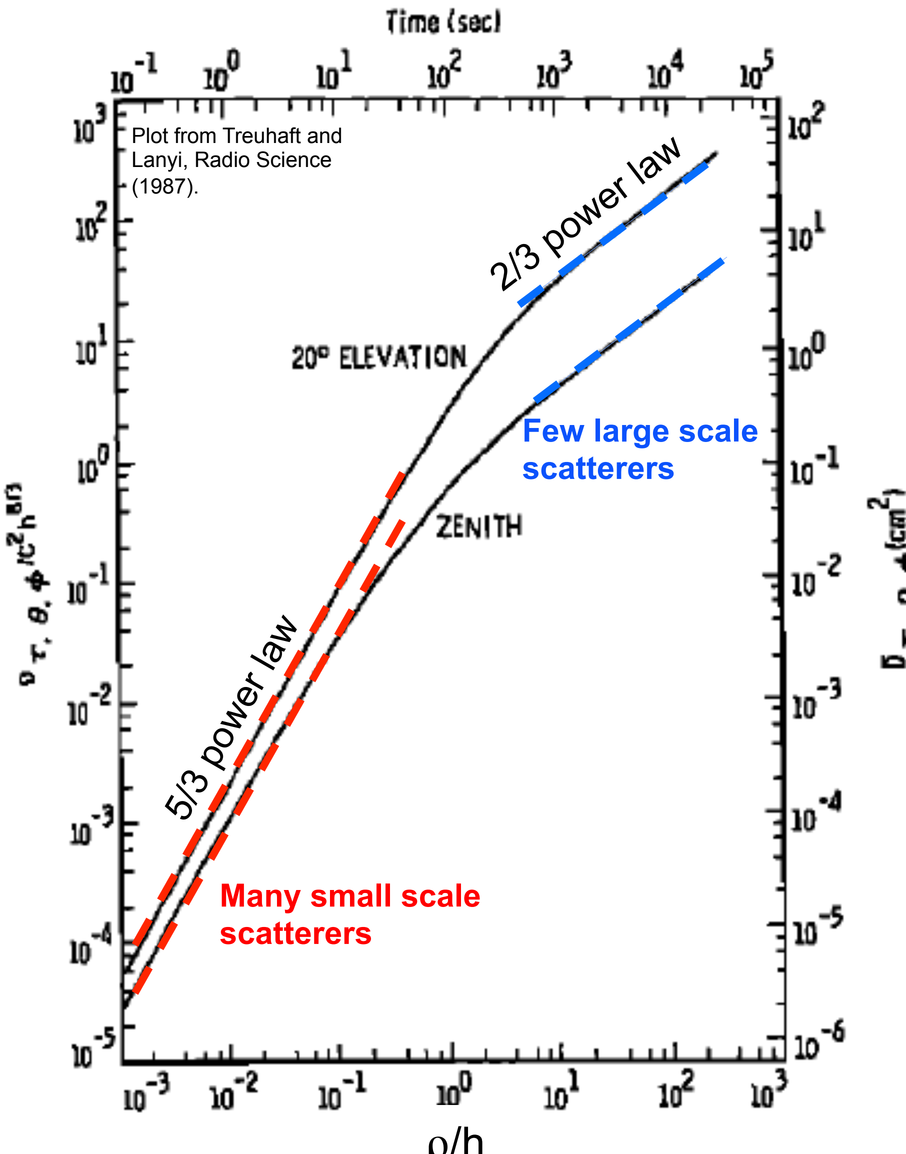
Tropospheric Effects on Delays

Delay structure function
$D_\tau(\rho) = \langle (\tau(\mathbf{x}+\rho) - \tau(\mathbf{x}))^2 \rangle$
takes in refractivity variations via the media effects on the delay.

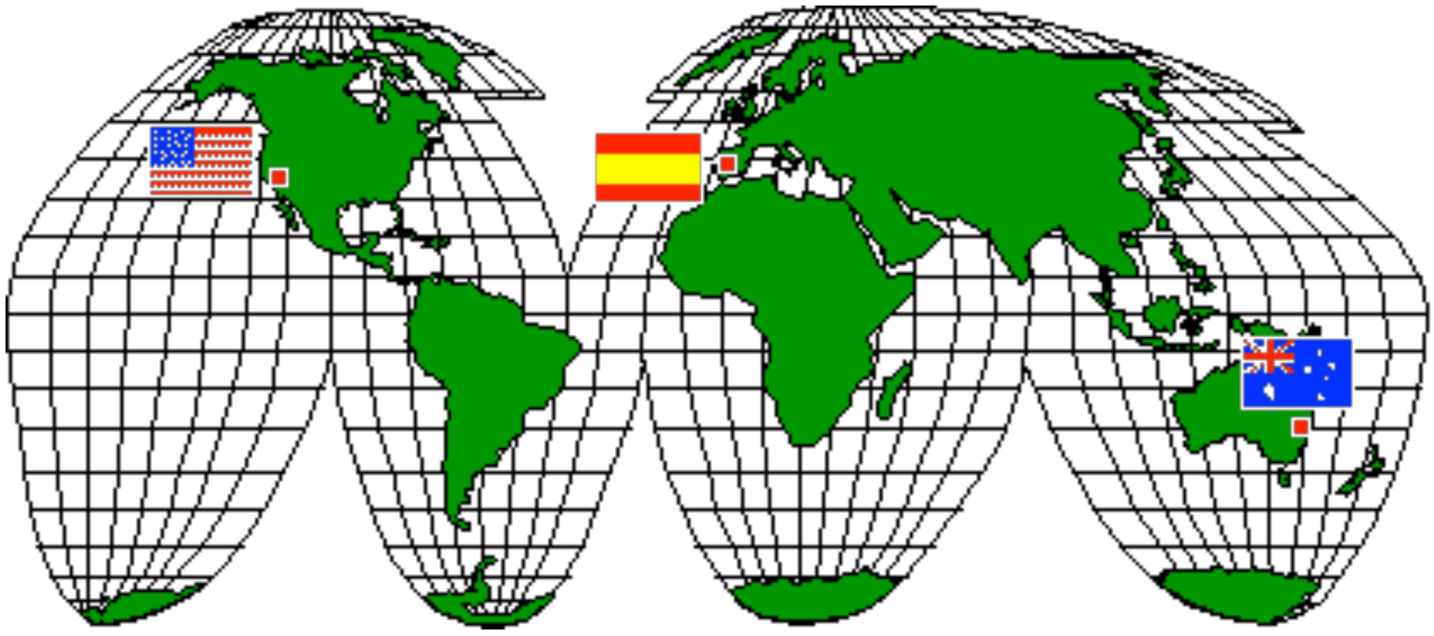
Delay error correlations depend on the ratio of antenna distance to troposphere height (ρ/h) and elevation angle.

Broken power law with smooth switch over at
ρ/h ~ 1.

Correlations in space and time are derived from structure functions.



The NASA Deep Space Network



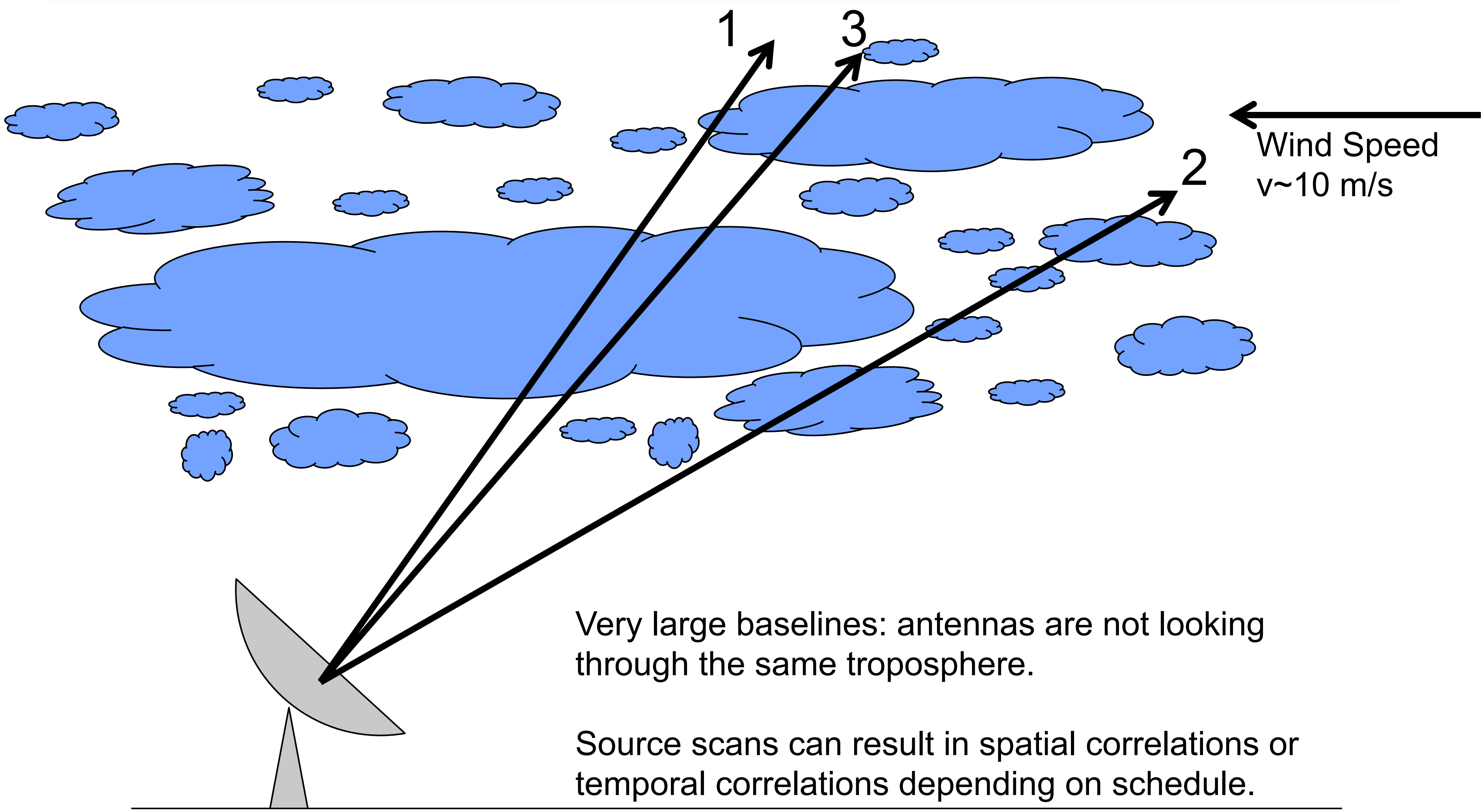
Credit: http://deepspace.jpl.nasa.gov/dsn/antennas/index.html

<u>VLBI Capabilities:</u>

California-Madrid:	8,400 km
California-Canberra:	10,500 km

X/Ka (34 m antennas)
S/X (34 m and 70 m antennas)

Single Site Spatio-Temporal Correlations



Very large baselines: antennas are not looking through the same troposphere.

Source scans can result in spatial correlations or temporal correlations depending on schedule.

Troposphere Covariance in X/Ka Catalog

X/Ka catalog effort determines celestial coordinates of radio sources, and baseline vectors between DSN stations, for use in spacecraft navigation.

Including trop. cov. in X/Ka catalog improves wRMS agreement with ICRF-2 by 7% (using the exact same data and exact same modeling).

A 7% improvement would take 14% more data to get the same result by pure averaging.

For X/Ka going into its 6th year that would mean almost another year of data to get the improvement we get from trop cov.

<u>wRMS in RA</u>
w/o Trop. Cov. : 215 μas
w/ Trop. Cov. : 198 μas

<u>wRMS in DEC</u>
w/o Trop. Cov. : 300 μas
w/ Trop. Cov. : 283 μas

<u>δDec vs. Dec slope</u>
w/o Trop. Cov. : 1.6 +/- 1.0 μas/deg
w/ Trop. Cov. : 1.1 +/- 0.9 μas/deg

TEMPO

Time and Earth Motion Precision Observations

Rapid turnaround VLBI measurements earth orientation.

Support of spacecraft navigation, which needs extremely timely and accurate earth rotation information.

Uses the California-Madrid baseline which is mostly East-West directed making it most sensitive to UT1-UTC measurements.

Analysis Comparison

Traditional:

a. Gaussian diagonal noise.

b. Elevation dependent weighting.

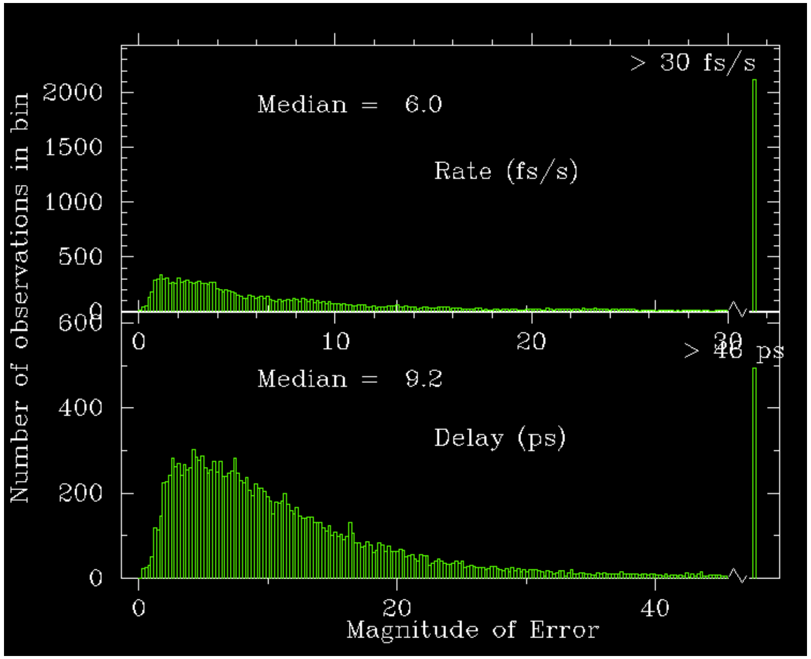
c. Troposphere parameter breaks.

Troposphere Covariance:

a. Correlated noise.

b. Spatio-temporal dependence.

c. Single troposphere estimate per site per session.



Thermal errors:

9.2 ps in delay

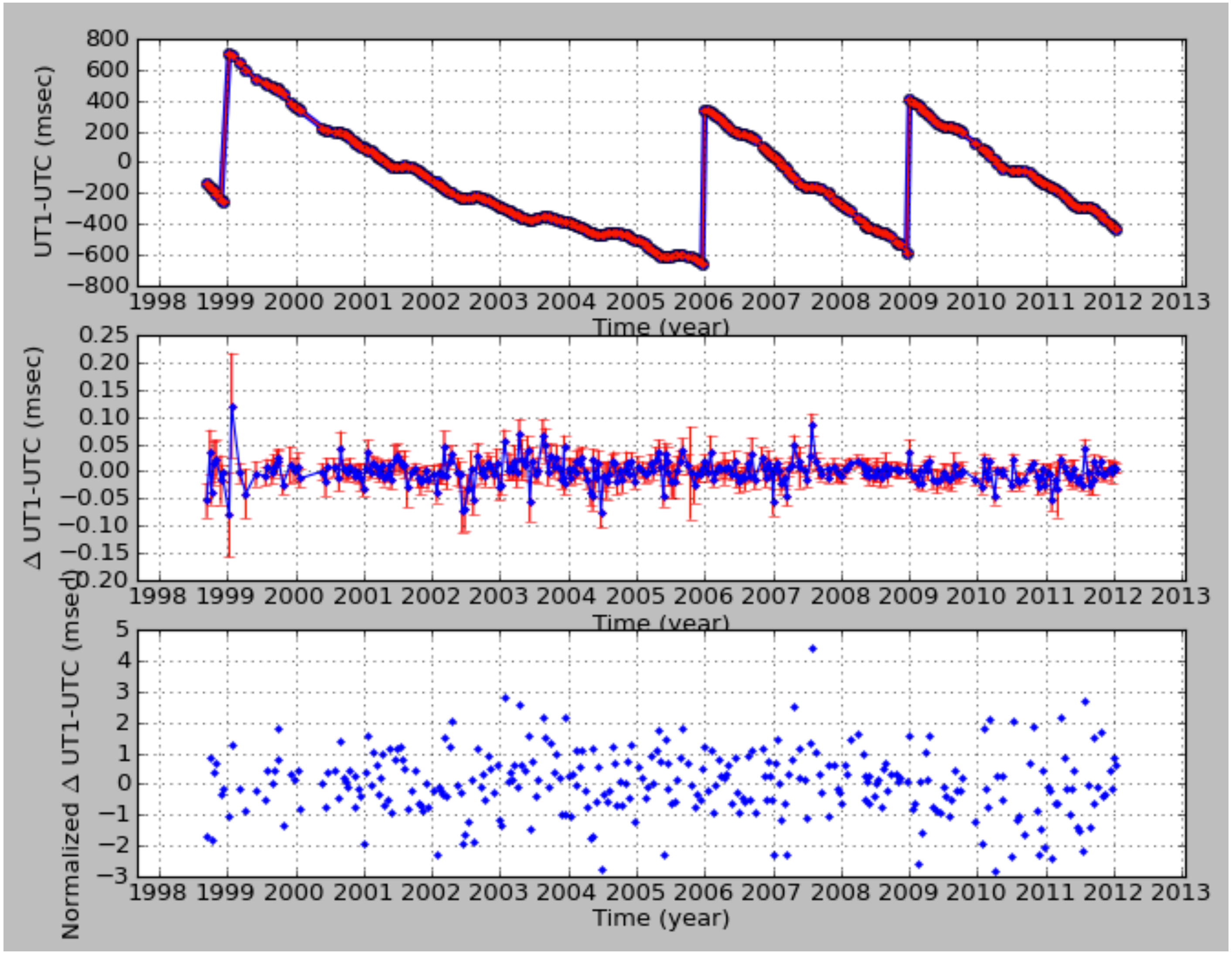
6.0 fs/s in delay rate

Trop. Cov. Vs. Traditional

Total UT1-UTC

Difference

Normalized Difference



TEMPO Analysis Results

Use JPL Kalman Earth Orientation Filter (KEOF) multi-technique combo as truth.

Subtract KEOF from TEMPO and compare wRMS of residuals.

The wRMS improves by 17% for baseline transverse direction and 27% in the baseline vertical directions.

<u>wRMS in Baseline Transverse</u>
w/o Trop. Cov. : 355 μas
w/ Trop. Cov. : 295 μas

<u>wRMS in Baseline Vertical</u>
w/o Trop. Cov. : 564 μas
w/ Trop. Cov. : 467 μas

Conclusions

As thermal errors are being reduced by higher bit-rates.

Correlated errors e.g. troposphere are becoming increasingly important.

This study shows that troposphere covariance error models improve data analysis results.

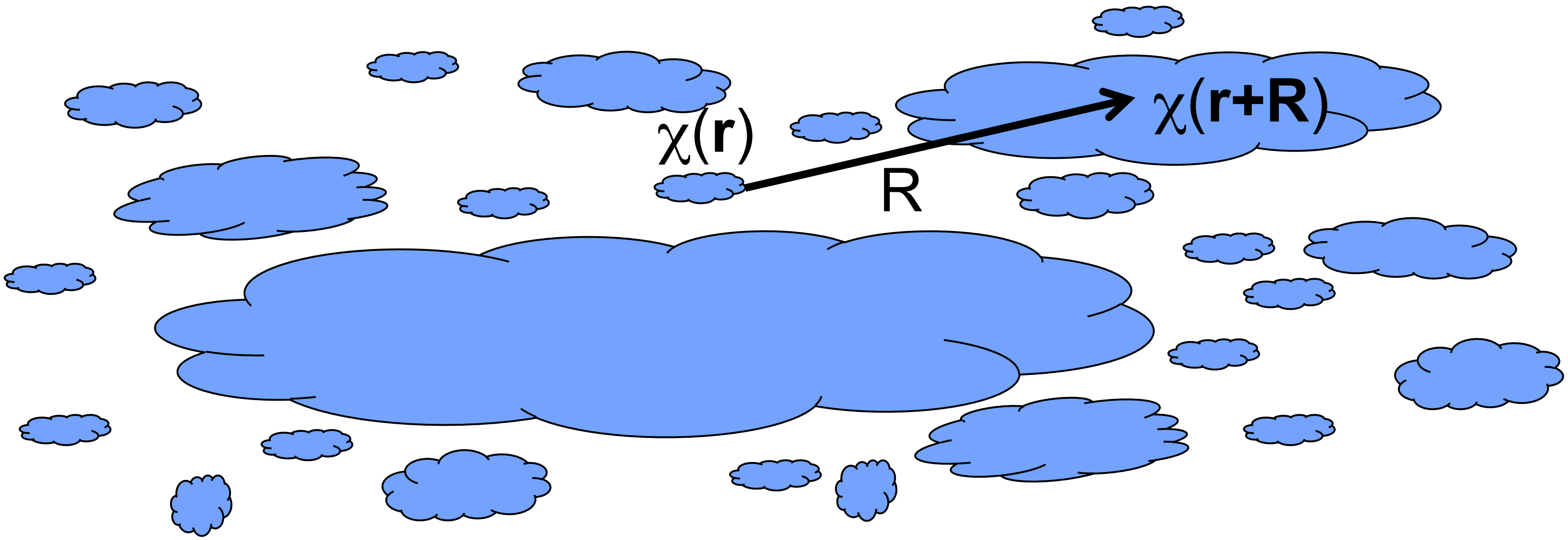
Outlook:
We expect to see stronger effects with higher data rates.

Research described herein done under contract with NASA.

Government sponsorship acknowledged.

BACK UP SLIDES

Kolmogorov Theory of Turbulence



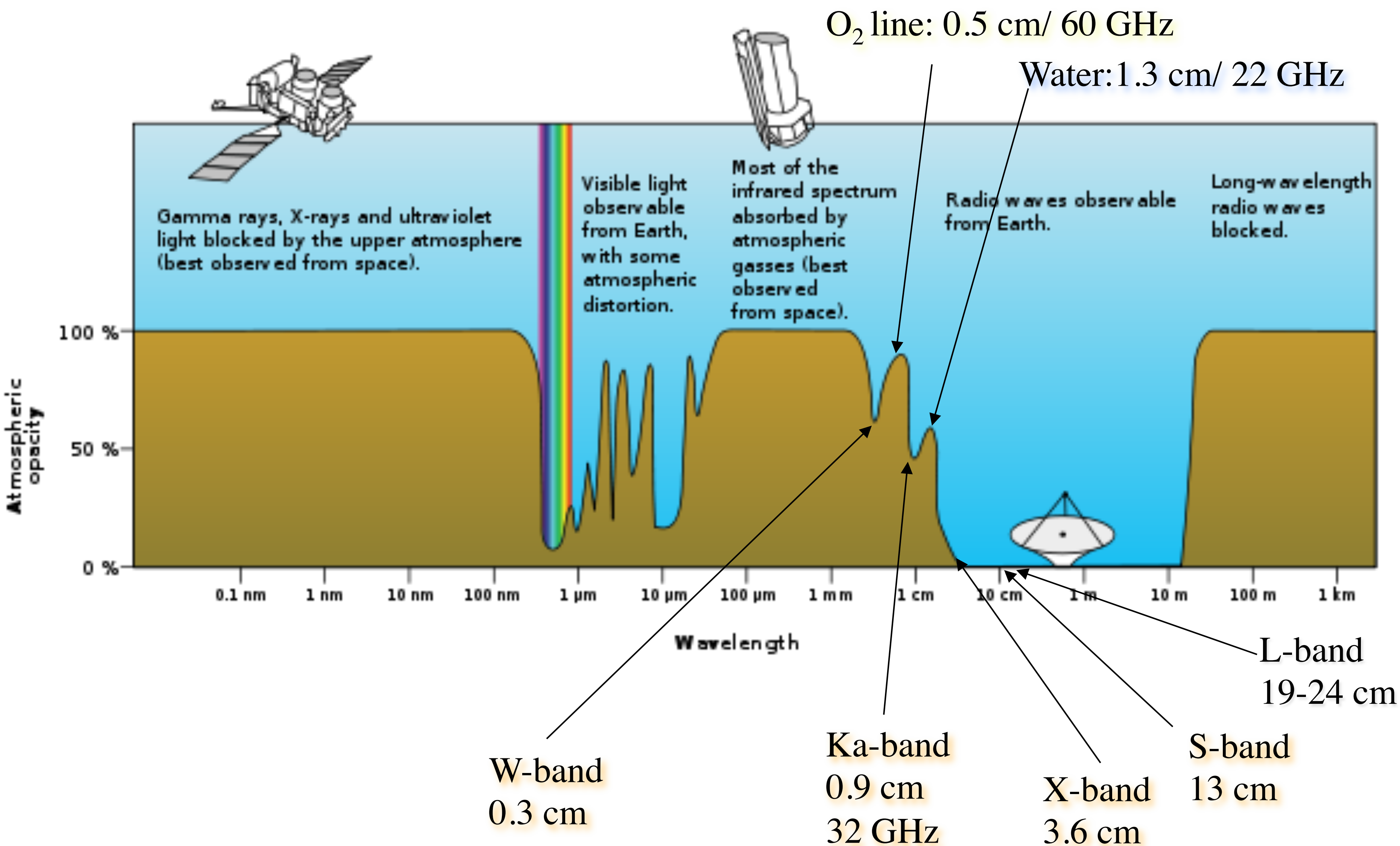
Structure function of refractivity (Tatarskii,1961)

$$D_\chi = < (\chi(\mathbf{r}+\mathbf{R}) - \chi(\mathbf{r}))^2 >$$

$$D_\chi = 2\sigma_\chi^2 - 2\mathrm{cov}(\chi(\mathbf{r}+\mathbf{R}), \chi(\mathbf{r}))$$

$$D_\chi = C^2 R^{2/3} \text{ (Kolmogorov)}$$

The Radio Window of the Atmosphere



Credit: NASA; http://en.wikipedia.org/wiki/Radio_window