



SI Traceability Applied To GPS Radio Occultation

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UCAR COSMIC Project

CLARREO Workshop

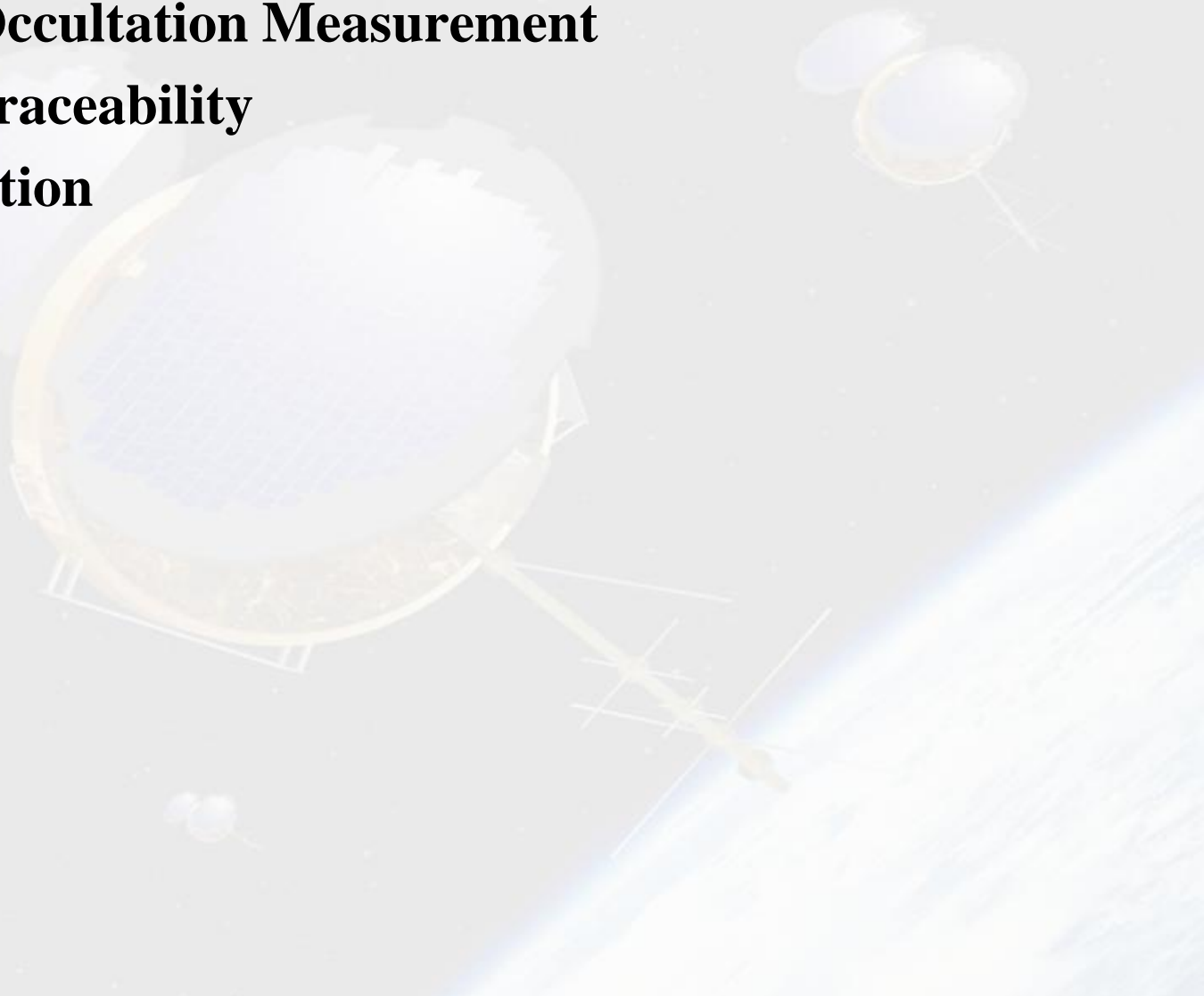
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Overview of Today's Talk

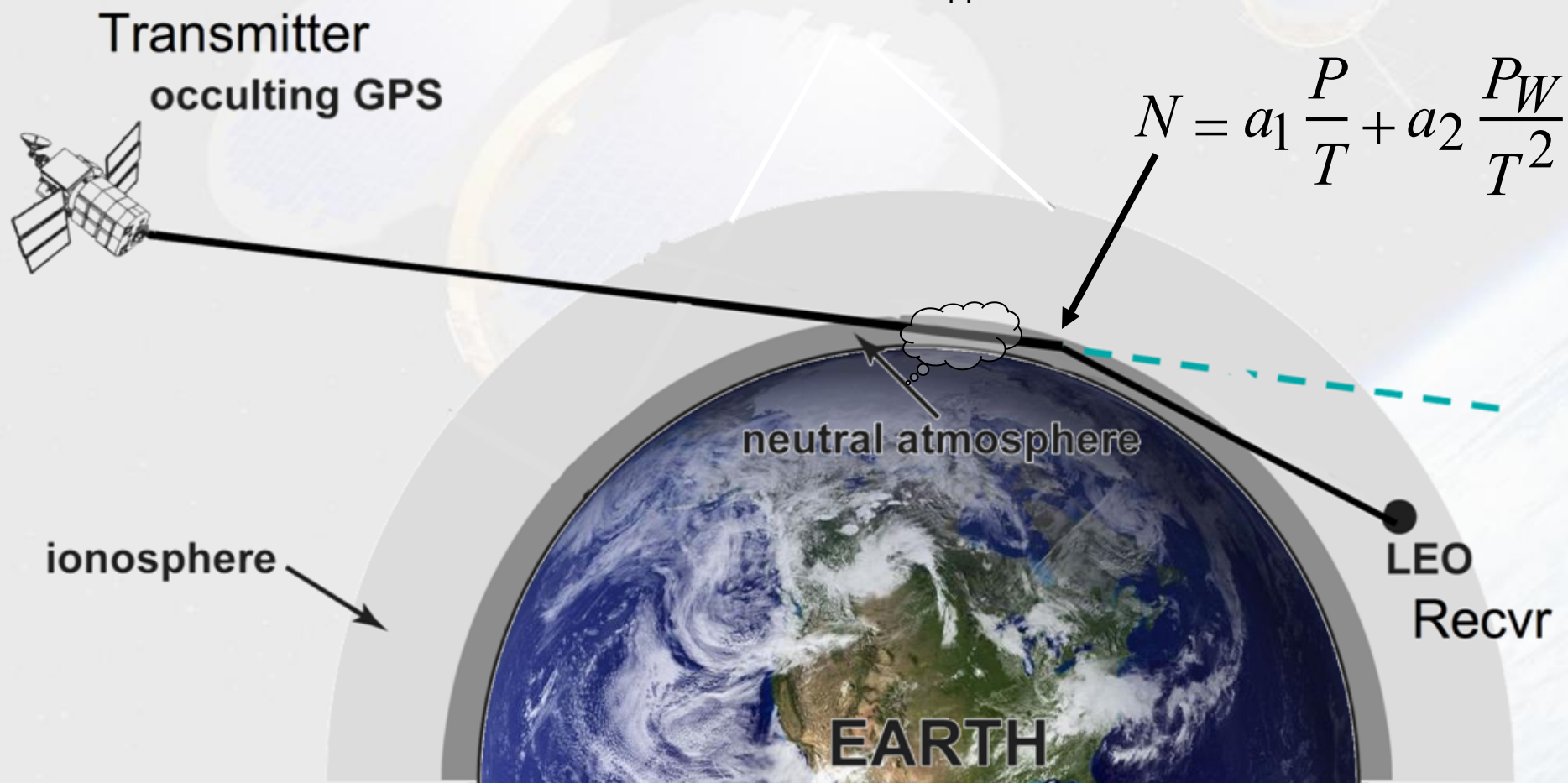
- **The Radio Occultation Measurement**
- **Applied SI-traceability**
- **Instrumentation**
- **Results**
- **Summary**





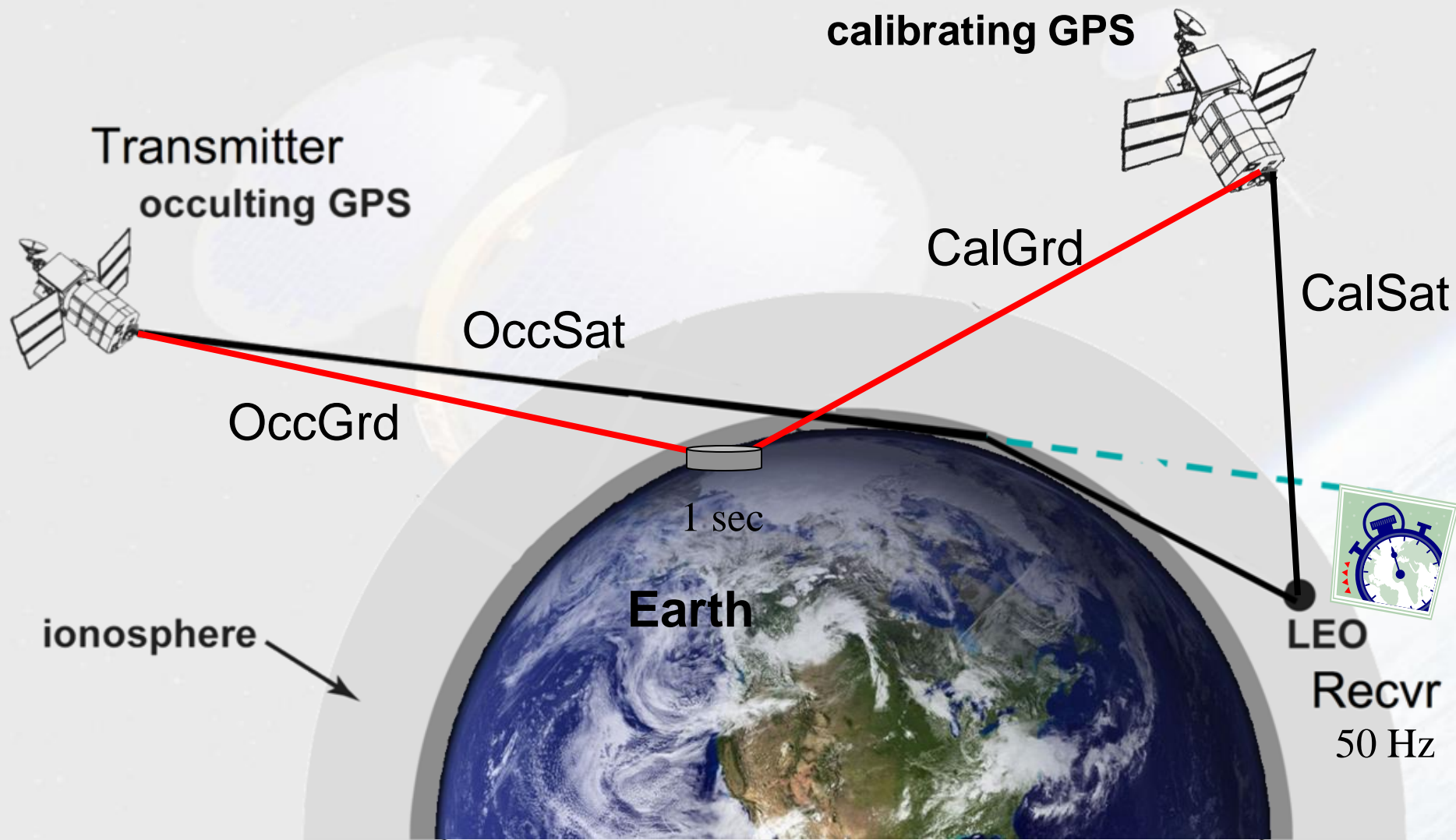
The Radio Occultation Measurement

Geometry of an acquisition





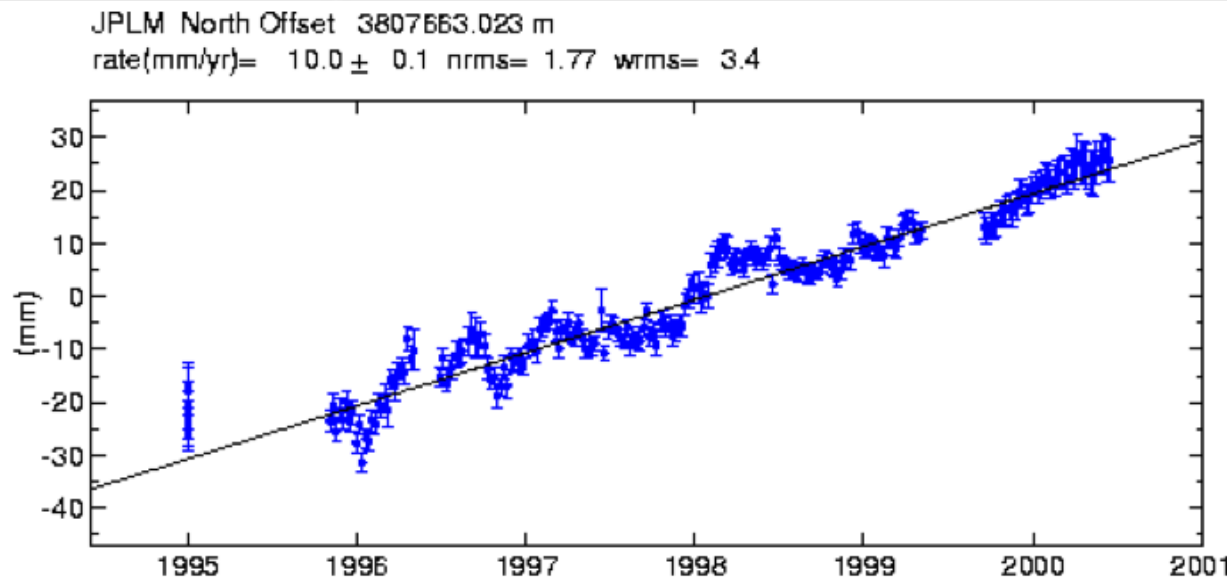
Applied SI-Traceability





Role Of Geodetic Modeling

General relativistic effects, solid Earth tides, UT variation, polar motion, S/C trajectory, troposphere, etc.

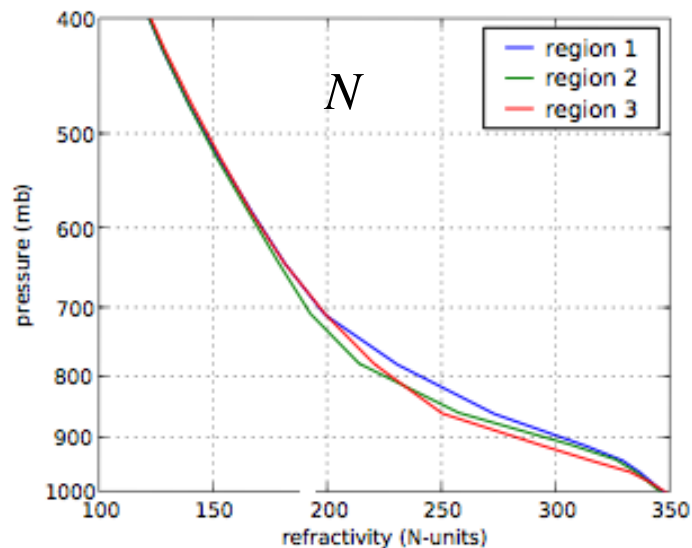
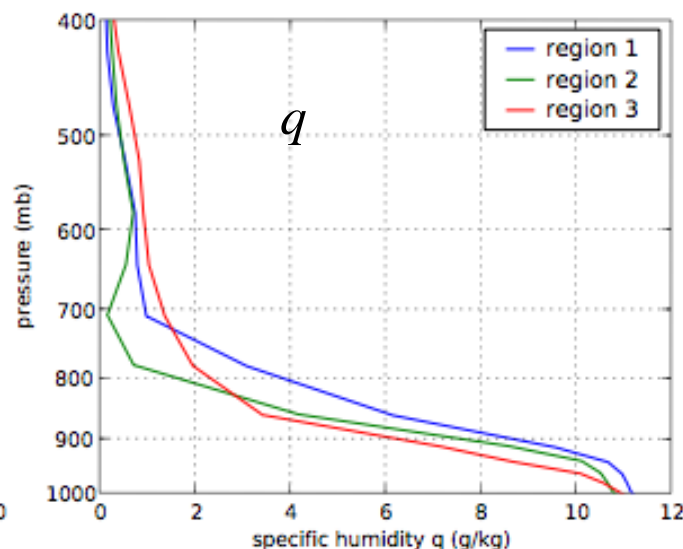
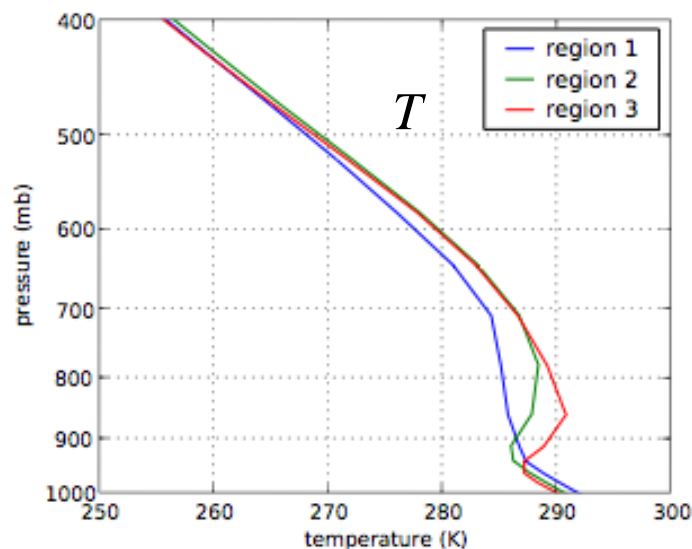


- **Geodetic modeling software systems solve directly for clocks**
 - GIPSY (JPL), Bernese (U. Berne), etc.
- **Satellite and ground locations assumed known**
 - Orbits to ~cm level are demonstrated
- **GPS time synchronized to atomic time via reference receivers (e.g. USNO)**

Occ
duration
~90s



Retrieval Products From WRF Model



$$N = a_1 \frac{P}{T} + a_2 \frac{P_W}{T^2}$$

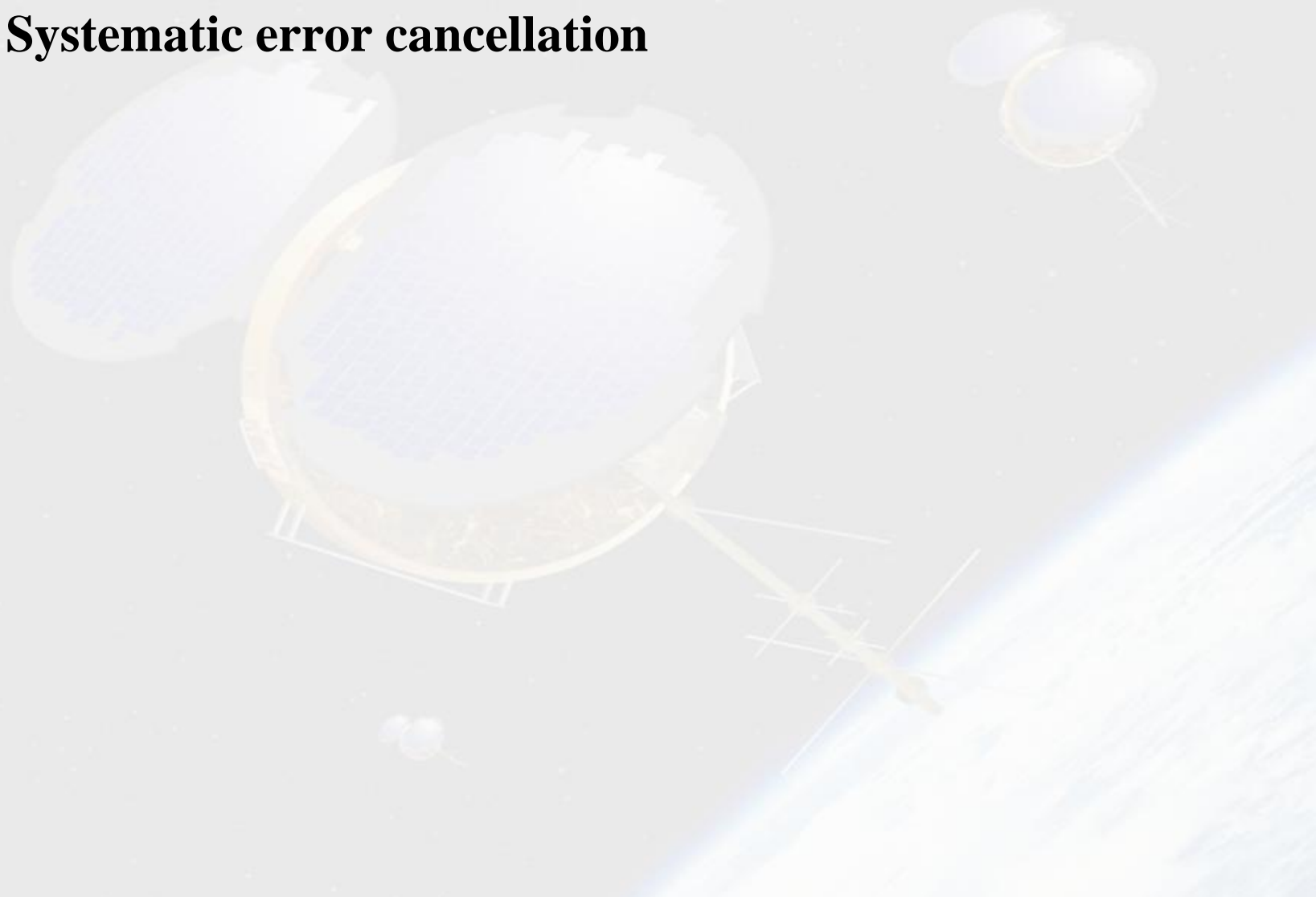
Ducting criterion
 $dN/dr \leq -157$ N-units per km

Negligible occurrence
above 4 km (Ao, Radio Sci, 2007)



Advantages Of Self-Calibration

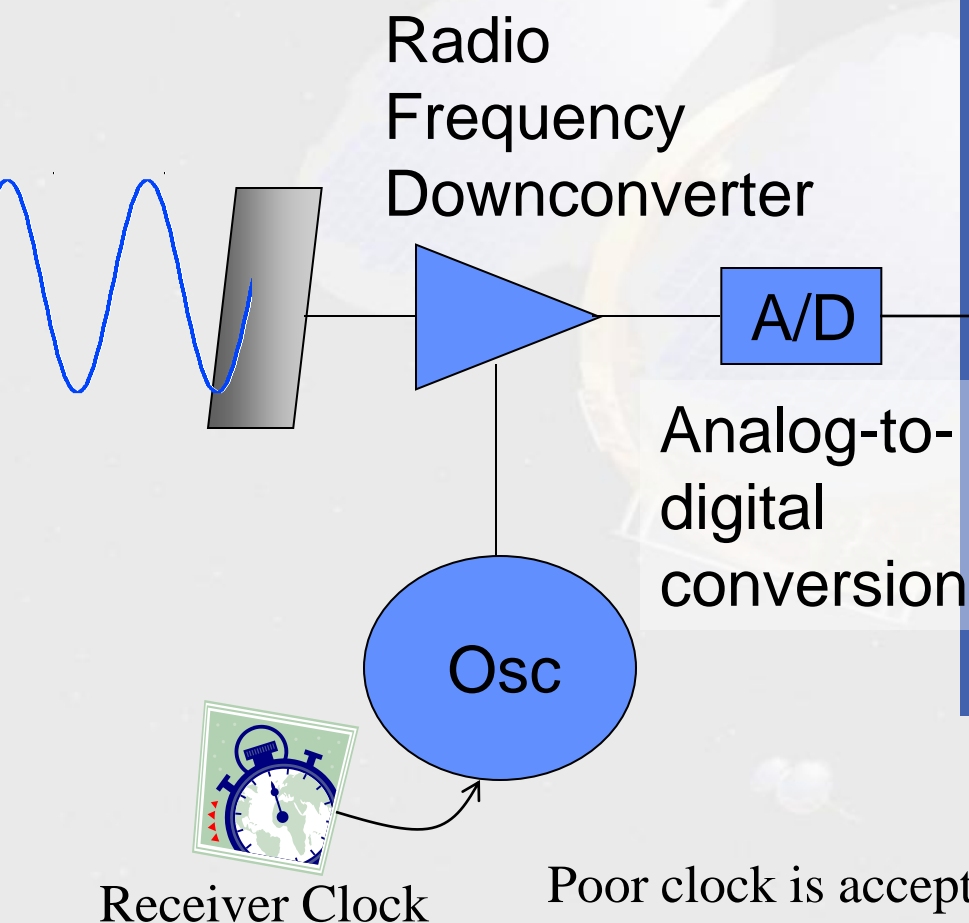
- **Systematic error cancellation**



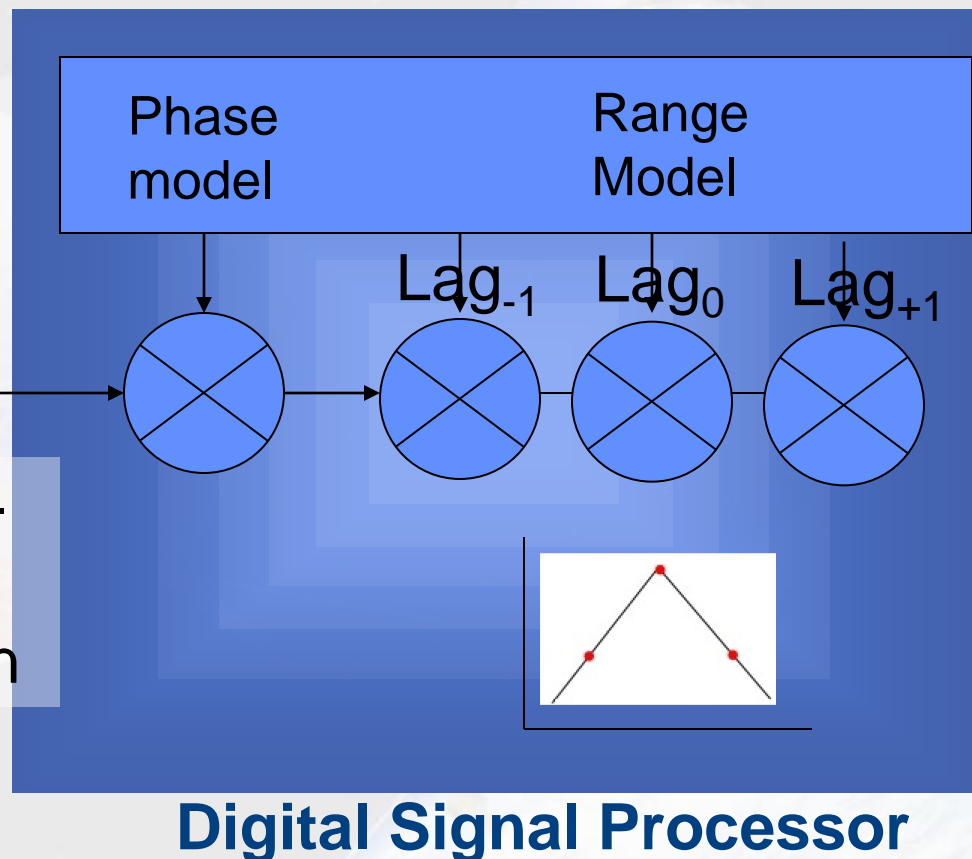


Instrumentation: Measuring Phase

Analog Electronics



Digital Electronics



Poor clock is acceptable (e.g. CHAMP clock is compromised)
Stability required over times ~50 msec (differential light times)



Research Issues

- **Ionospheric residual at high altitudes**
 - Imperfect cancellation from dual frequency
 - In situ mesosphere residual
 - Improve algorithm and characterization
- **Multipath**
 - Proper design
 - Monitor in-situ
- **Antenna phase center variation**
 - Monitor in-situ

Retrieval systems must be carefully analyzed and vetted by the community



Results

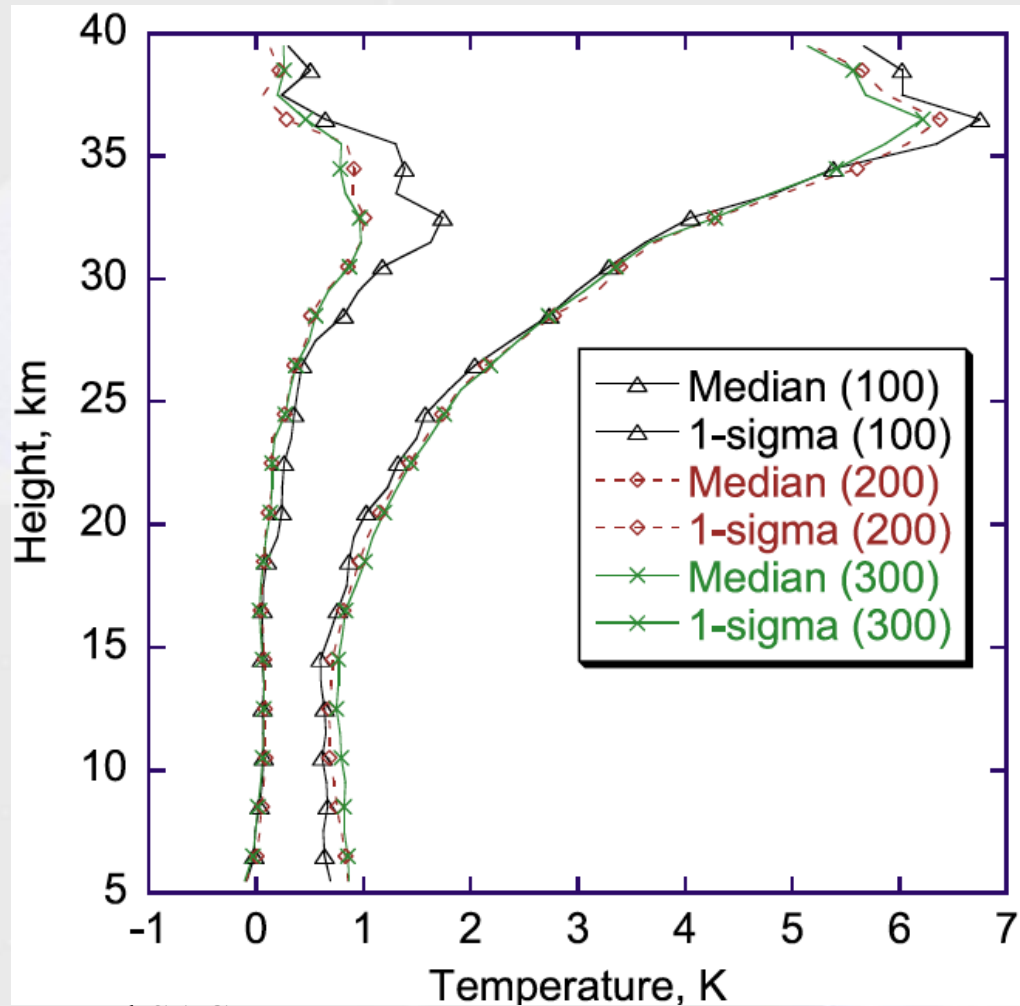
- **Compare collocated soundings from different RO satellites**
- **CHAMP-SAC-C**
- **COSMIC/FORMOSAT-3 six satellite**
- **No bias (no drift) is confirmed**
- **Does not directly assess all possible sources of systematic error**



Coincident Soundings From CHAMP and SAC-C

Coincident
Observations
Within
1/2 hour
100-300 km

Jul '01-Mar'03
N = 212



Differences:
Median and
standard
deviation versus
separation

Hajj et al., (2004) "CHAMP and SAC-C
atmospheric occultation results and
intercomparisons", JGR.

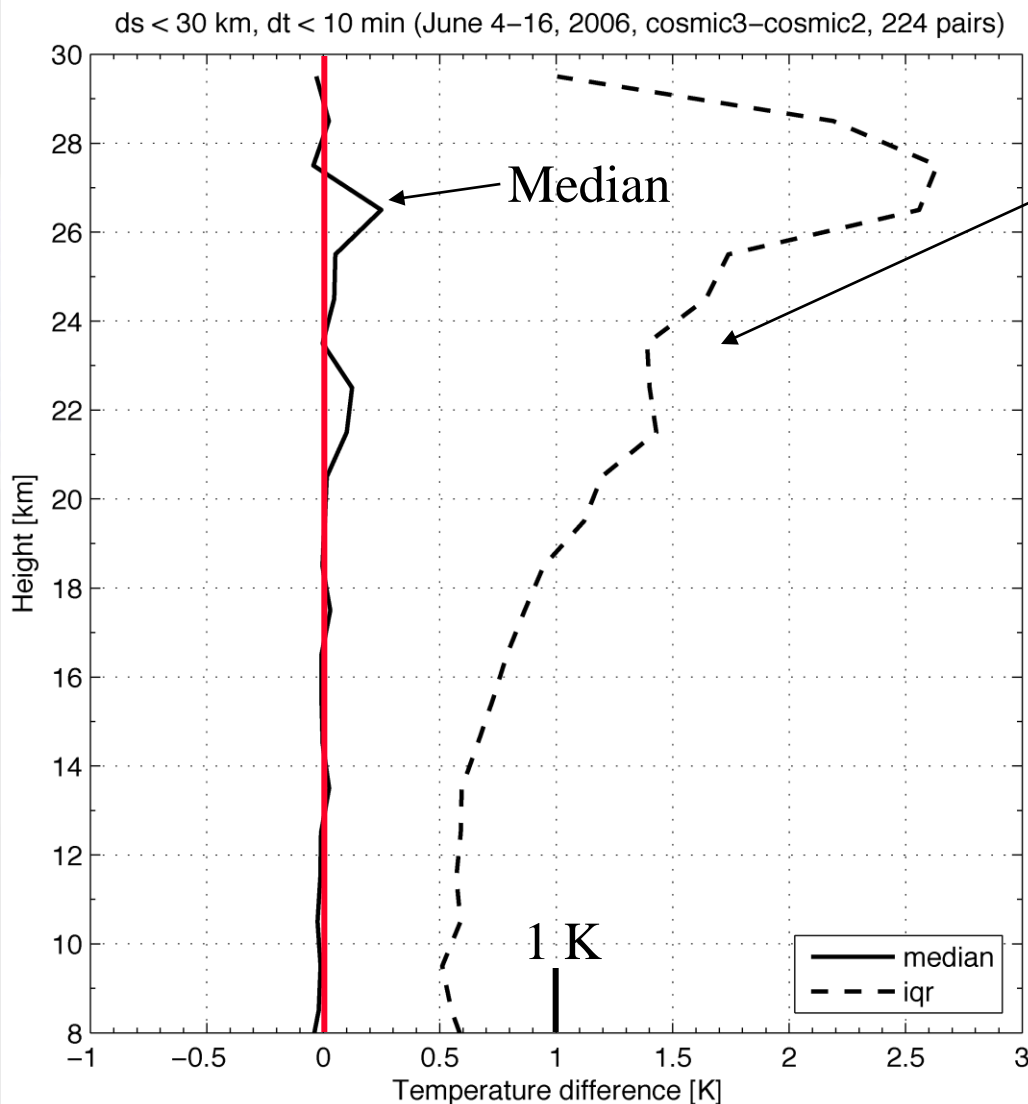
Careful accounting for decorrelation with distance



Soundings From COSMIC – JPL

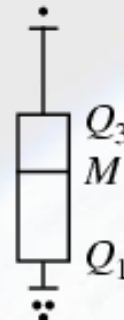
COSMIC3 -
COSMIC2

Window:
30 km
10 minutes
June 4-16, '06
224 pairs



Inter-quartile
Range

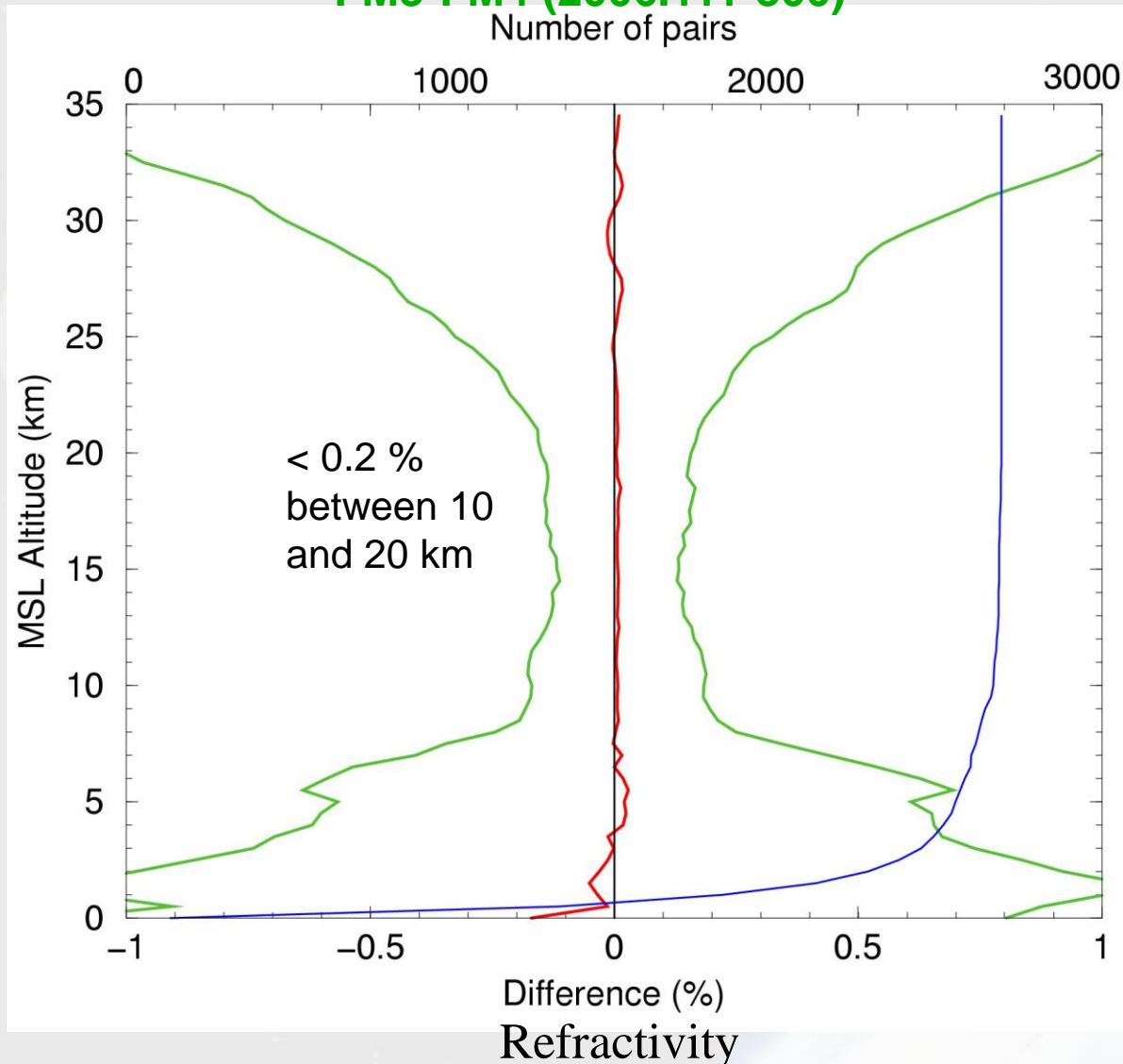
Contains
central 50% of
differences





UCAR COSMIC Results

FM3-FM4 (2006.111-300)





Other Results

- **RO Trends study: analysis of inter-center differences in monthly mean refractivities**
 - JPL, UCAR, GFZ, Wegener Center (Austria)
 - CHAMP 2002-2007
 - 8-25 km altitude
 - Independent implementations
 - Differing geodetic software, orbit determination
 - Varying quality control criteria
- **Trends determined much better than absolute differences**
 - Different center retrievals have small but fixed offsets that do not vary in time

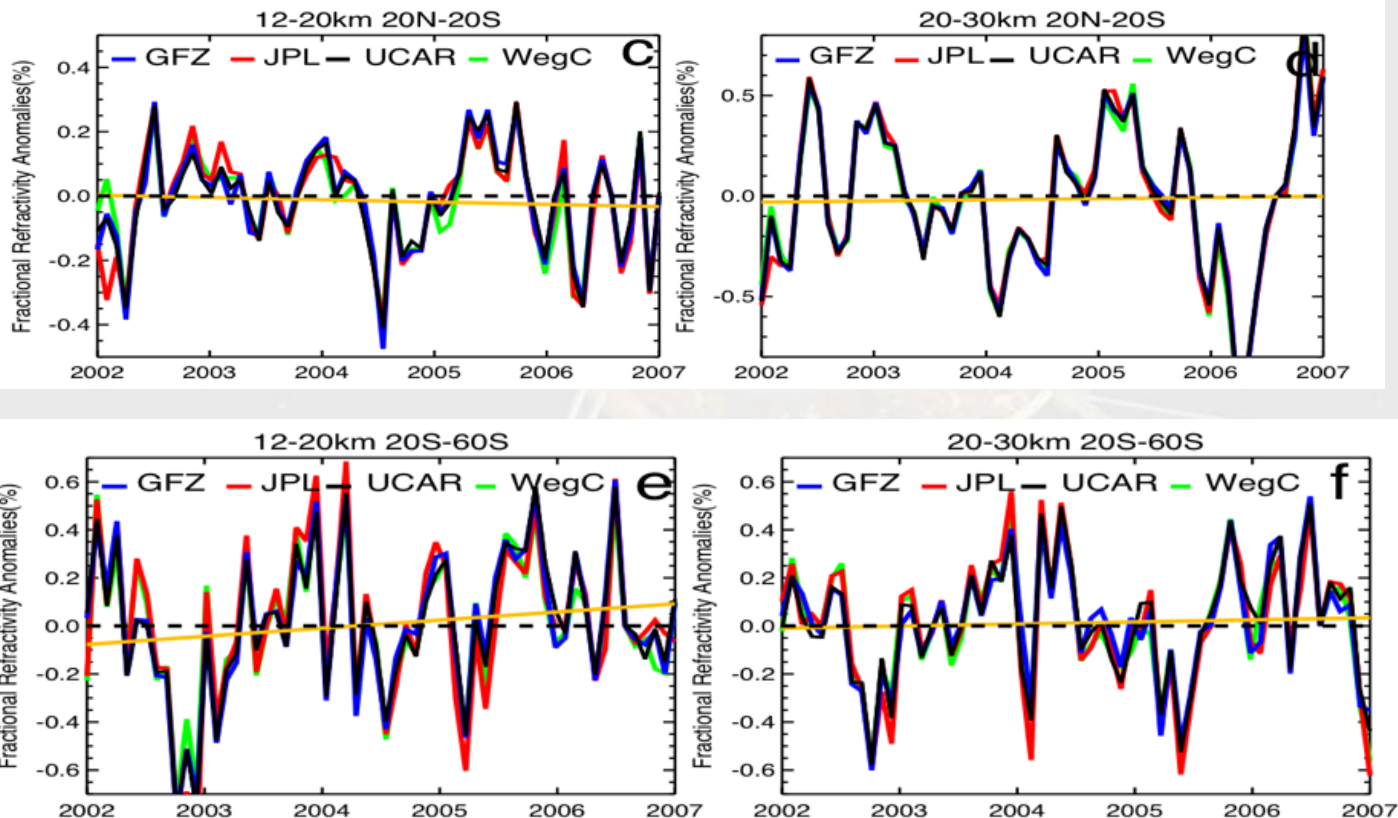


RO Trends: Four Processing Centers Compared

JPL, UCAR, GFZ, Wegener Center
Deseasonalized fractional refractivity anomalies
monthly mean climatologies (profile set not common)

CHAMP
2002-2007

Uncertainty of the
trend for fractional
refractivity anomalies
among centers is
within $\pm 0.04\%/5$ yrs
globally.





Summary

- **Radio occultation is a geodetic technique for measuring climate trends**
 - Physics of the measurement is highly advantageous
 - **Self-calibrating time delay measurements yield high quality SI-traceable accuracy**
 - Accuracy implies stability
 - Negligible inter-satellite biases
- “Climate index tied to atomic clock standards”**
- **CLARREO provides data we urgently need for the long term climate record**
 - **Research is ongoing to fully quantify all sources of systematic error that do not completely difference out**