GNSS Radio Occultation Instrument Characteristics Relevant To Climate Observation and Monitoring

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Motivation

- **Limited documentation on key design features of an RO instrument for long-term climate observation**
- **Coming increase in different RO receiver designs**
- **Promised CLARREO publication**
- **Book chapter in Wiley-IEEE Two-Volume set "GPS Theory and Applications"**

GPS "Blue Books"

Review of Radio Occultation Retrieval

Measure phase rate of change

↓ *Ionosphere correction*

Bending Angle vs Altitude

↓ *Abel transform*

Refractivity vs Altitude

↓

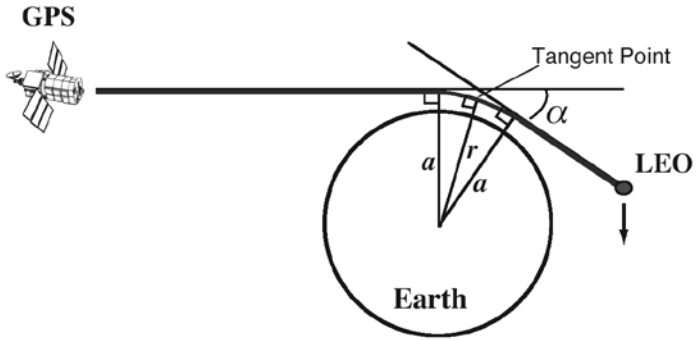
Ideal gas, hydrostatic equilibrium

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

$$\frac{dP}{dh} = -\rho g$$

↓

***T*, *P* versus height**



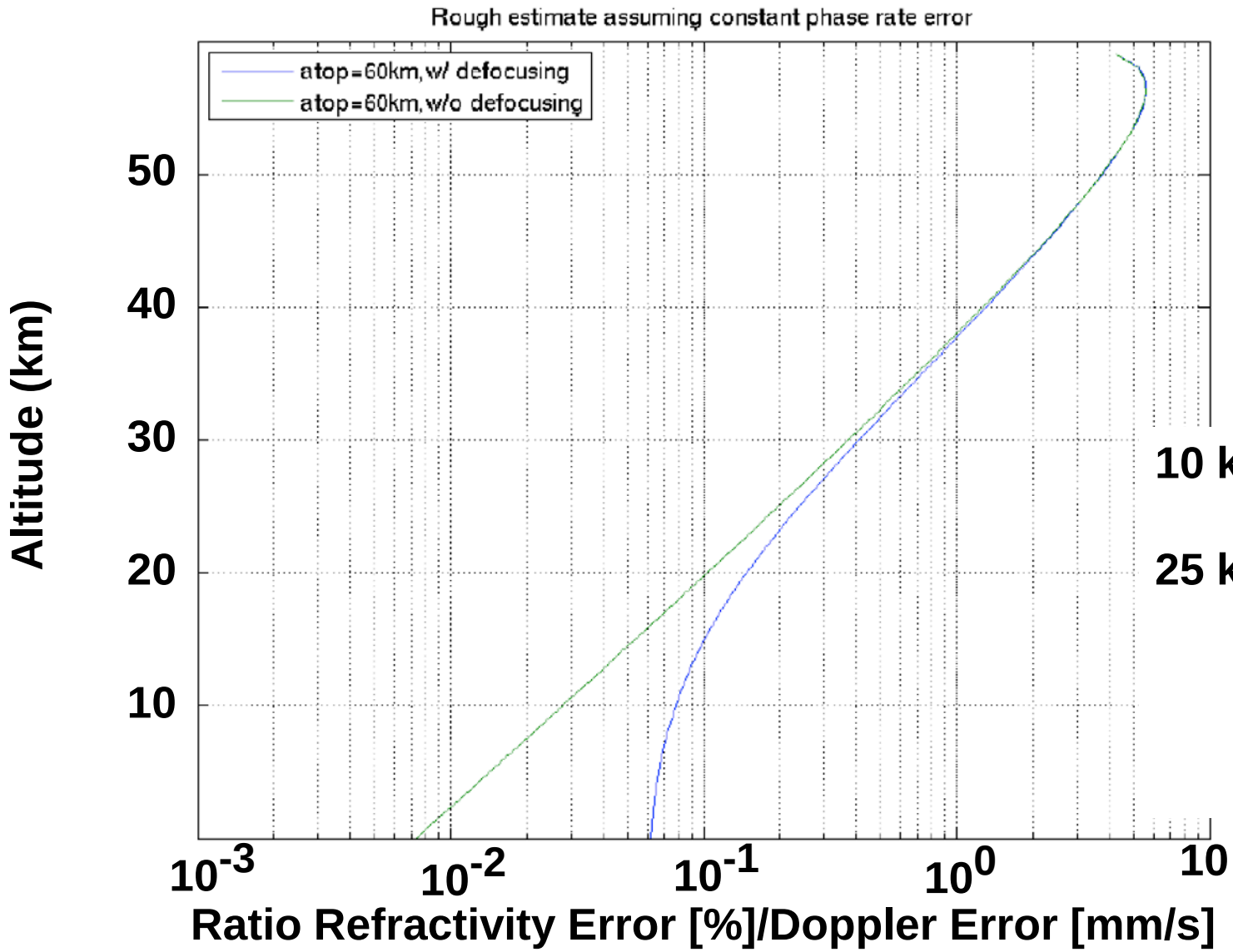
$$\lambda \Delta f = [\mathbf{v}_t \cdot \hat{\mathbf{k}}_t - \mathbf{v}_r \cdot \hat{\mathbf{k}}_r - (\mathbf{v}_t - \mathbf{v}_r) \cdot \hat{\mathbf{k}}]$$

$$a = r_t n_t \sin(\theta_t + \delta_t) = r_r n_r \sin(\theta_r + \delta_r)$$

Horizontal resolution: 100-200 km
Vertical resolution: 200m - 1 km

"Unaffected" by liquid water and ice

CLARREO Requirements



CLARREO: 0.03% Refractivity Error

⬇

10 km 0.391 mm/s

25 km 0.128 mm/s

0.128 mm/s

⬇

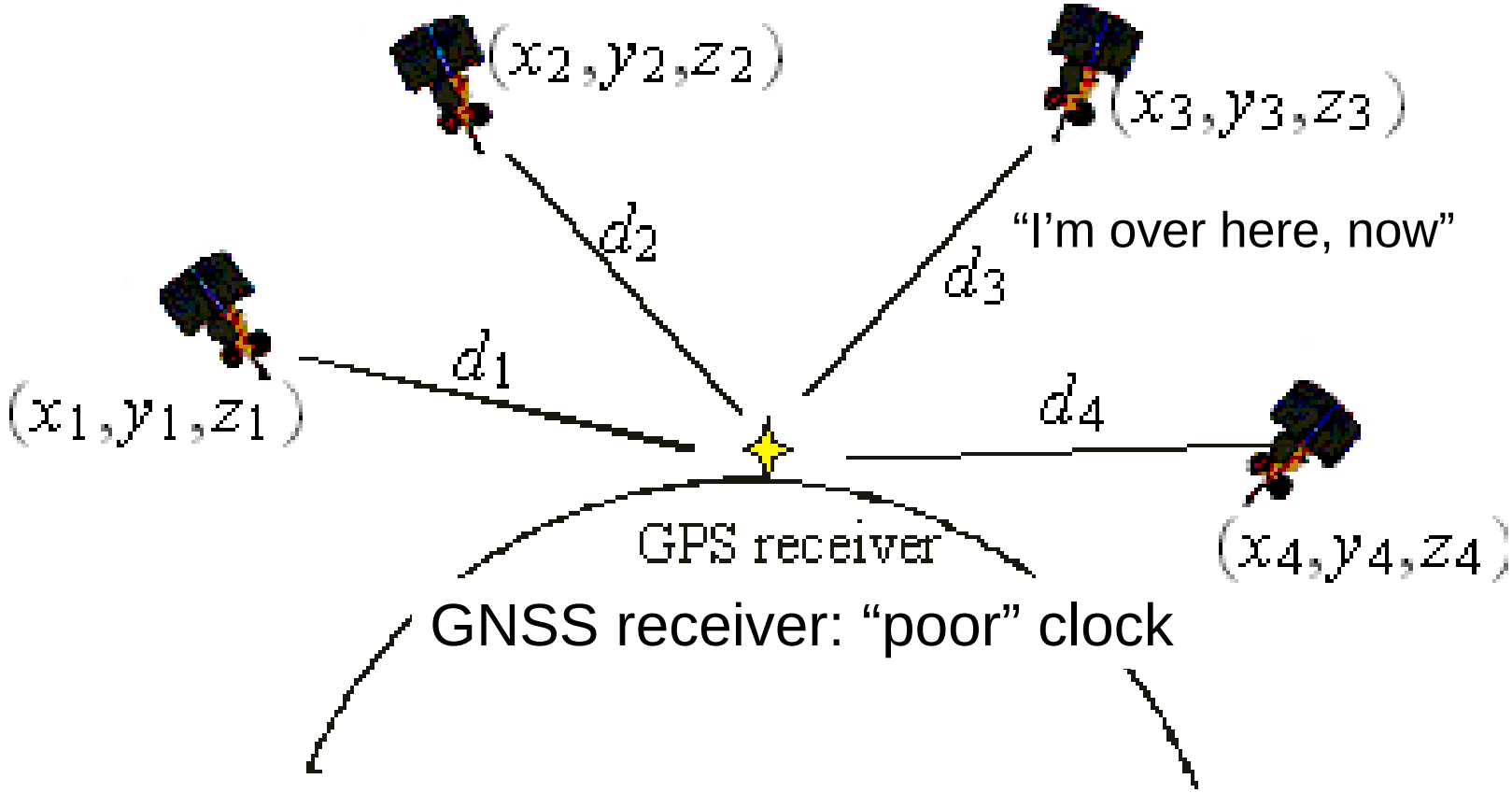
6.7×10^{-4} Hz

What is Time?

- **Time is the number of times per second that an electrical signal crosses zero**
- **“Second” is defined by a clock (a digital instrument that tells us what time it is)**

GNSS Perspective on Time

GNSS transmitters: “good” clocks



Note: radio occultation retrieval requires only that rates of change be measured

http://www.math.tamu.edu/~dallen

Algorithm: Measuring A Time "Residual"

Model phase Residual

Incoming signal

$$\sin(\omega t + \phi(t))$$

$$\sin(\omega t)\cos(\phi(t)) + \cos(\omega t)\sin(\phi(t))$$

Digital multiplication – "in phase" – I

$$\cos(\omega t)\cdot(\sin(\omega t)\cos(\phi(t)) + \cos(\omega t)\sin(\phi(t)))$$

$$I = \frac{1}{2}\sin(\phi(t)) + \frac{1}{2}\cos(\phi(t))\sin(2\omega t) + \frac{1}{2}\cos^2(\omega t)\sin(\phi(t)) - \frac{1}{2}\sin^2(\omega t)\sin(\phi(t))$$

Digital multiplication – "quadrature" – Q

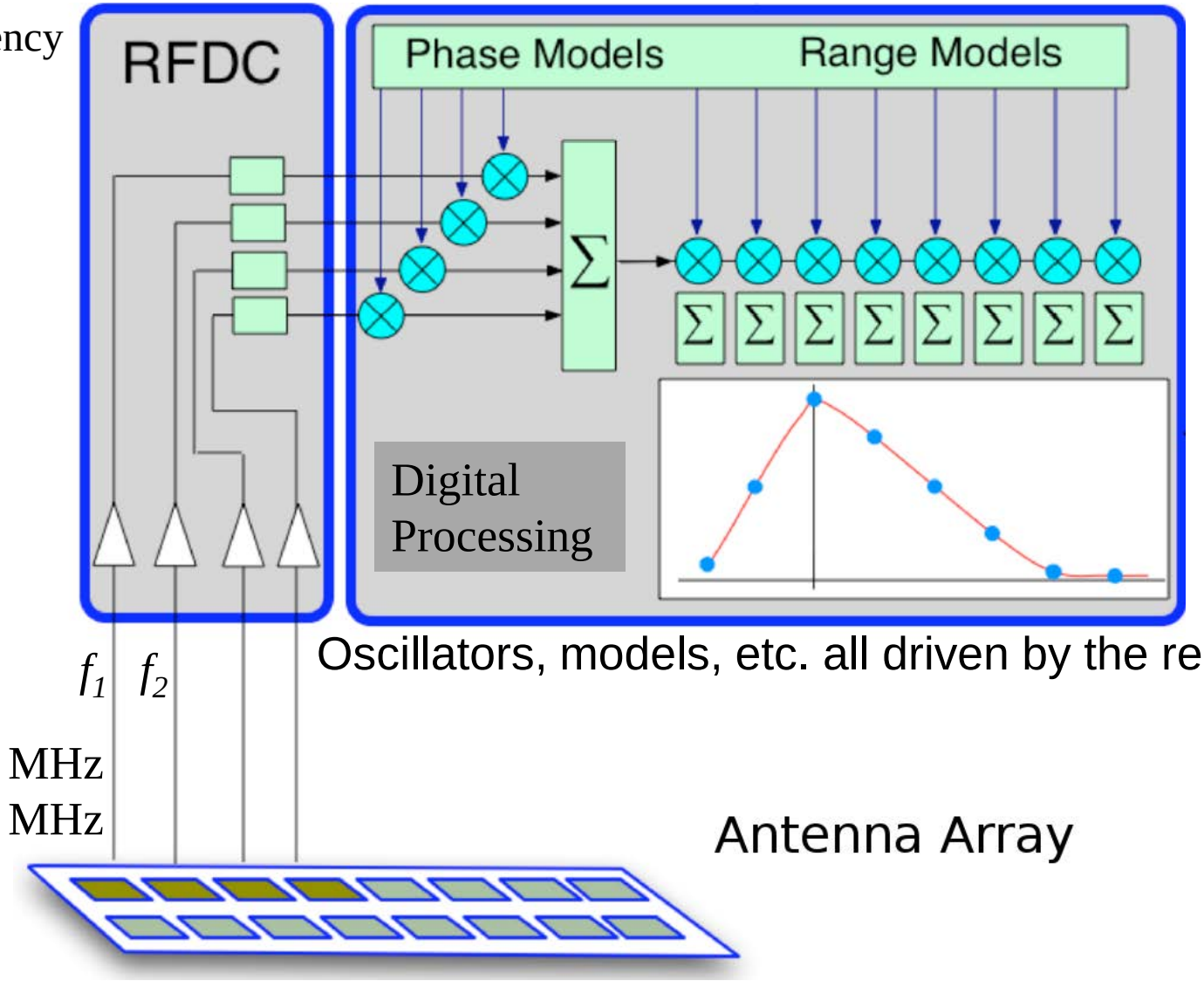
$$\sin(\omega t)\cdot(\sin(\omega t)\cos(\phi(t)) + \cos(\omega t)\sin(\phi(t)))$$

$$Q = \frac{1}{2}\cos(\phi(t)) - \frac{1}{2}\cos^2(t\omega)\cos(\phi(t)) + \frac{1}{2}\cos(\phi(t))\sin^2(t\omega) + \frac{1}{2}\sin(2t\omega)\sin(\phi(t))$$

"Sum and dump" then arctan: $\phi(t) = \tan^{-1}\left(\frac{Q}{\mathrm{I}}\right)$

Anatomy of a Radiometric Instrument

Radiofrequency Down Converter



Oscillators, models, etc. all driven by the receiver clock

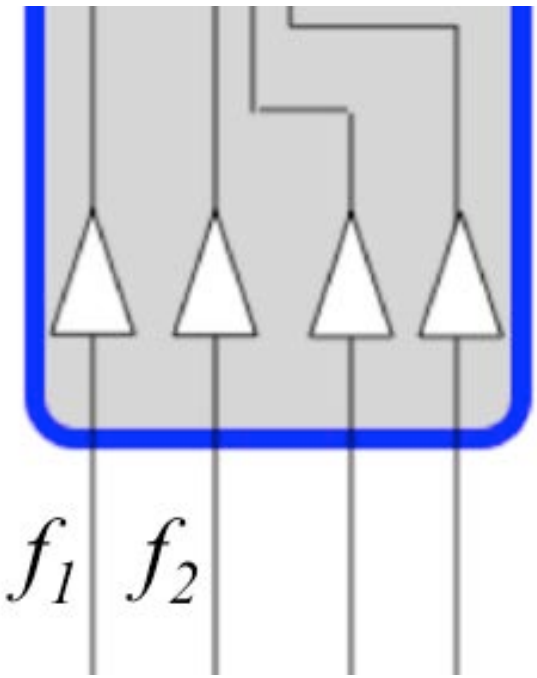
f_1=1575.42 MHz
f_2=1227.60 MHz

Potential Instrumental Sources Of Doppler Bias

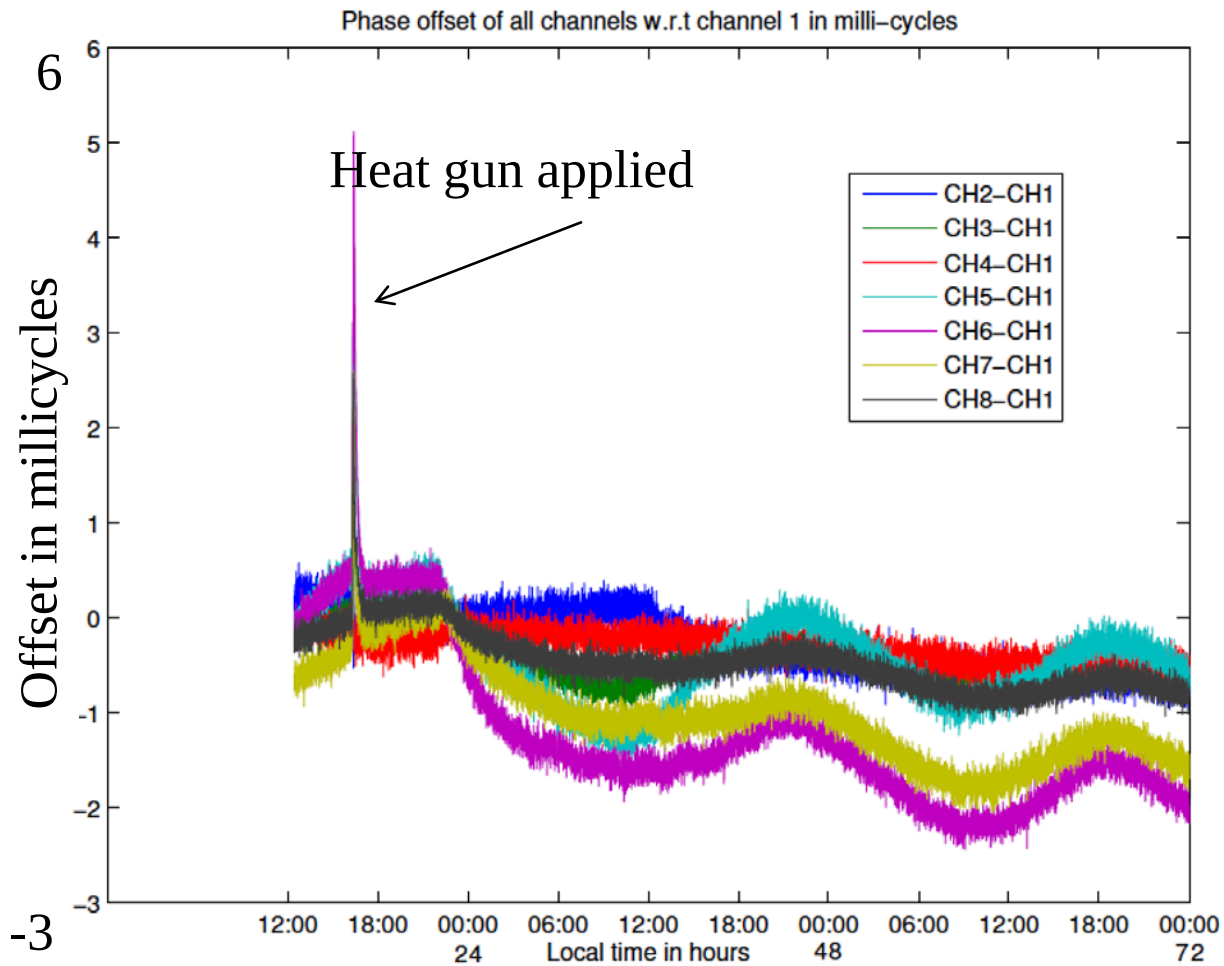
Duration of an occultation ~100 seconds

- Temperature related inter-channel drift
- Residual phase variation over the integration interval
- Data interval bias
  - Bookkeeping/dead time
- Multipath ("stray light")
- Residual receiver clock rate
  - Brings in geodetic system
  - Geodetic system: stability over light travel times, etc
  - Relativistic corrections
- Phase center variation and COM offset

Inter-channel Drift



Requirement	Occultation Duration	Max Drift (cycles)
0.1 mHz	100 s	0.01

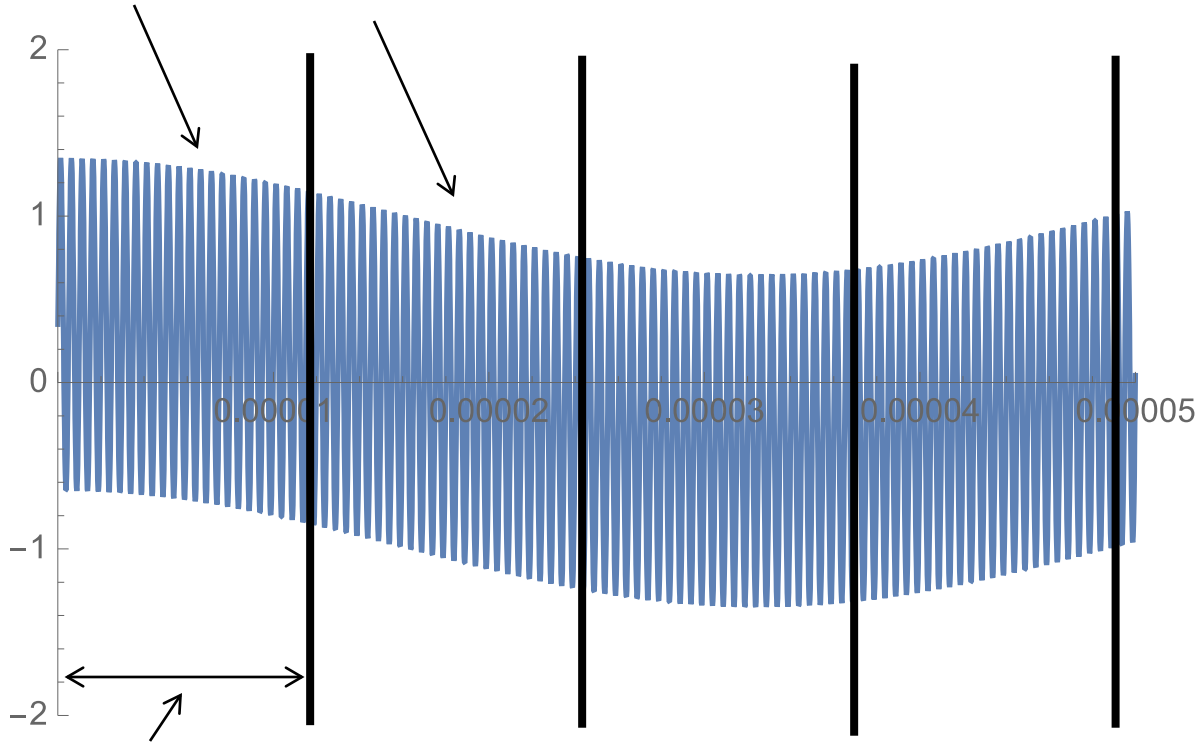


Inter-channel drift may be reduced by using a clock differencing satellite (shown later)

Esterhuizen et al., ION Mtg 2009

Variation of Residual Phase Over Integration Periods

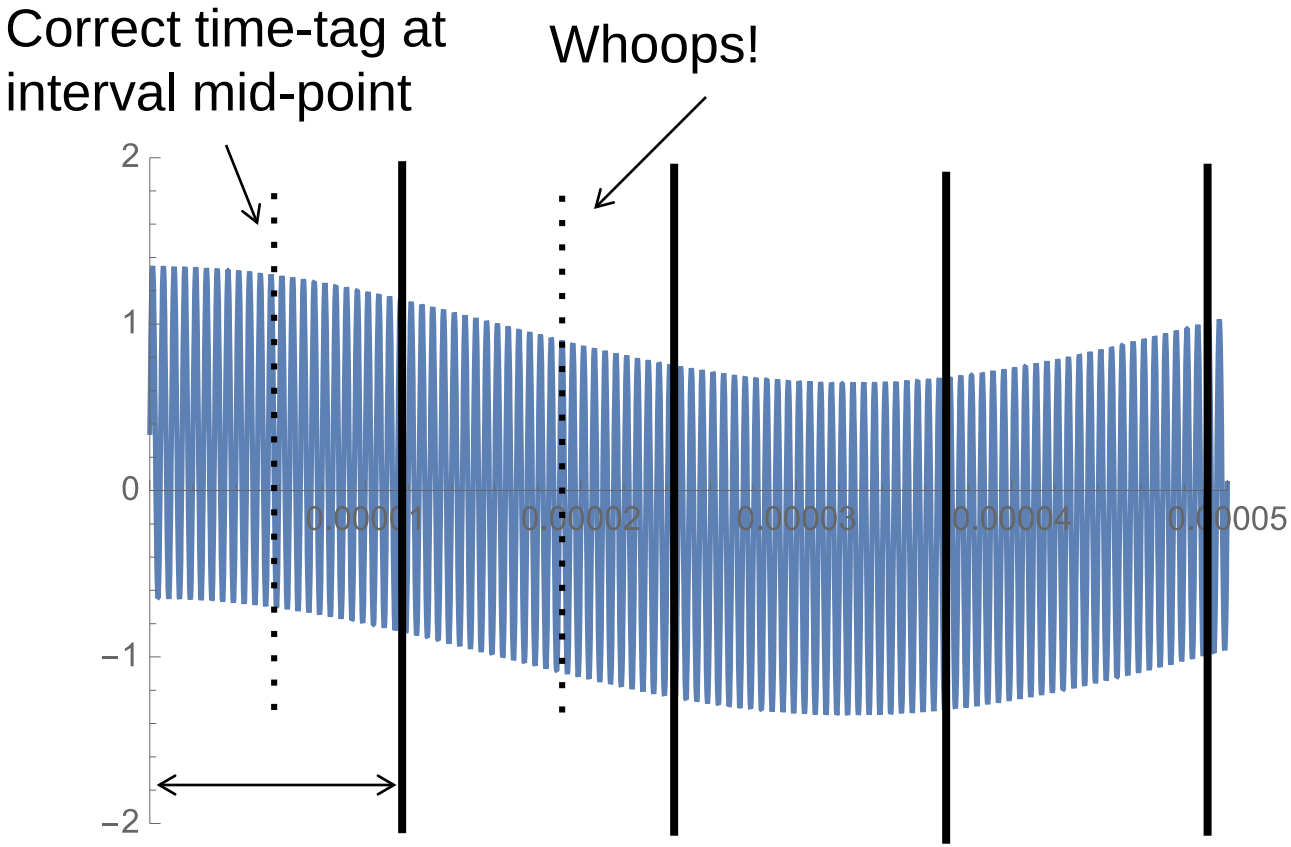
One phase value
extracted per interval



Sum and dump interval ~1-20 msec

- Desired: extract phase independently for each S&D interval
- Some receiver designs correlate extracted phase for several intervals

Time-Tag Error

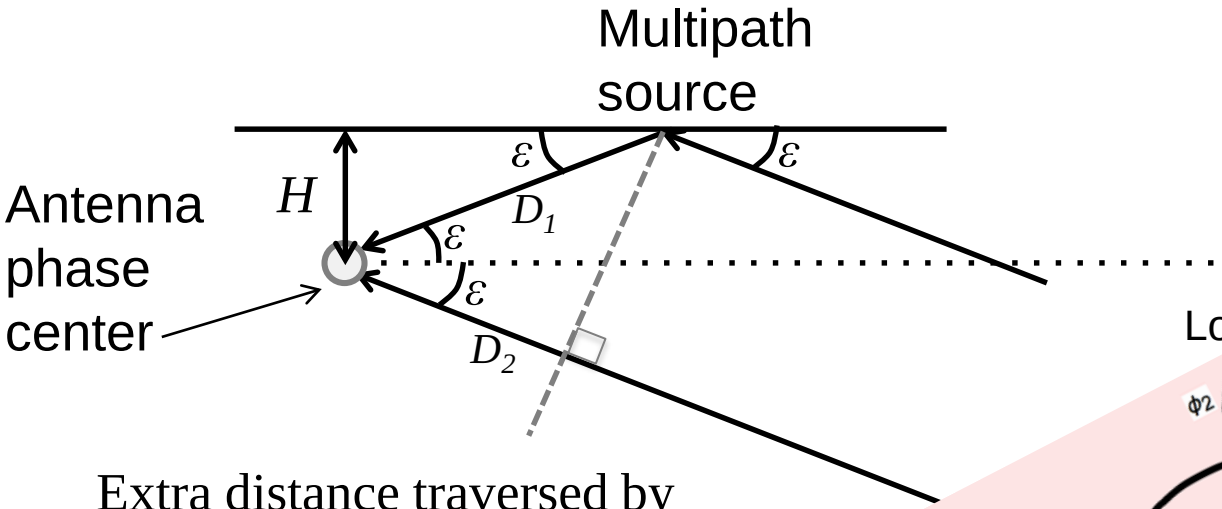


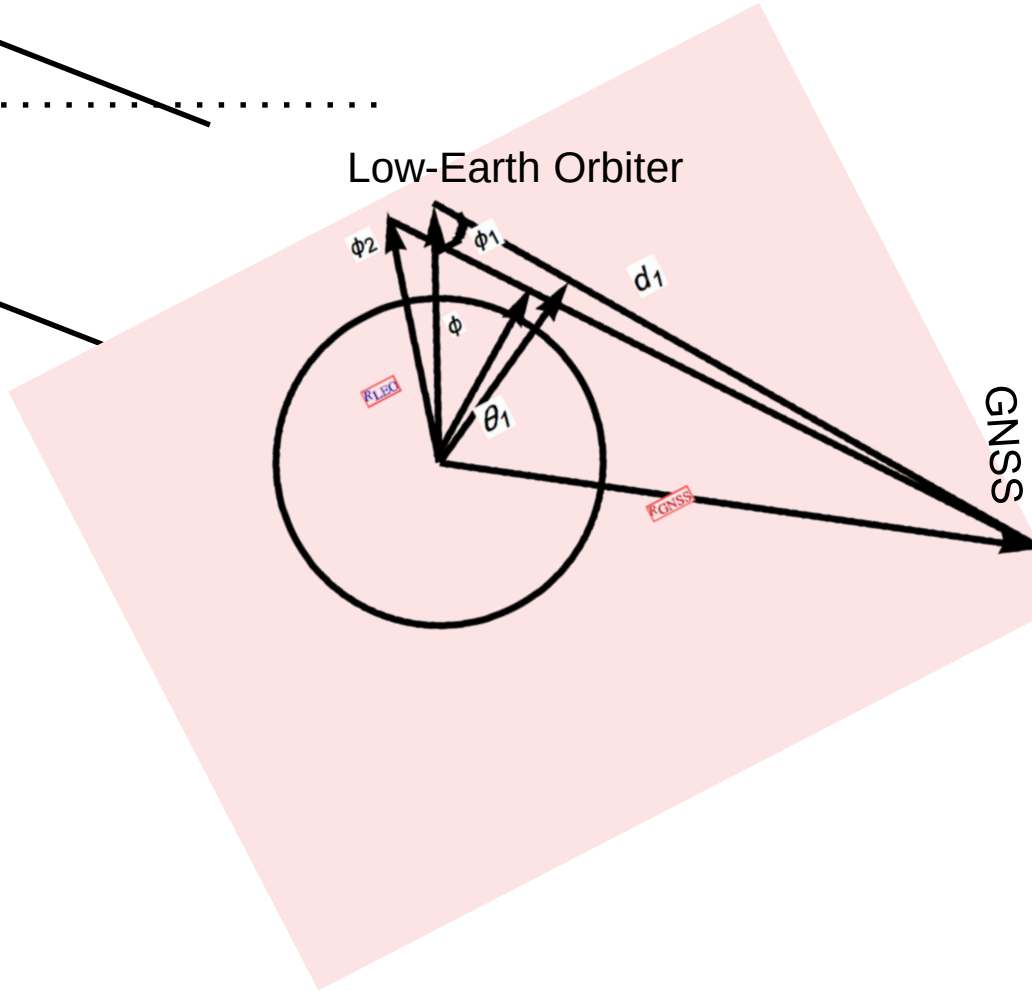
Sum and dump interval ~1-20 msec

Amplitude Related Errors

- **Monarch receiver: SNR change caused range shift**
  - **Truncation error in some 4-bit algorithm**
- **One-bit sampling – amplitude goes away**
  - **Emphasize time over power measurement!**
  - **Easier digital logic**

Multipath

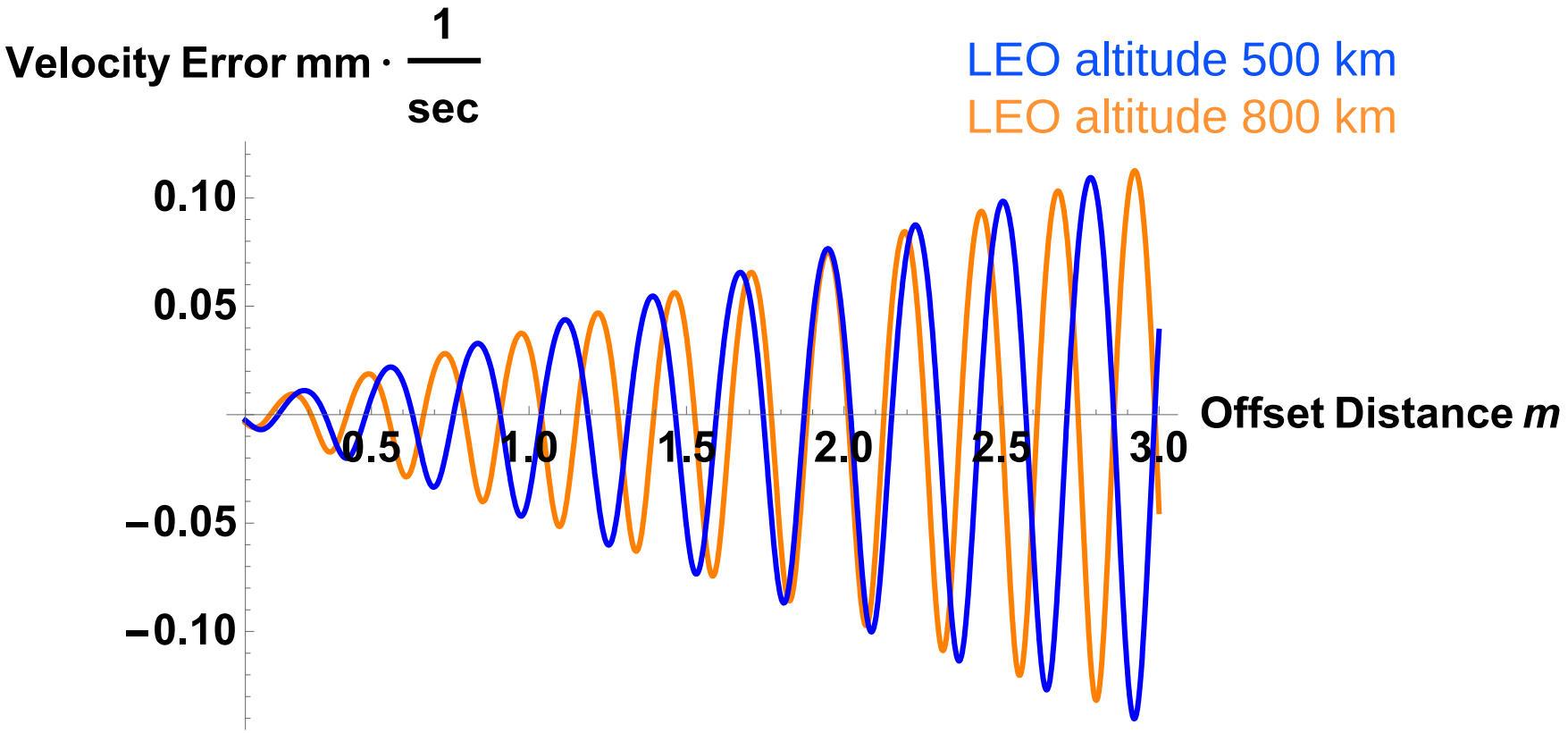




Extra distance traversed by reflected signal: $D_1 - D_2$

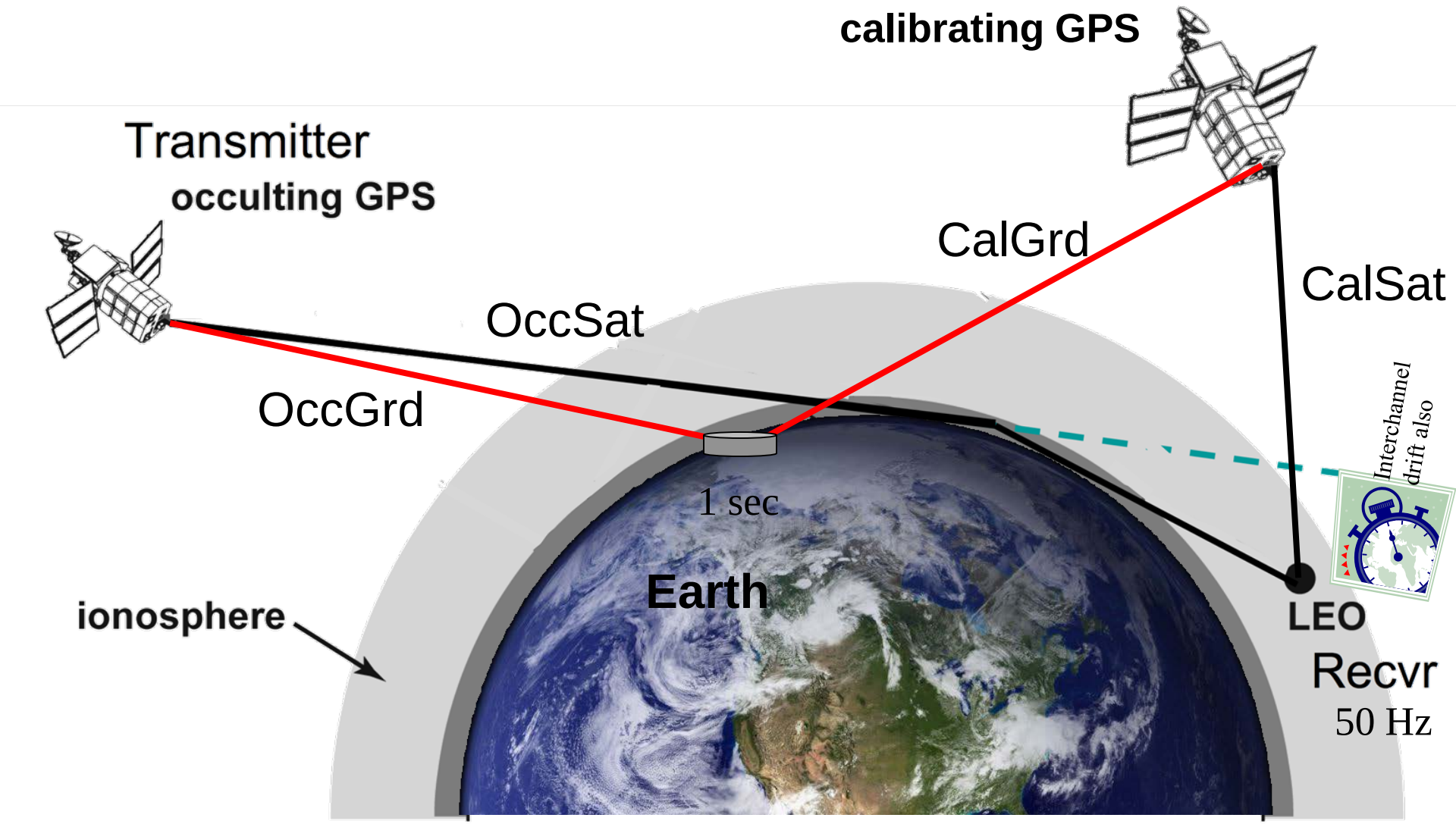
- Look angle ε changes by -1.3° over ~100 secs for an angular rate of 2.3×10^{-4}

Multipath



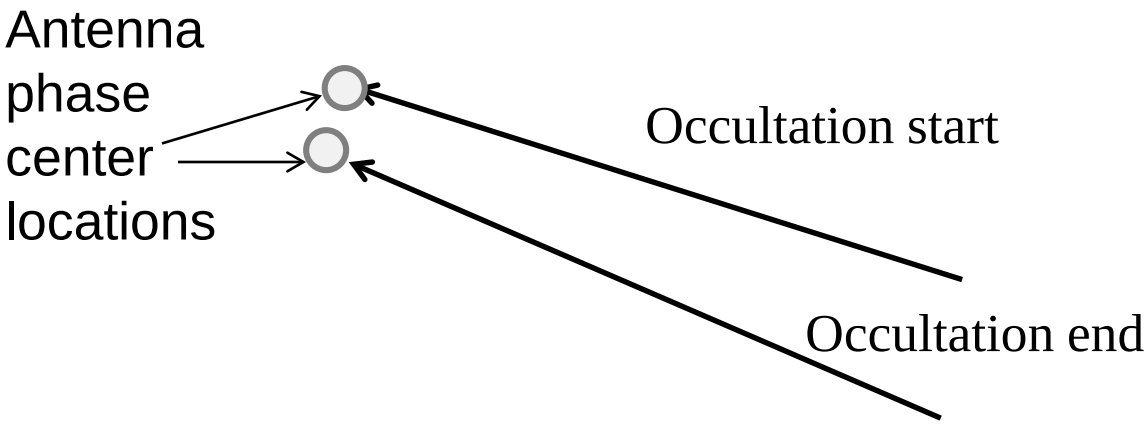
Assumes 10% amplitude reflection
CLARREO Requirement: 0.13 mm/sec

Receiver Clock Error



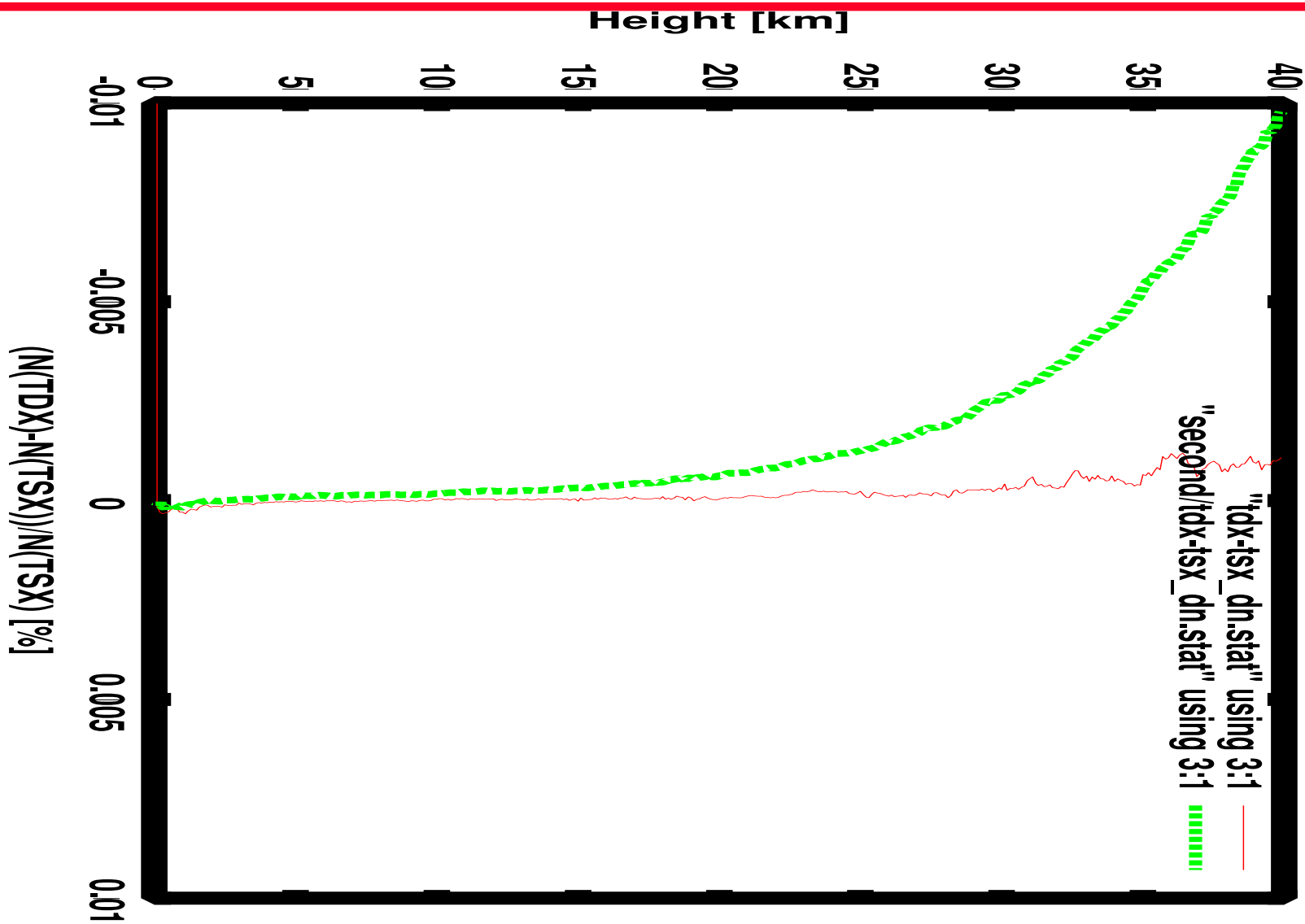
Phase Center Variations

- **Phase center variation with occulting angle**



- **Phase location wrt center of mass – accurately characterized to < 1 cm**

Incorrect Center-of-Mass Location
Identical Spacecraft

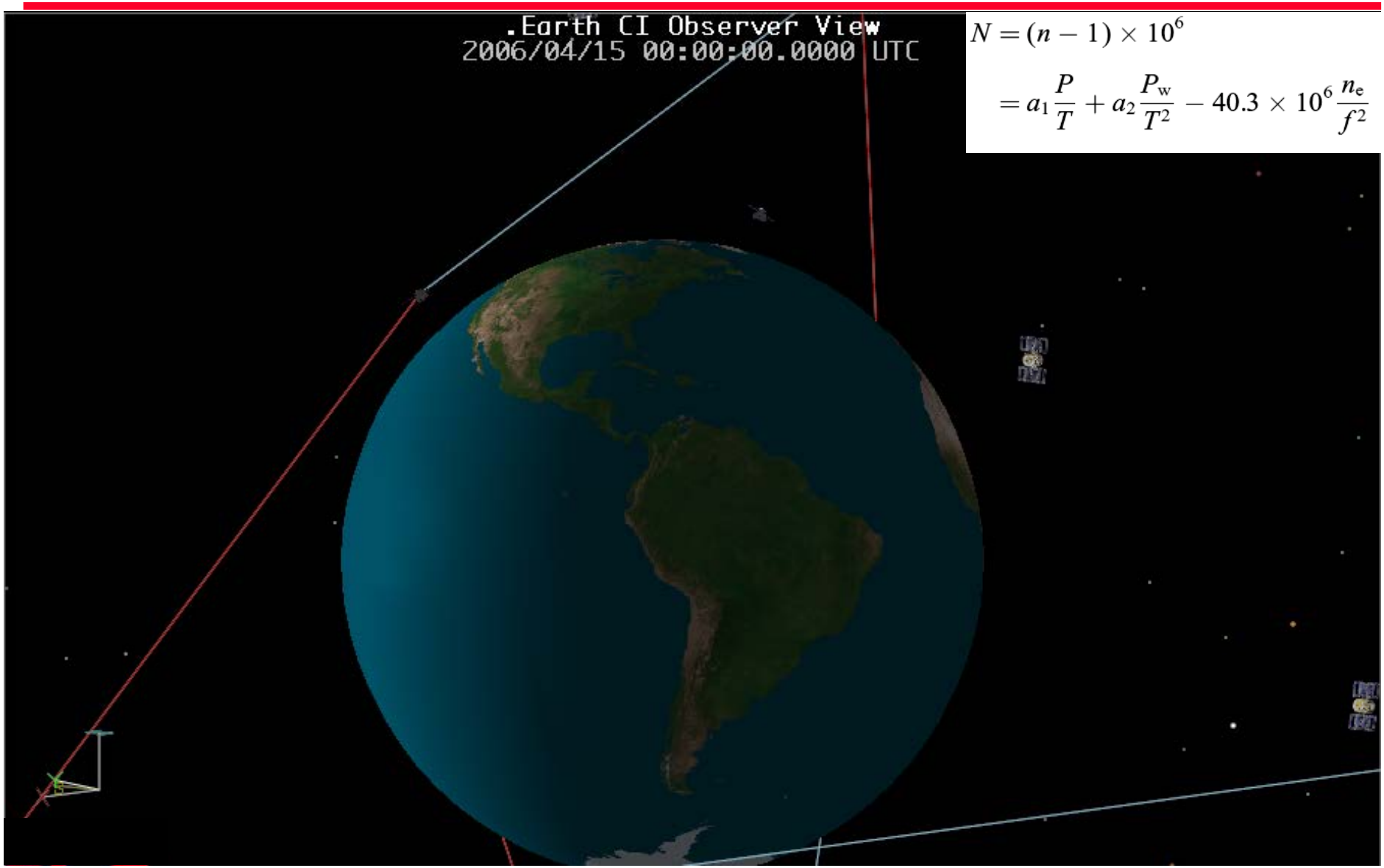


Concluding Remarks

- **Prospect of a heterogeneous RO constellation: instrument requirements for climate observing should be verified on the ground and in orbit**
- **More work needed to monitor receiver performance in orbit**
  - **RO maintains advantage of a relatively simple measurement physics that gives robust climate change information**
- **Not all sources of systematic error lead to significant climatic errors– this needs further work**
  - **"Long-term" drift/degradation is hard to get with RO – this is good**
- **Weather forecasting requirements and climate observing requirements are not overlapping**

BACKUP SLIDES

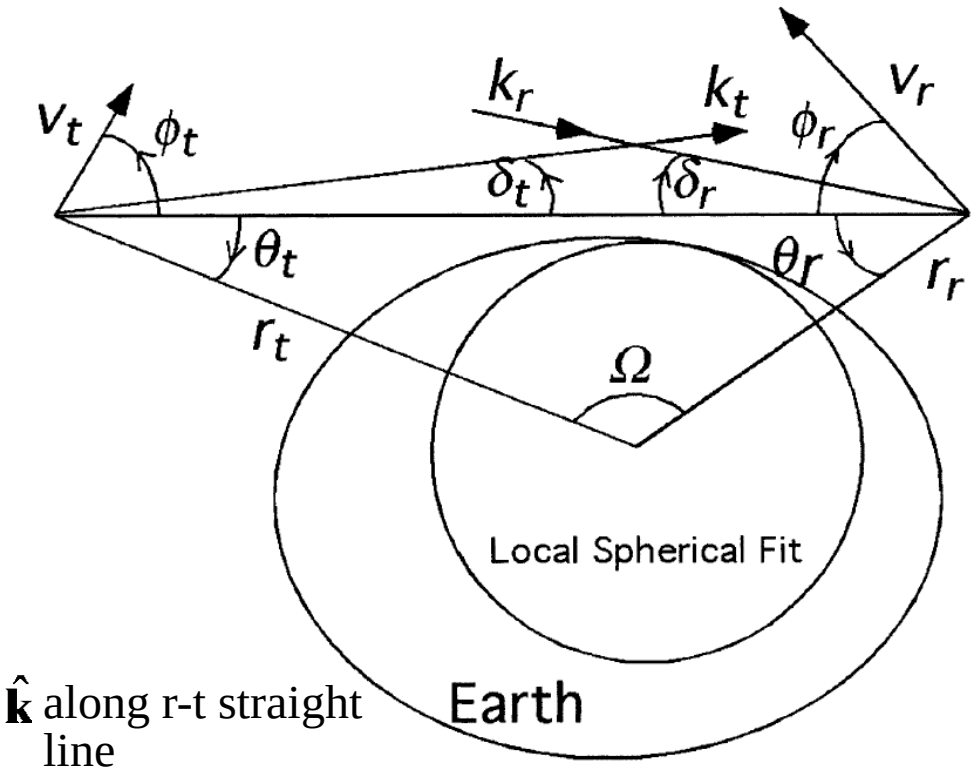
Radio Occultation



$$N = (n-1) \times 10^6$$

$$= a_1 \frac{P}{T} + a_2 \frac{P_w}{T^2} - 40.3 \times 10^6 \frac{n_e}{f^2}$$

GPS: Bending Angle to Doppler Shift



$\hat{\mathbf{k}}$ along r-t straight line

Rate of change of atmospheric delay:

$$\frac{d\gamma}{dt} = \lambda \Delta f = [\mathbf{v}_t \cdot \hat{\mathbf{k}}_t - \mathbf{v}_r \cdot \hat{\mathbf{k}}_r - (\mathbf{v}_t - \mathbf{v}_r) \cdot \hat{\mathbf{k}}]$$

Assuming spherical symmetry:

$$\frac{d\gamma}{dt} = (v_t \cos(\phi_t - \delta_t) - v_r \cos(\phi_r - \delta_r)) - (v_t \cos\phi_t - v_r \cos\phi_r)$$

$$a = r_t n_t \sin(\theta_t + \delta_t) = r_r n_r \sin(\theta_r + \delta_r)$$

Doppler shift: Δf

- Time is clearly the fundamental measurement in a radio occultation, leading to accurate measurements of Doppler shift
- Orbits must be known to high accuracy also (~cm, < 0.1 mm/sec)

Requirements Meeting

- **A meeting was held at JPL on February 2, 2010 to discuss the CLARREO RO requirements document**
  - **JPL, Harvard (Leroy), U. Arizona (Kursinski), UCAR, CLARREO project (Young and Corliss, Wielicki)**
- **Identify the error sources (13) that deserve more scrutiny, and possible new requirements (23) levied on the observatory, processing system, receiver, etc.**

Stephen Leroy

Requirements partitioning (18km)

$$\underbrace{\sigma^2_{\text{error}}\left(\frac{1\,\text{yr}}{\tau_{\text{mission}}}\right)}_{0.03\%} = \underbrace{\sigma^2_{\text{systematic}}}_{0.017\%} + \underbrace{\sigma^2_{\text{1-yr random}}\left(\frac{1\,\text{yr}}{\tau_{\text{mission}}}\right)}_{0.025\%}$$

Fractional refractivity error

Refractivity Requirements

- There is no clear proof that current GPS RO measurements satisfy CLARREO mean refractivity requirement of 0.03%.
- However, increased SNR and reduced multipath from the instrument along with improved processing to reduce errors due to ionospheric residuals and Abel upper boundary conditions should ensure that the CLARREO requirements can be met.

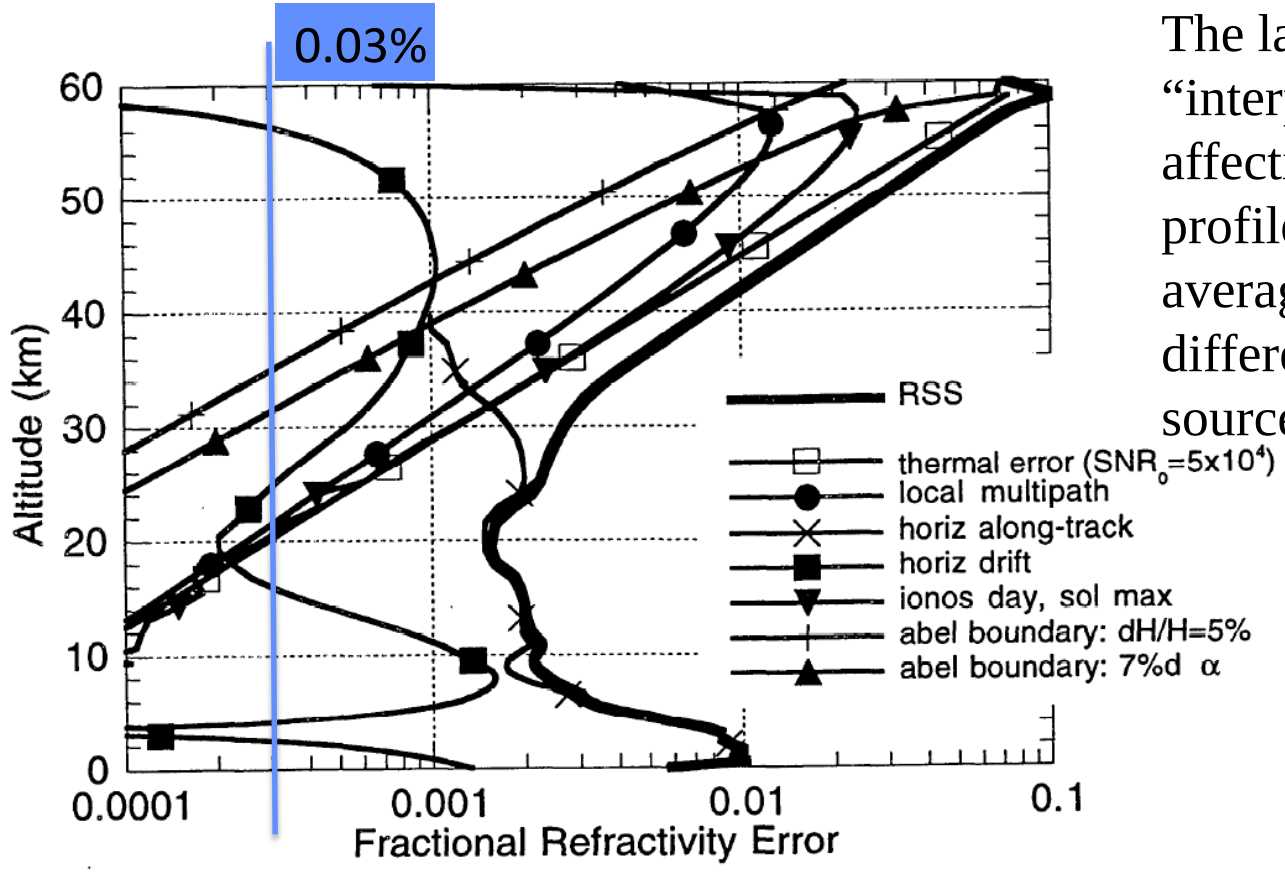
Survey of Existing Estimates (5-20 km)

Theoretical	Comparison with Others (Measurements and Analyses)	Comparison with Self (Precision, Sensitivity tests)
End-to-end calculations (RMS ~ 0.2% from Kursinski et al., 1997)	Radiosondes (Mean ~ 0.2 %, RMS ~ 1.5 % in refractivity from Kuo et al., 2005)	CHAMP-SACC, COSMIC-COSMIC pair analysis (RMS ~ 0.2%-0.4% in refractivity from Schreiner et al., 2007 and Hajj et al., 2004)
	Satellite measurements: AIRS, MLS, MSU, etc. (RMS ~ 1.5 K from various pubs; implies ~ 1% in refractivity)	Comparison among different processing centers (Zonal means ~ 0.1% in refractivity from Ho et al., 2010)
	ECMWF/NCEP (RMS ~ 1% in refractivity from various pubs)	

Chi Ao, JPL

Theoretical Estimates

KURSINSKI ET AL.: OBSERVING EARTH'S ATMOSPHERE BY OCCULTATION USING GPS



The largest errors are "interpretive" affecting individual profiles. Climate averages provide different error sources.

1997

Figure 10. Summary of refractivity errors versus height. Thermal error, 1 s SNR=5 x 10^4; local multipath, 10 mm rms spread over 0.01 Hz; horizontal refractivity structure, along track from simulation and horizontal motion of ray path tangent point from tropospheric and stratospheric climatologies near 30°S for June-July-August; ionosphere error, daytime, solar maximum conditions; Abel boundary errors, 7% in α, 5% in H_α.

Errors Requiring Further Analysis (Sample)

Category	Component	Description	Comments/Mitigation
ERROR E.1	Systematic	"Worst-case" ***correlations among systematic biases*** must be taken into account, for example, between missions or interannual error correlation. Biases may be correlated within their error bars. How does that affect the time-to-detect analysis?	Requires additional analysis, including plausible error sources that create correlations.
ERROR E.9	Mission	***Sampling error for the threshold mission of one satellite*** may exceed requirements. Opinions differed on adequacy of existing analysis to handle the one-satellite case, and whether one satellite is sufficient.	
ERROR E.10	Systematic	***Horizontal grazing error could create biased climate averages.*** Grazing occultations across semi-stationary features of the atmosphere might cause errors that change slowly (inter-annually).	Will rising and setting occultations help to compensate this error in climate averages?
ERROR E.13	Systematic	***The contribution of liquid water to the refractivity will be known to within (TBD refractivity units) for each occultation.***	Liquid water contribution must be bounded.

Additional Requirements (Sample)

Category	Component	Description	Comments/Mitigation
REQMNT R.4	Observatory	***Survey center of mass of the observatory.*** Corliss wants to know how accurately center of mass needs to be surveyed throughout the mission duration. Issues: propellant, vertical and horizontal components, articulating solar array.	
REQMNT R.5	Observatory	***The observatory shall carry a USO*** (10^{-13} over 1 second) to permit multiple paths to SI traceability to be carried out.	
REQMNT R.10	Processing and Instrument	***The processing system will use three frequencies to mitigate ionospheric error and the instrument will track three GNSS frequencies.***	Correction to $<5x10^{-8}$ rad is achievable. We lack consensus on this requirement.
REQMNT R.21	Instrument	The ***occultation scheduling algorithm on the instrument*** shall not increase the sampling bias more than (TBD)% relative to the simulation studies used to determine the sampling bias.	We need to make sure that the occultation scheduler provides suitable occultation distributions.
REQMNT R.23	Observatory	The observatory shall carry satellite laser ranging mirrors to provide multiple independent pathways to determining orbit error.	This needs further review.

Summary (2010)

- **Extensive review of requirements and potential error sources has occurred**
  - **By no means complete**
- **Discussions have been held with the project on implications for the antenna**
- **New technology that can aid SI-traceability has been identified**
- **The TriG receiver is under development now**
- **COSMIC-Follow-On is an encouraging development that might benefit CLARREO**

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