Open-Loop Tracking and Water Vapor Retrieval Accuracy for GPS Radio Occultations

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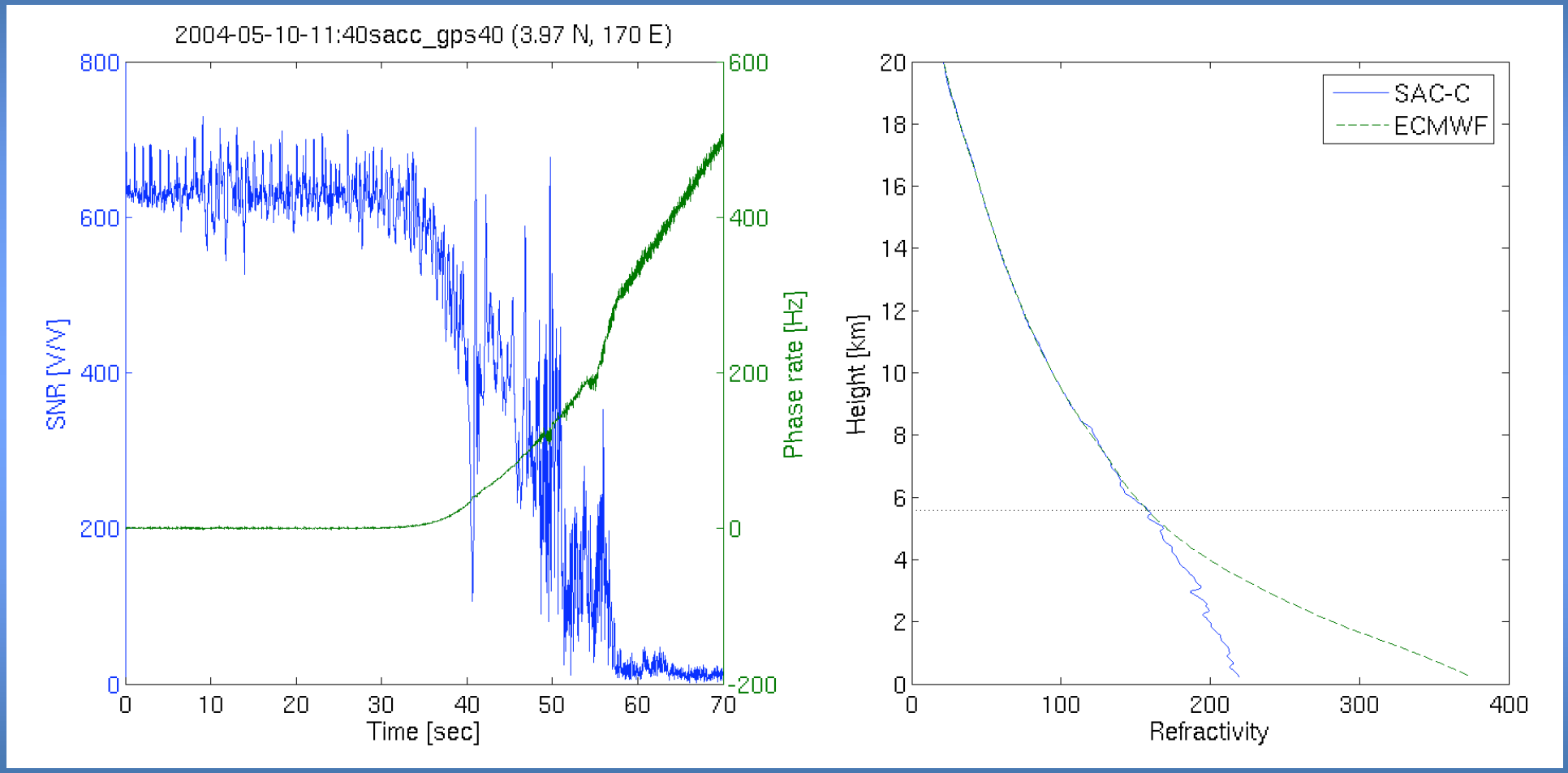
Outline

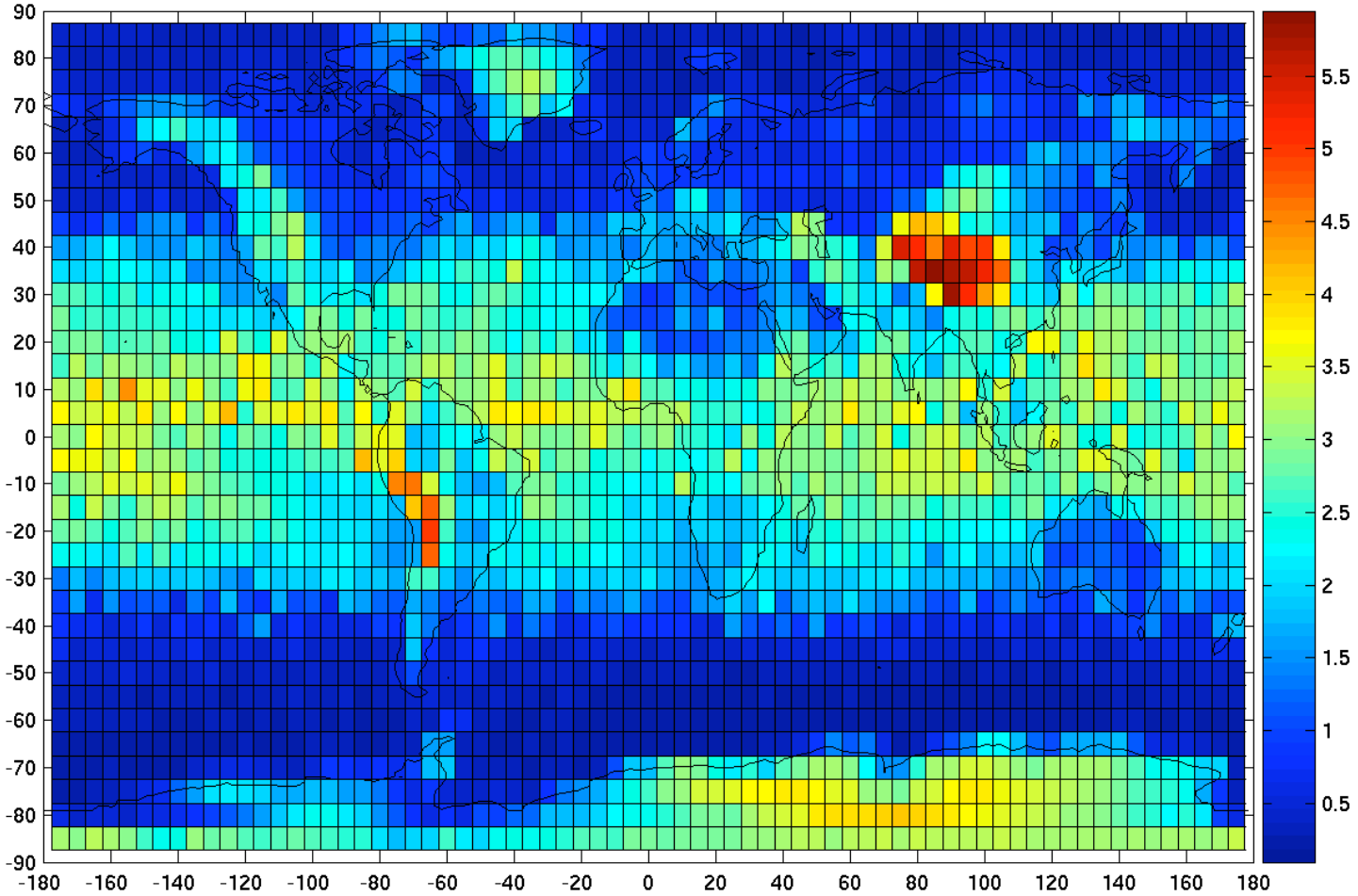
I. Open-loop (OL) tracking
   - Description of OL models used on COSMIC & SAC-C
   - Assessment

II. Accuracy of OL water vapor retrievals
   - Theoretical estimates
   - Comparisons with global analyses, radiosondes

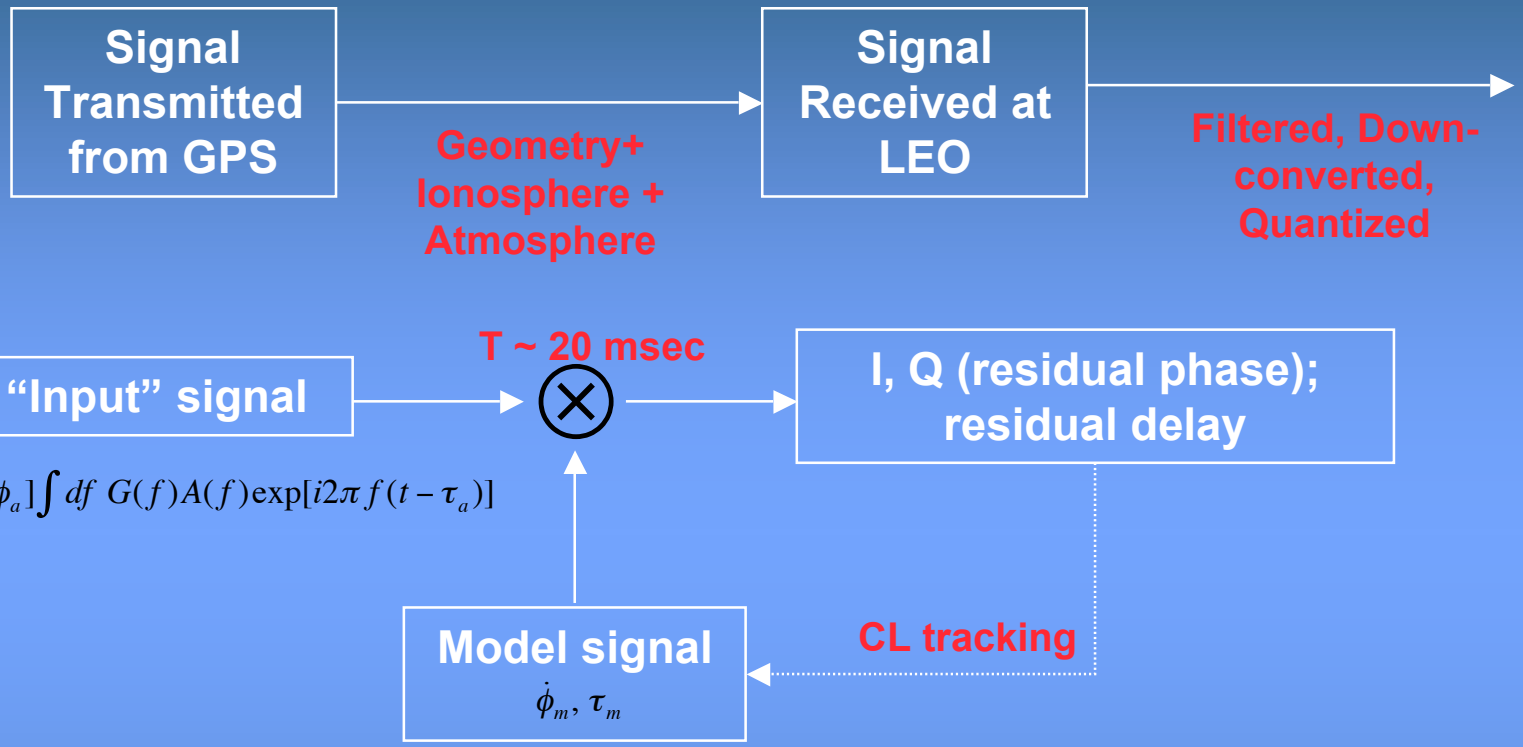
The Problem with Closed-Loop Tracking



Depth Penetration (CL): CHAMP



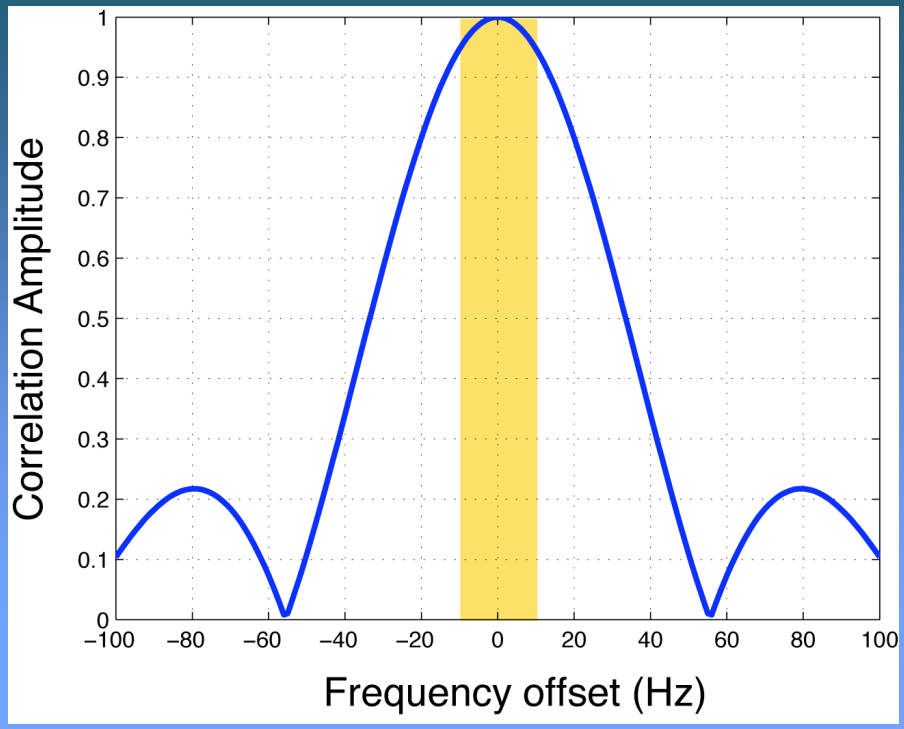
Tracking GPS Occultation Signal



$$u_\ell(t) = \langle V(t)V_m(t,\ell)\rangle$$

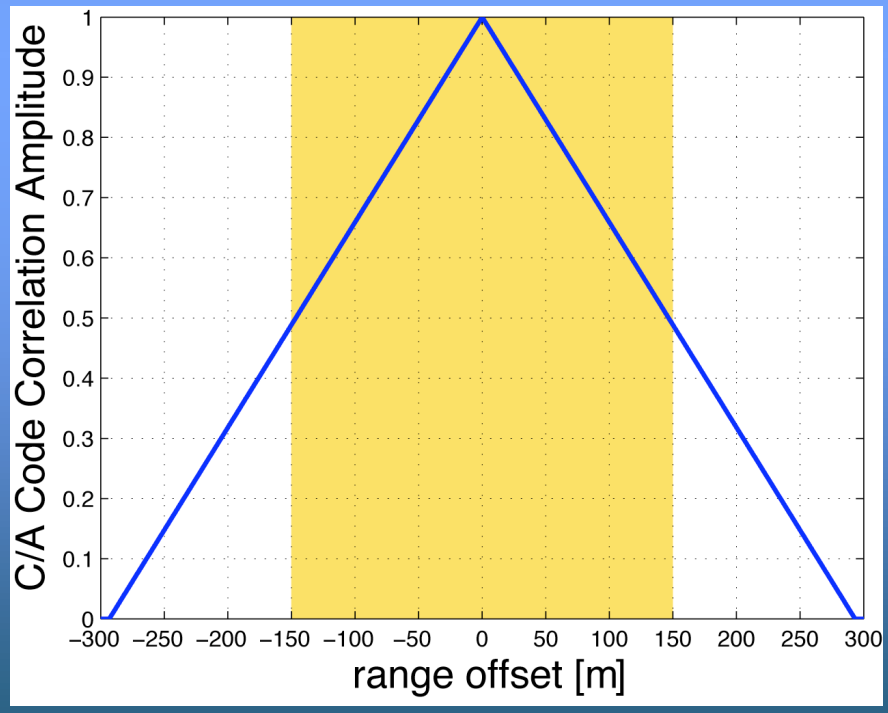
$$\sim \exp[i2\pi\phi_d]\left[\frac{\sin(\pi\dot{\phi}_d T)}{\pi\dot{\phi}_d T}\right]\int df\ G(f)\left[\frac{\sin(\pi f T_{C/A})}{\pi f T_{C/A}}\right]^2 \exp[i2\pi f(\tau_a-\tau_m-\ell s)]$$

$$\phi_d = \phi_a - \phi_m$$



Frequency model offset causes amplitude reduction & cycle slips.

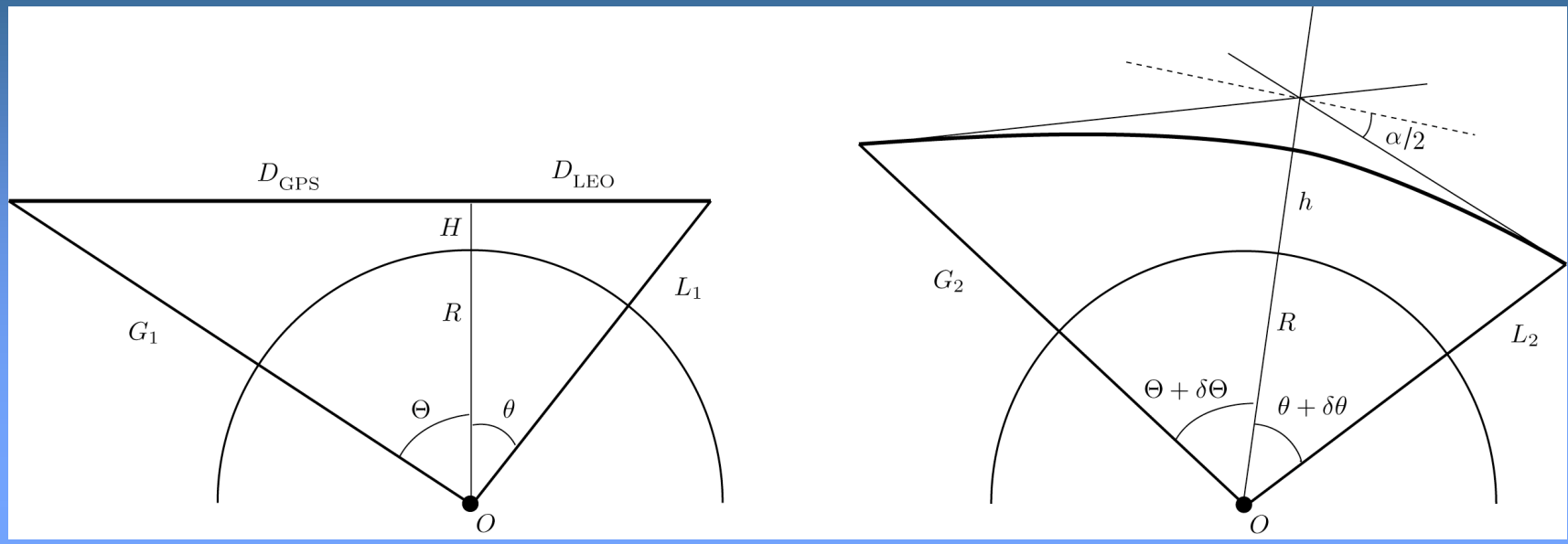
Delay model offset causes amplitude reduction



OL Options

- **Narrowband Digital Recording (BlackJack)**
  - Needs Accurate Atmospheric Model (± 10 Hz in Doppler and ± 150 m in range) but only ~ 50 MB/Day
- **Moderate Wideband Digital Recording (MetOp/GRAS?)**
  - Needs Only Geometric Model, Special DSP HW,
    ~ 450 MB/Day
- **Very Wideband Digital Recording**
  - No OL Model, Simple HW, but... ~800 GB/Day
  - Intensive Ground Based Processing

Predicting Atmospheric Doppler



$$\alpha(h) + \left[\frac{1}{D_{GPS}} + \frac{1}{D_{LEO}}\right](H - h) = \delta\Theta + \delta\theta$$

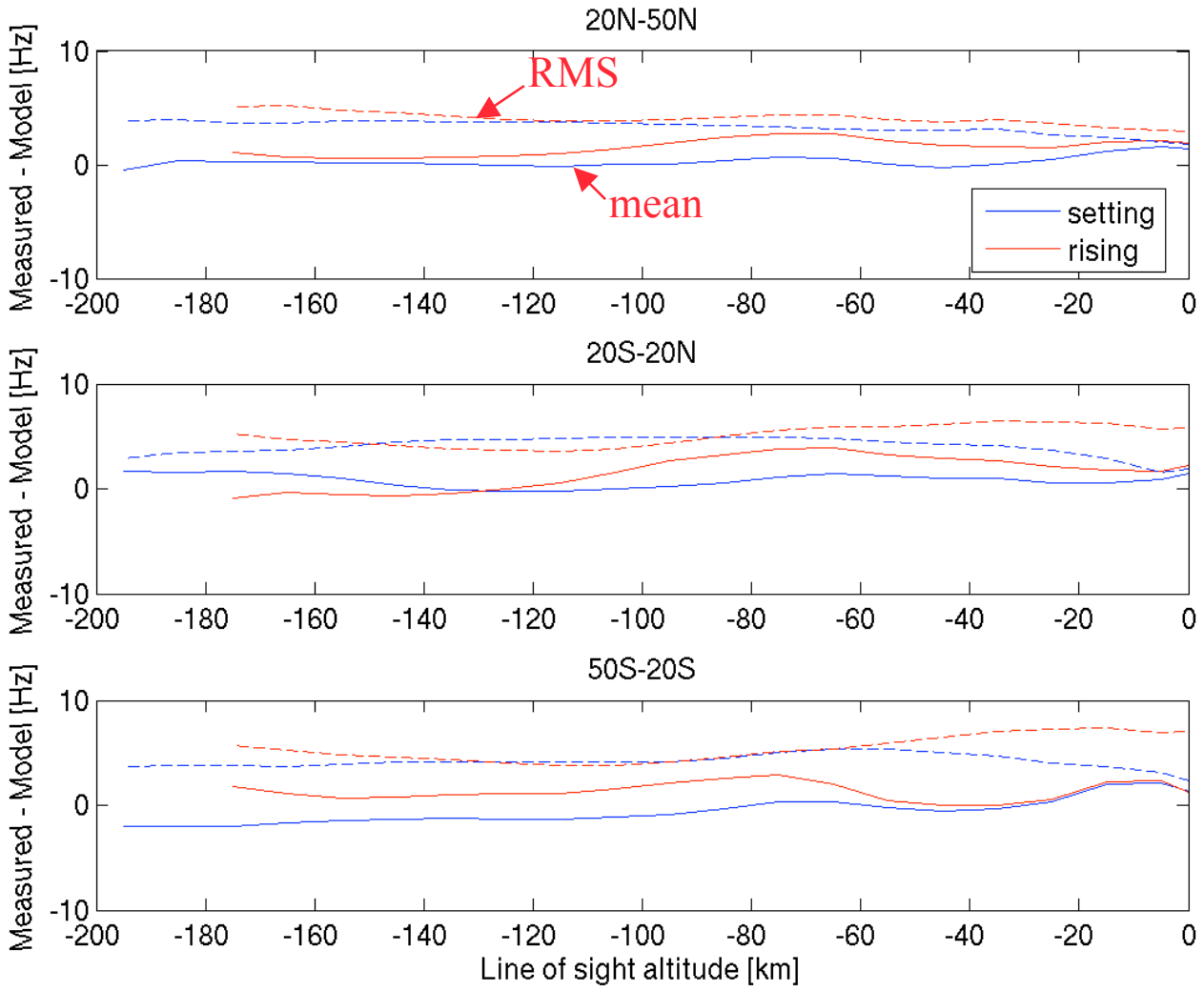
$\alpha_j(h_j)$ *from data fitting*

→ **Bending as a function of time**

↓

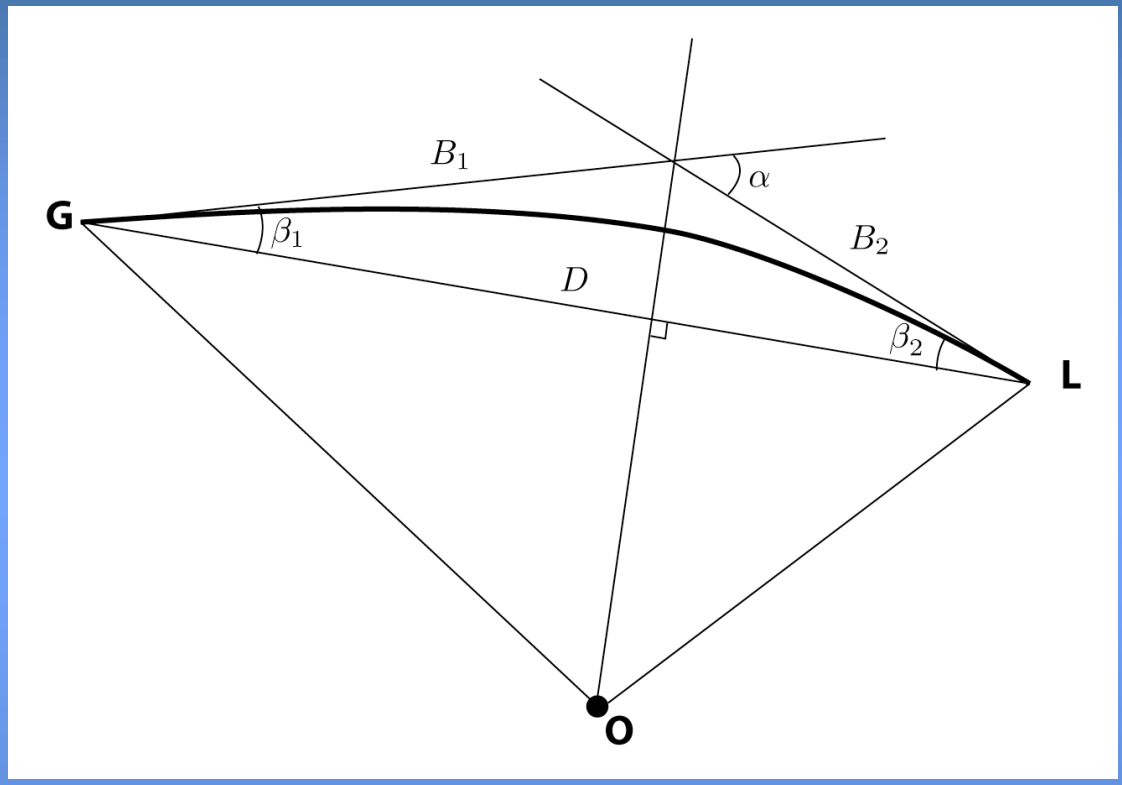
Doppler as a function of time

How Good is the Doppler Model?



Predicting Atmospheric Range (Delay)

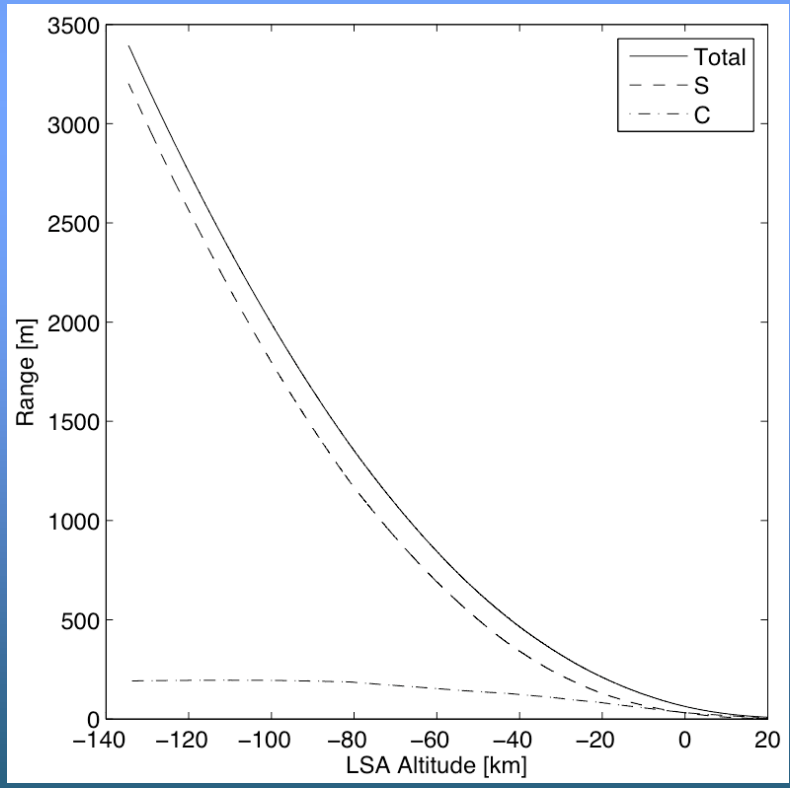
(needed for rising occultations)



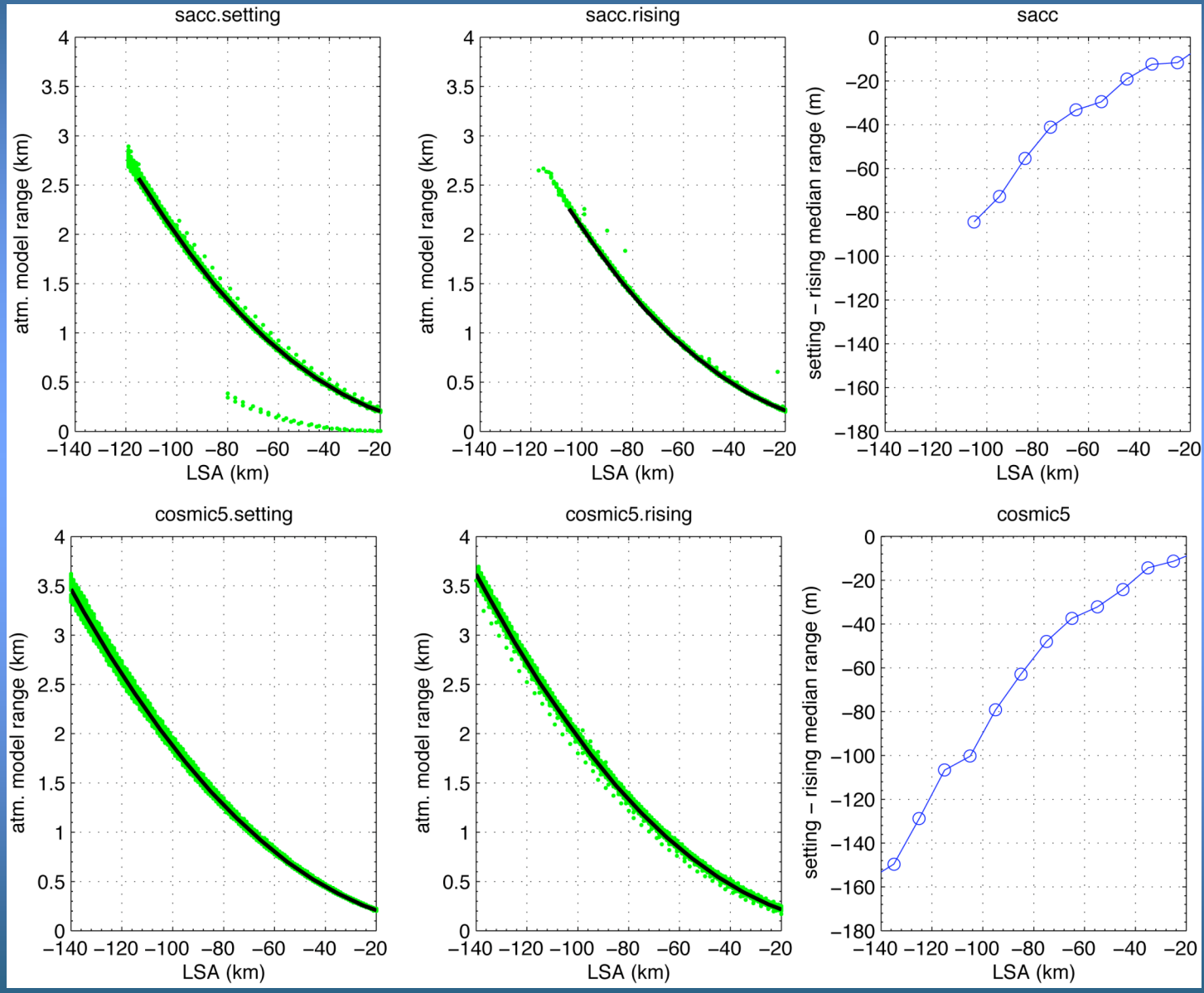
$$GL - D = S + C$$

$$S = B_1 + B_2 - D$$

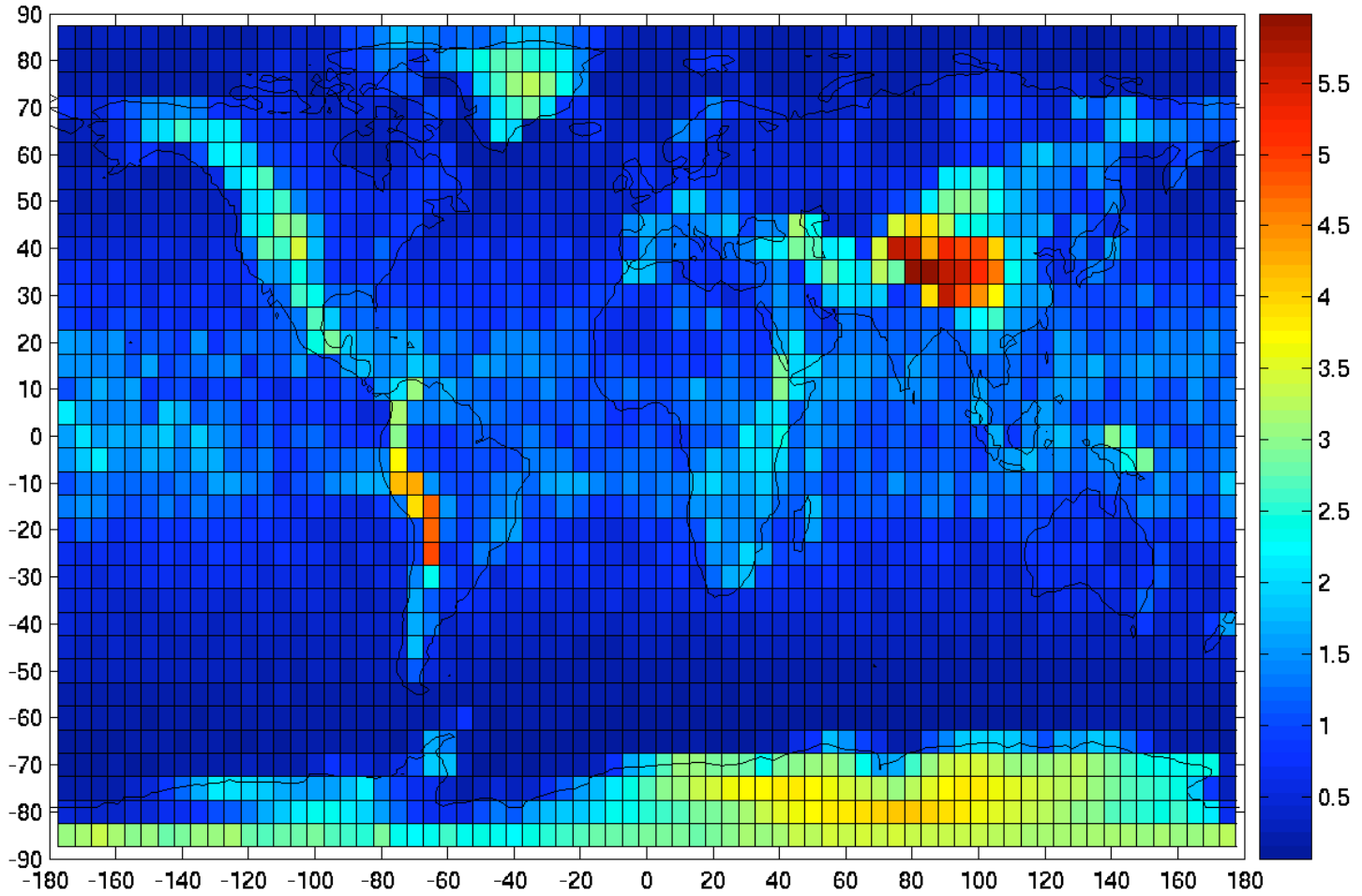
$$C = data\ fitting$$



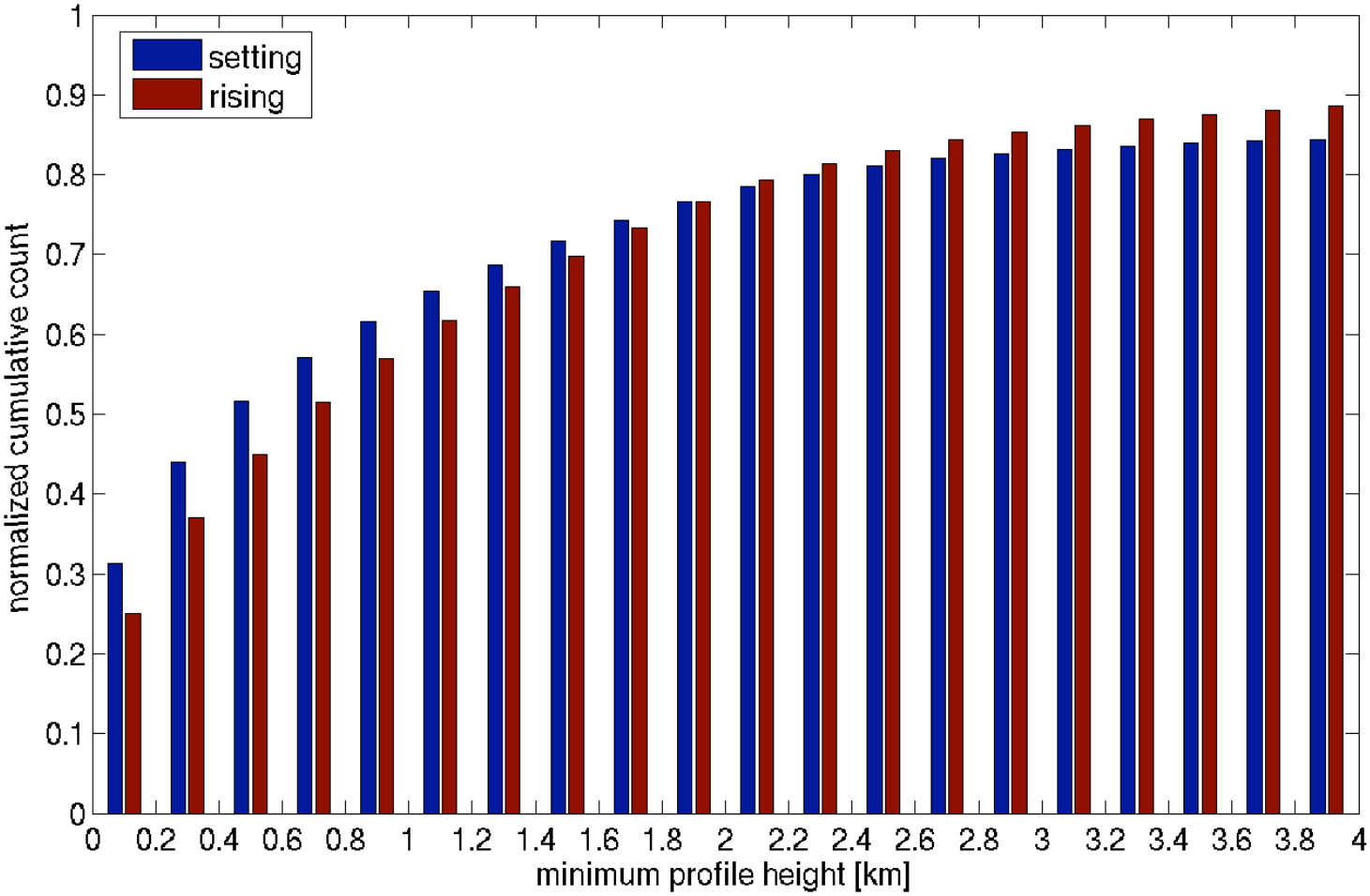
How Good is the Range Model?



Depth Penetration (OL): COSMIC



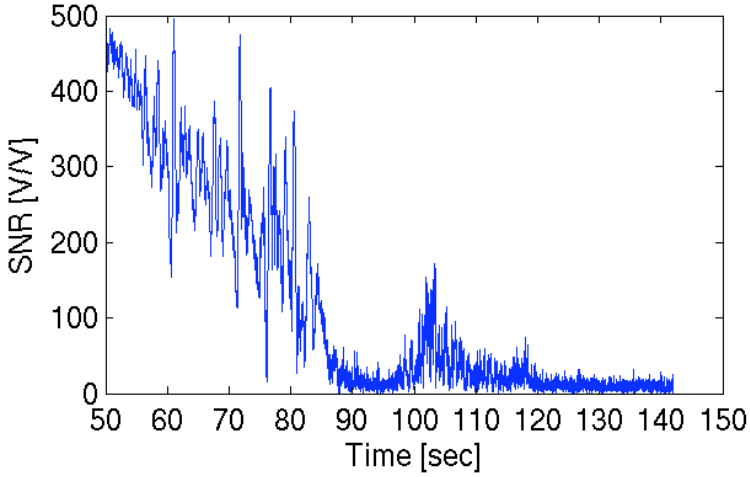
Setting vs. Rising (Over Ocean)

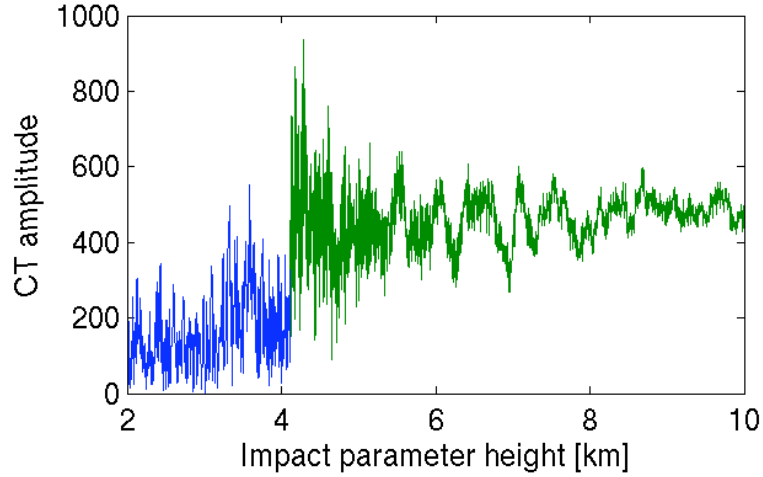


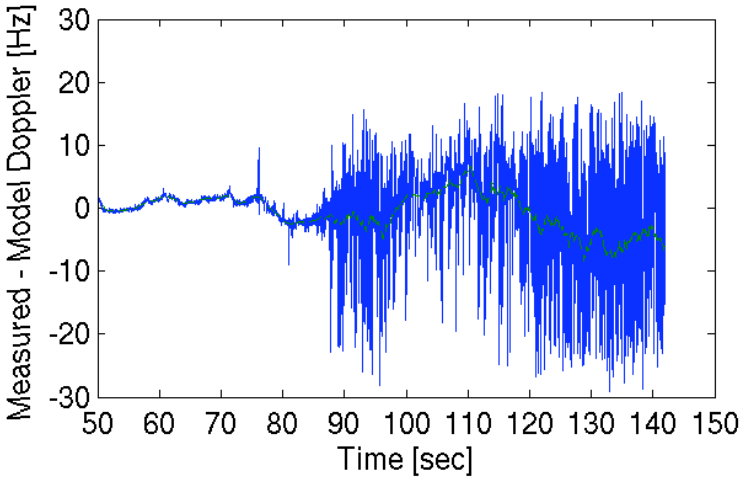
Summary & Discussion

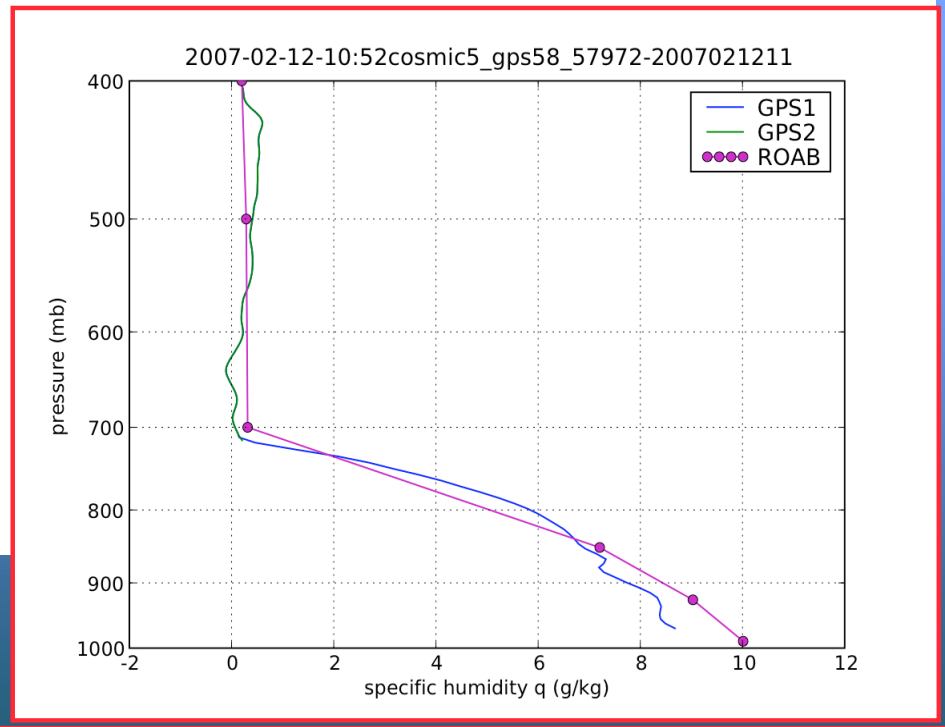
- OL tracking on COSMIC and SAC-C allows RO observations to probe deeper into free troposphere/PBL.
- Doppler and range models were shown to be “reasonably” accurate.
- But… < 50% reach the surface. Can this be improved?
  - Better OL models
  - Higher bandwidth (100 Hz vs. 50 Hz)
  - Minimize on-board “glitches”

Example


SNR [V/V]
Time [sec]


CT amplitude
Impact parameter height [km]


Measured - Model Doppler [Hz]
Time [sec]


2007-02-12-10:52cosmic5_gps58_57972-2007021211
GPS1
GPS2
ROAB
pressure (mb)
specific humidity q (g/kg)

Water Vapor Profile Retrievals

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

$$\frac{dP}{dz} = -\frac{m_d g}{R}\frac{P}{T} - \frac{(m_w - m_d)g}{R}\frac{P_w}{T}$$

"Traditional" approach [Kursinski *et al.*, 1995]:

Assume *T* from global weather analyses and solve *P*, P_w iteratively

- **1D Var [Healy and Eyre, 2000]**
- **Direct (non-iterative) retrieval assuming both *T*, *P* from the analyses [Heise *et al.*, 2006]**

Uncertainty in Water Vapor

Kursinski and Hajj [2000]

$$\Delta q = (cT + q)\frac{\Delta N}{N} + (cT + 2q)\frac{\Delta T}{T} + (cT + q)\frac{\Delta P_s}{P_s}$$

$$\langle \Delta q \rangle = (cT + q)\frac{\langle \Delta N \rangle}{N}$$

$$\sigma_q^2 = (cT + q)^2 \frac{\sigma_N^2}{N^2} + (cT + 2q)^2 \frac{\sigma_T^2}{T^2} + (cT + q)^2 \frac{\sigma_{P_s}^2}{P_s^2}$$

ignored

Uncertainty in LT Refractivity

Extensive theoretical analysis by Kursinski *et al*. [1997] (Too optimistic?)

Kuo *et al*. [2005] suggests ~ 3x larger errors (based on analysis of 1 month of CHAMP & SAC-C CL data)

Main sources of error:

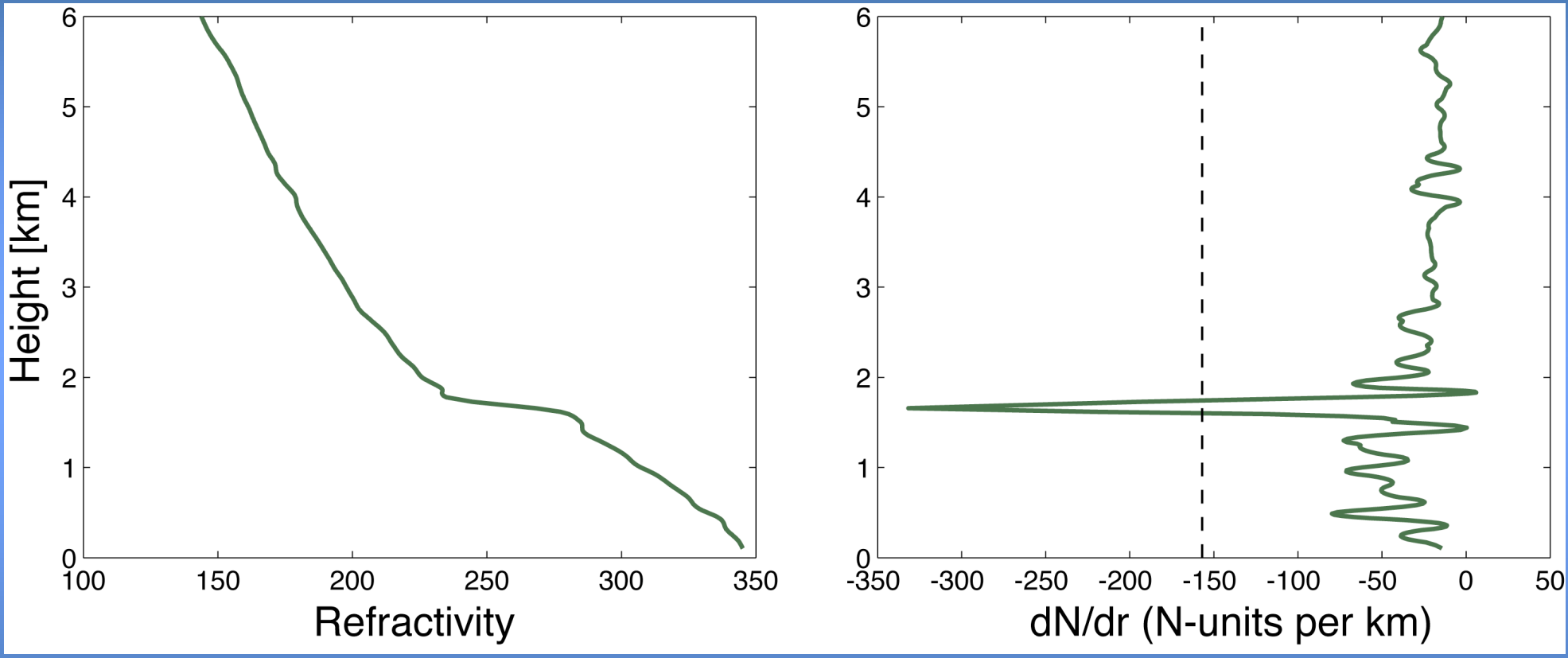
- **Horizontal gradient (along-track)**

  not considered in Kursinski et al. [1997] --

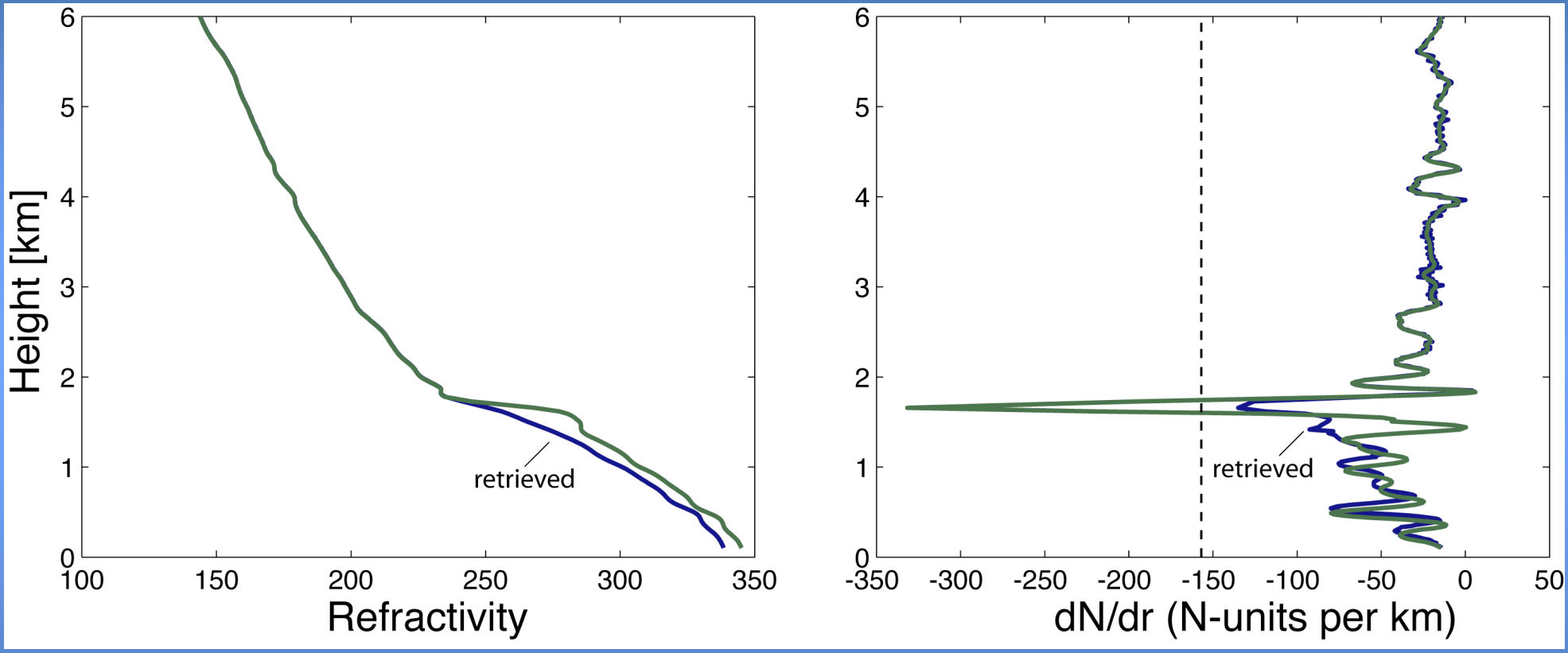
- **Negative bias from the presence of elevated ducts due to sharp water vapor layers (often associated with strong inversion layer on top of PBL)**

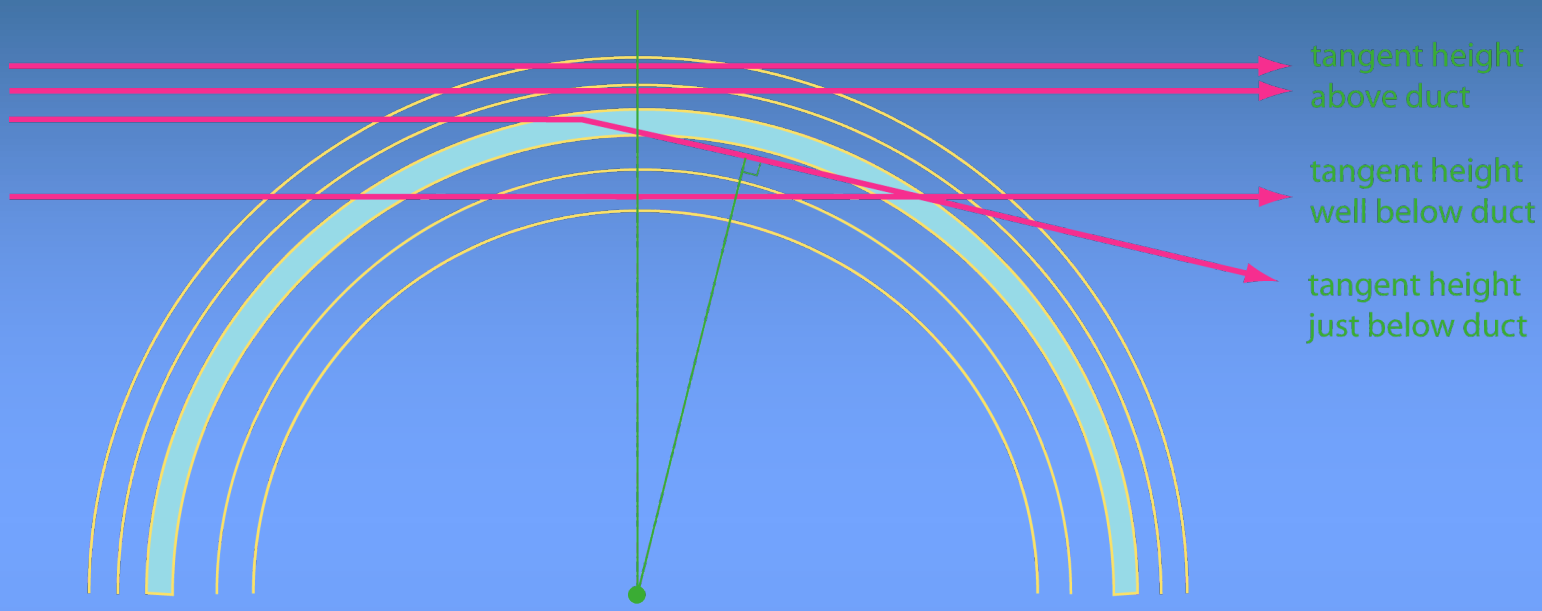
- **Instrument errors (cycle slips, noise): not a big contributor for OL?**

Ducting Bias



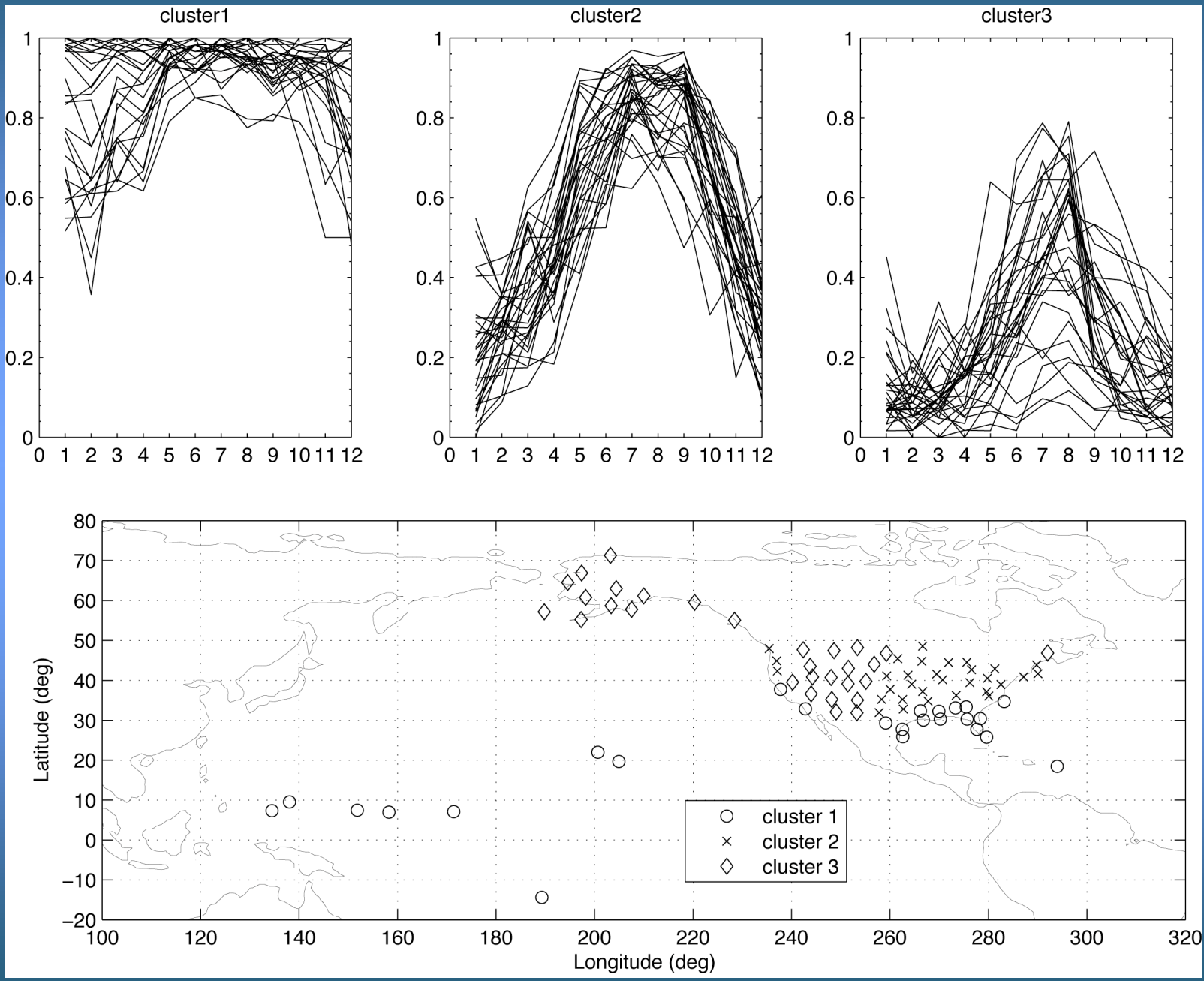
Ducting Bias



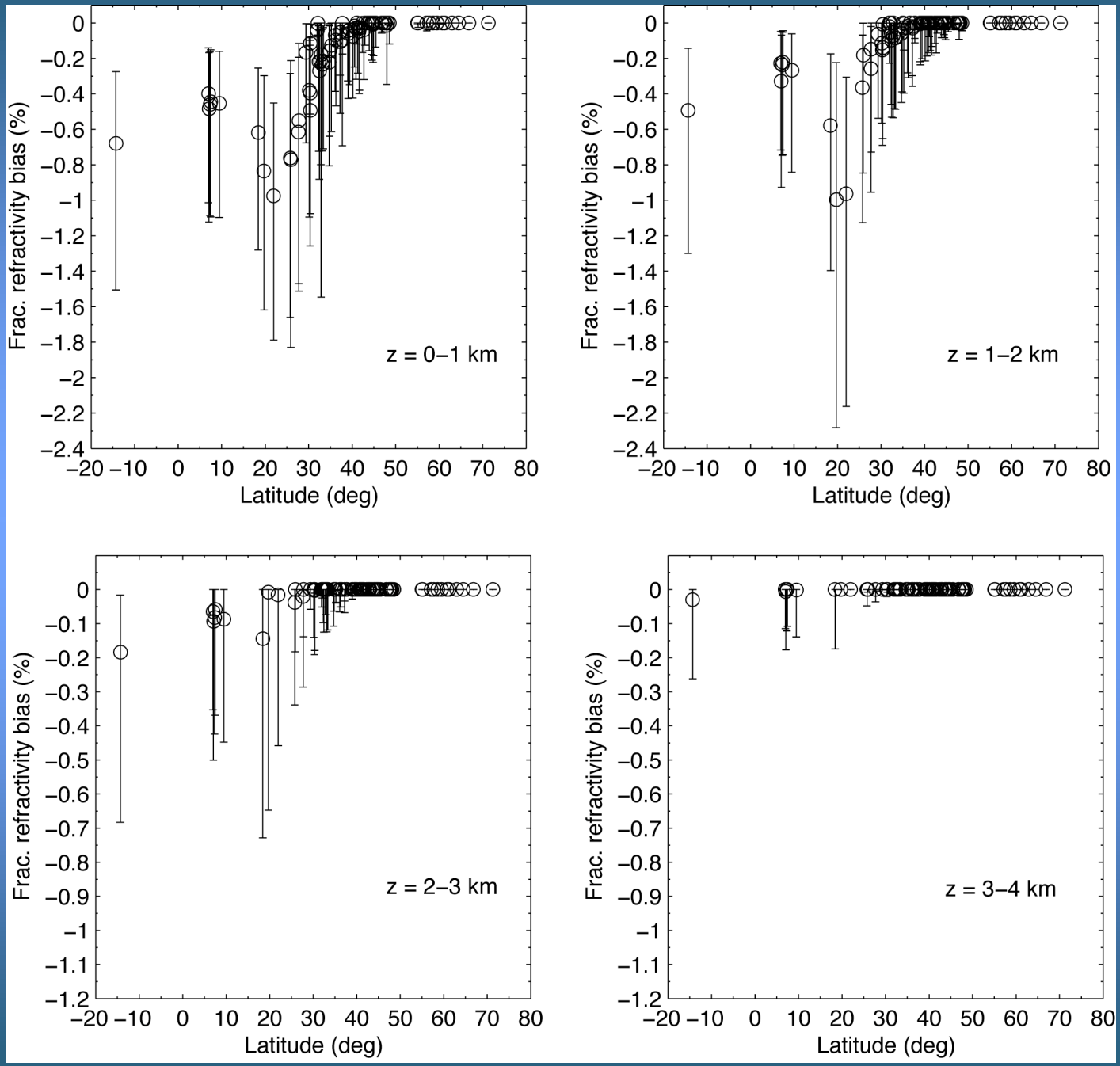


Non-existence of tangent points within the duct means that Abel inversion (onion-peeling) will fail within and below the duct

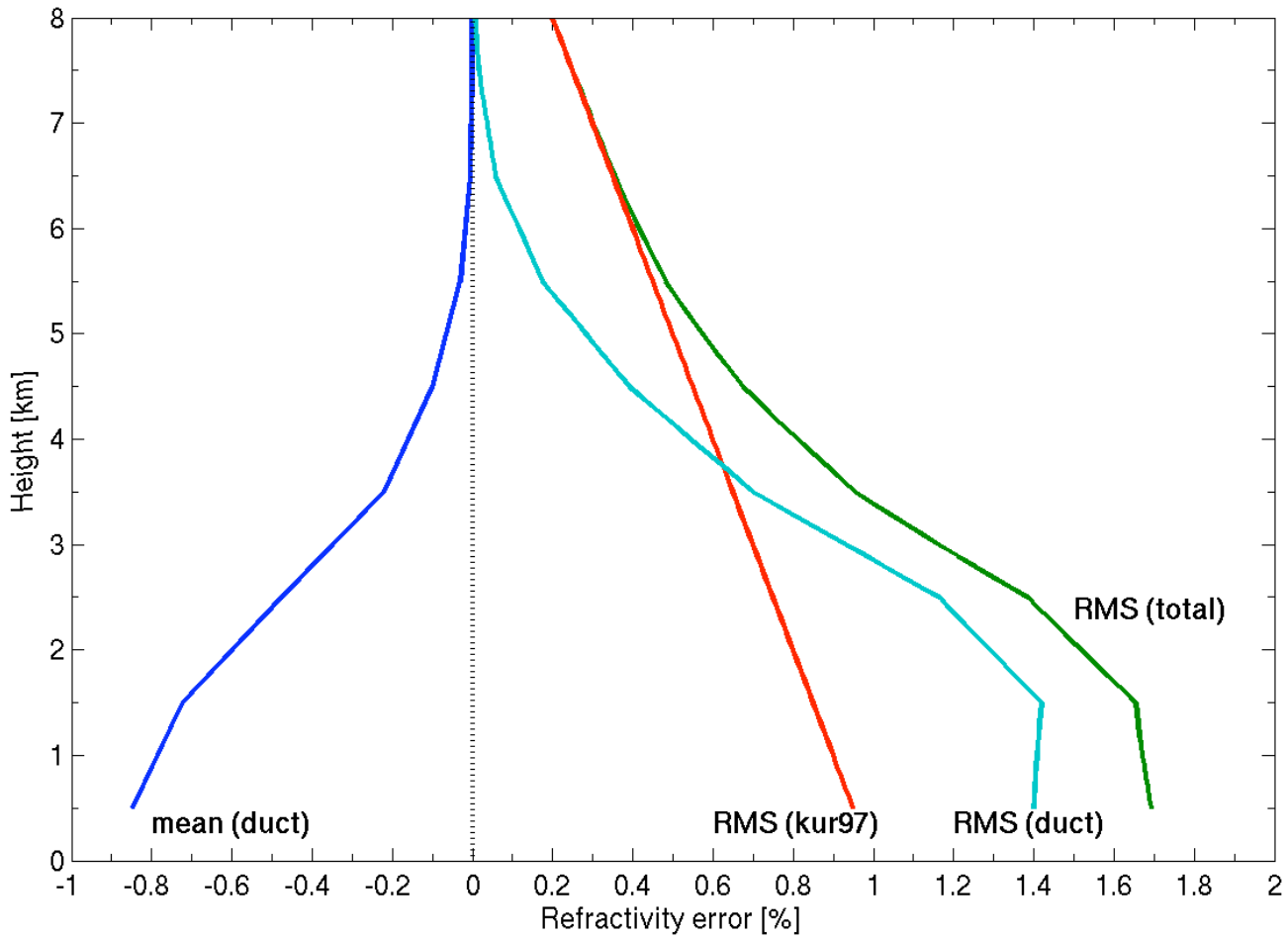
Duct frequency based on high-resolution radiosondes



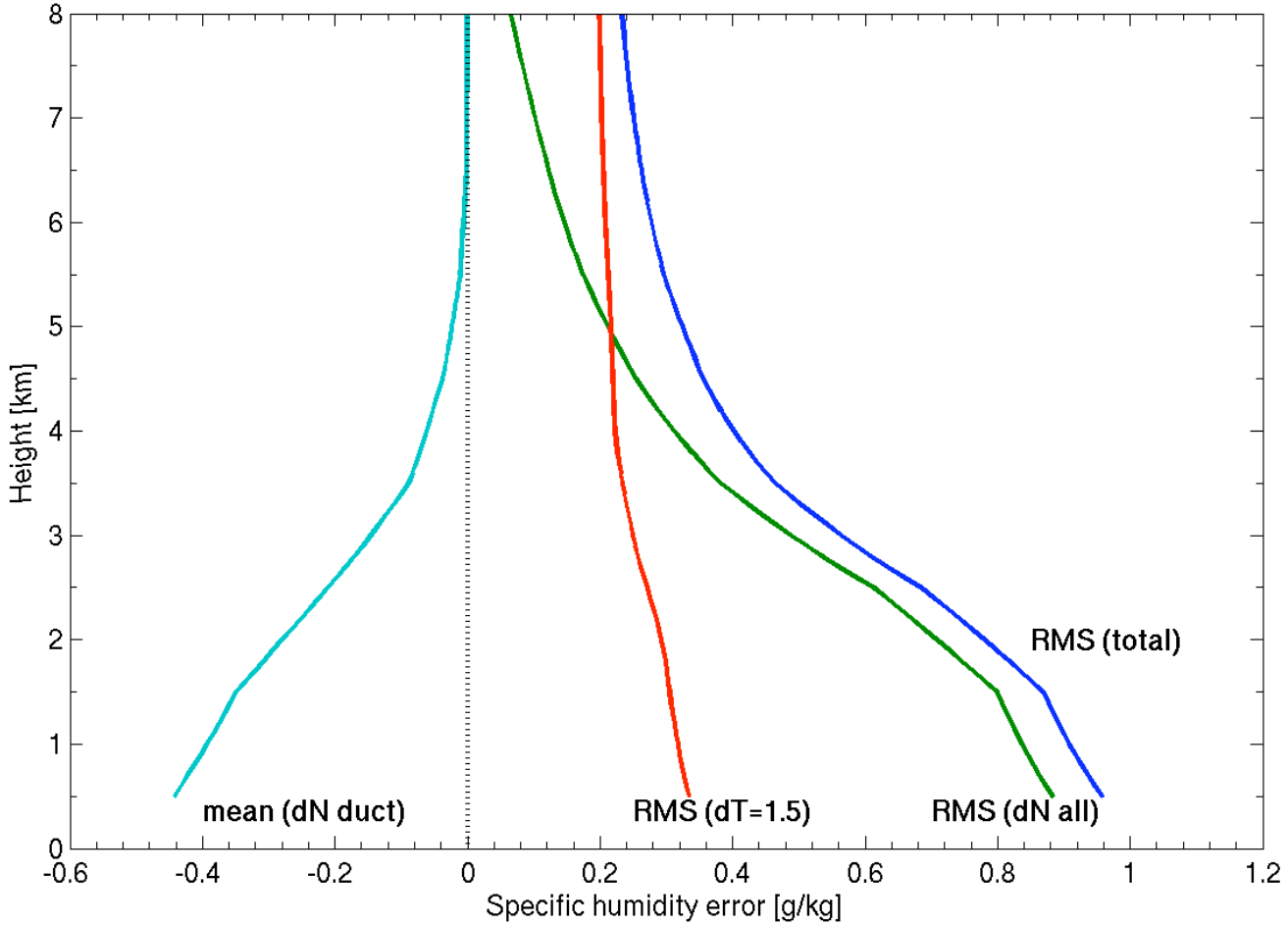
Refractivity biases



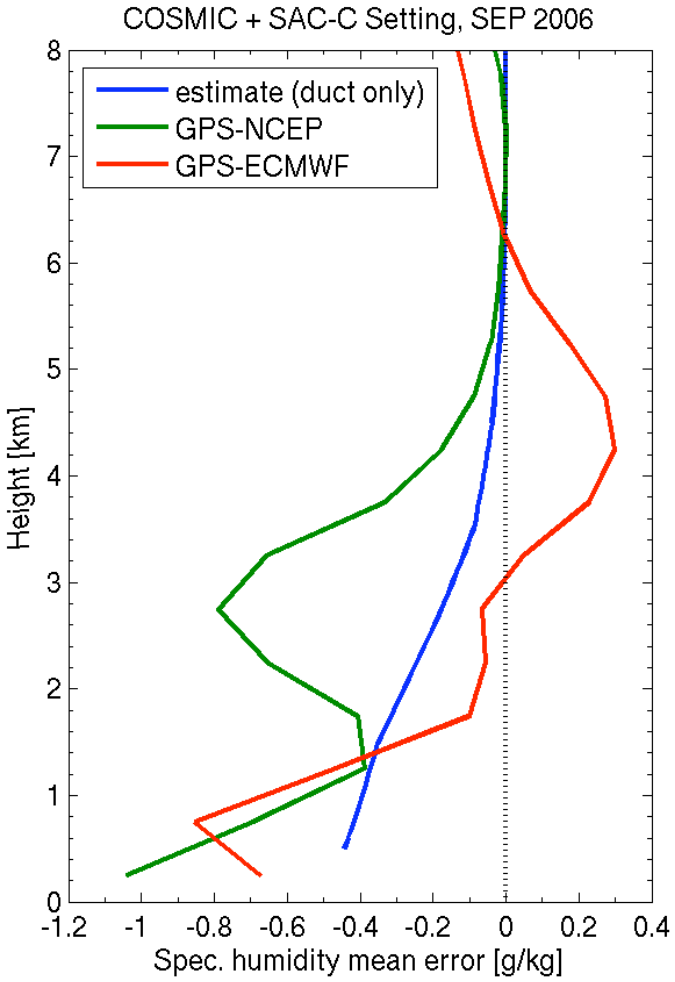
Estimate of Refractivity Uncertainty (Tropics)

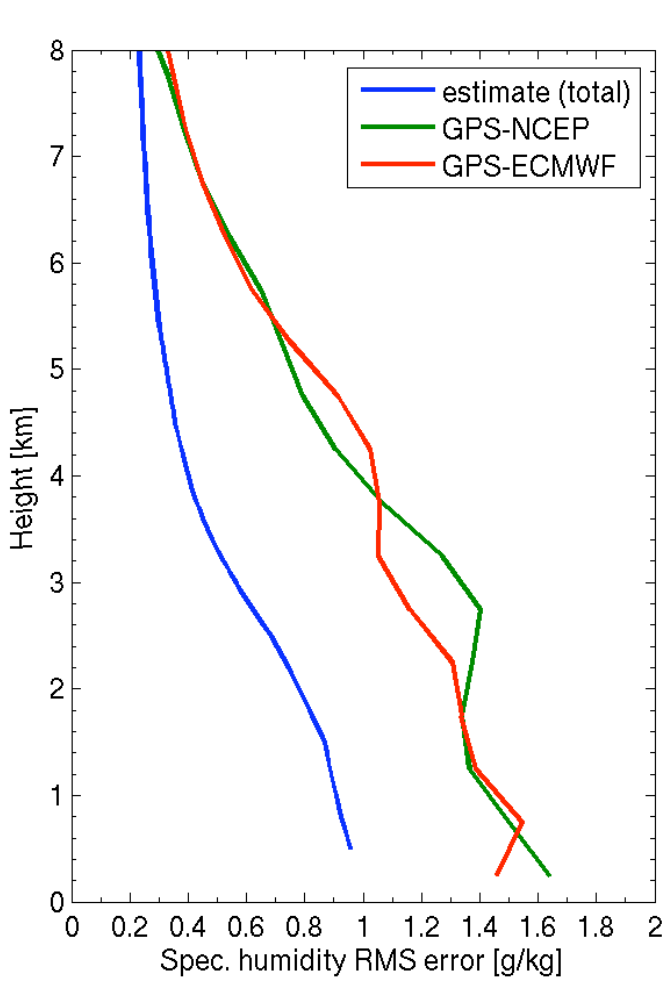


Estimate of Water Vapor Uncertainty (Tropics)



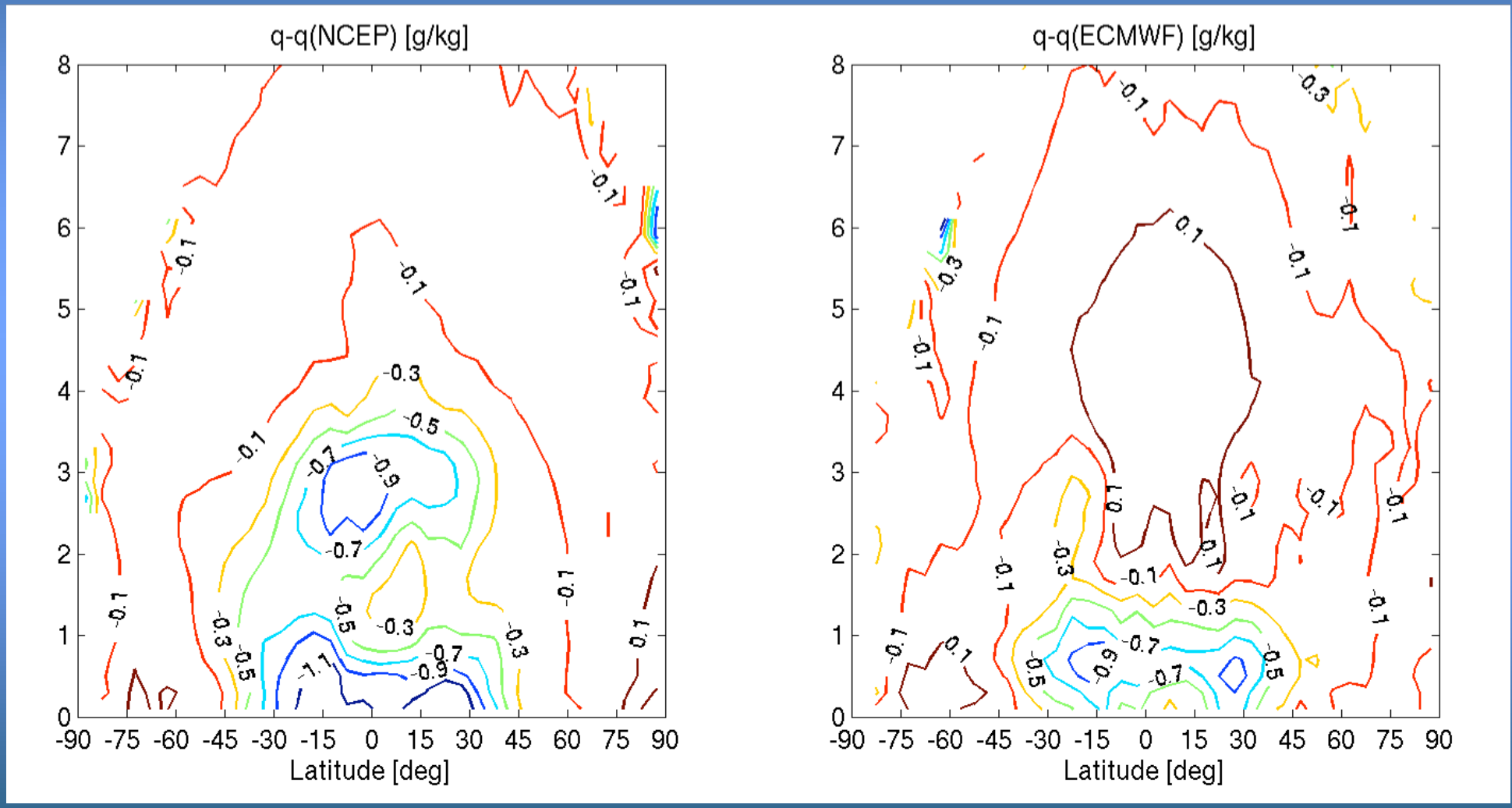
Comparison with Analyses (Tropics)



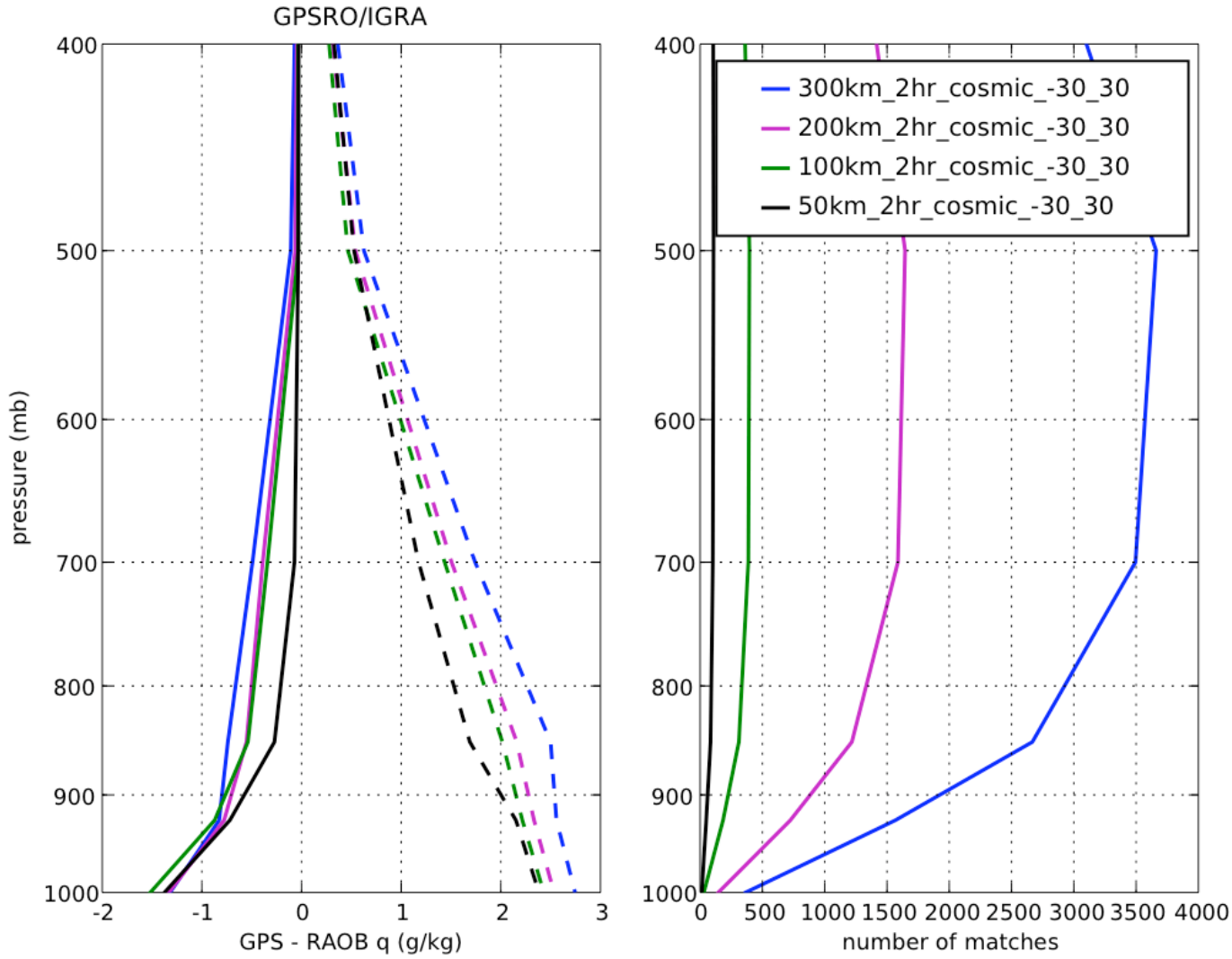


Zonal Mean: Humidity Bias

COSMIC + SAC-C, SEPT-OCT 2006

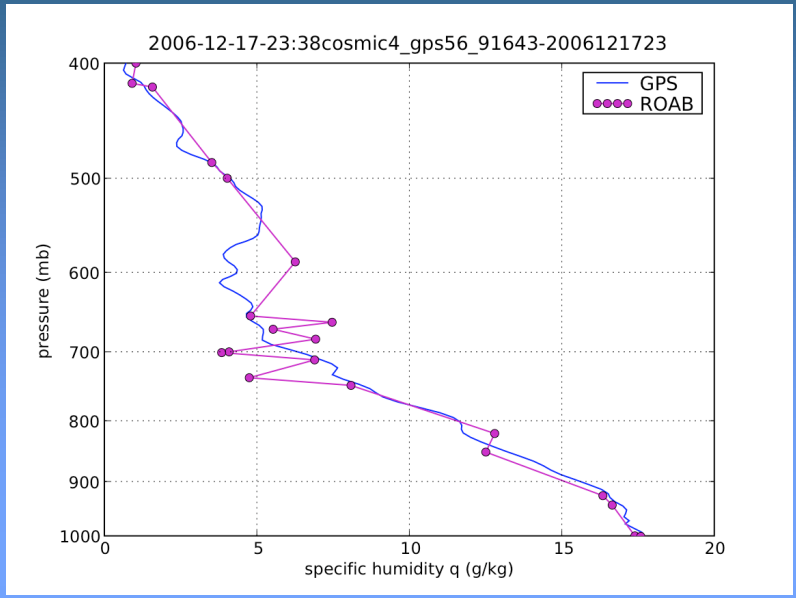


Comparison with IGRA/RAOB (Tropics)

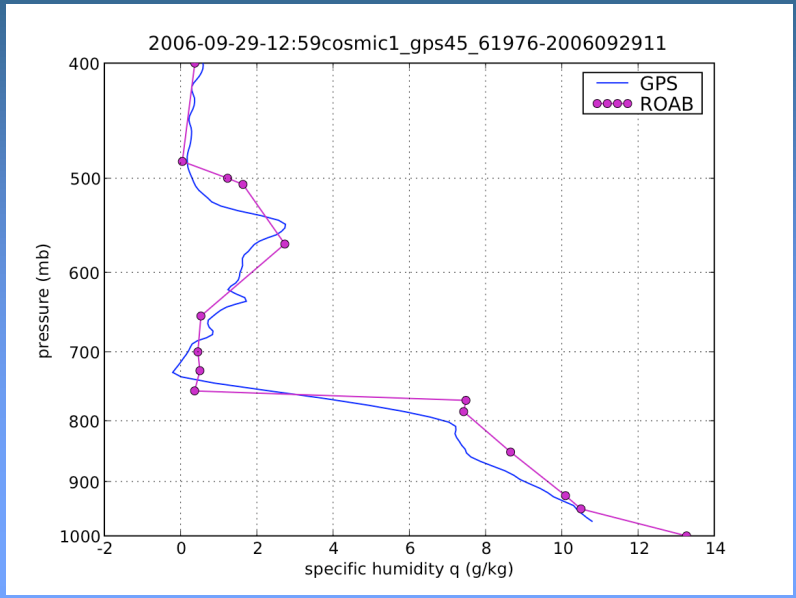


Examples

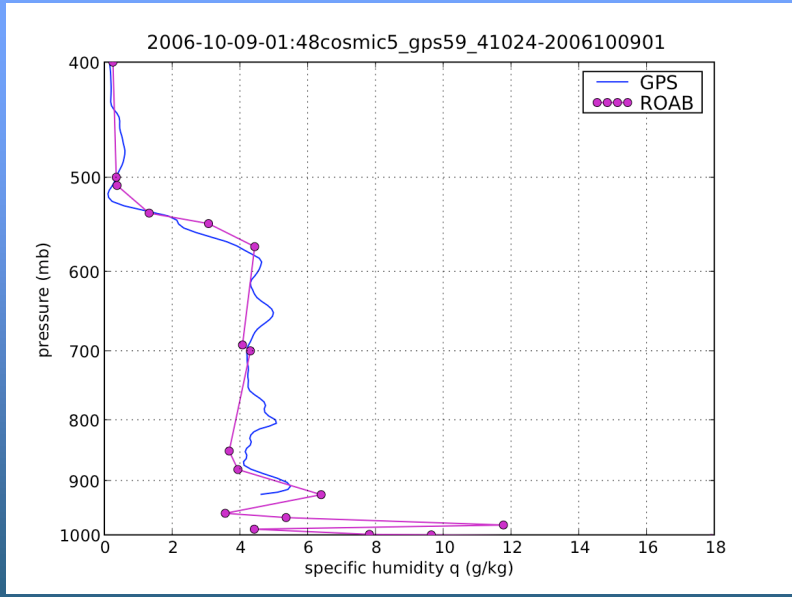
Central Pacific



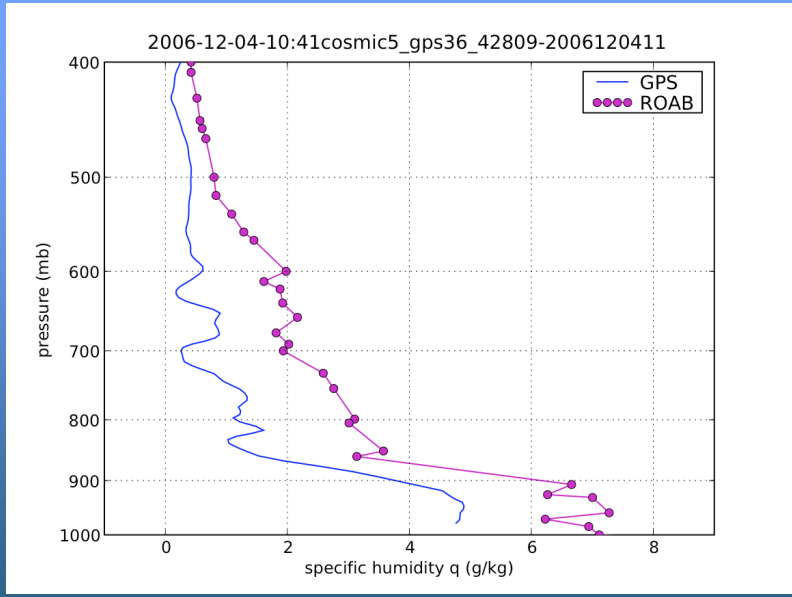
Indian Ocean



Saudi Arabia



India



Summary & Discussion

- Theoretical error estimates by Kursinski *et al*. [1997] were improved by including refractivity errors due to ducting.
- COSMIC & SAC-C OL WV retrievals were assessed by comparing with global analyses & RAOB (focusing on the tropics)
  - Theoretical estimates are ~ 2 times smaller than GPS-NCEP, GPS-ECMWF, & GPS-RAOB.
  - Substantial differences between NCEP & ECMWF at ~ 2–5 km, indicating large wet bias for NCEP and small dry bias for ECMWF.