On the Resolution and Noise Characteristics of GPS Radio Occultation Retrievals: A Simulation Study

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Outline

1. Bending angle accuracy vs. vertical resolution
   - Geometric optics (GO) vs. radioholographic (RH) retrieval

2. Precision of planetary boundary layer height derived from RO

Geometric optics (GO)

Error estimate is simpler with GO due to the direct relationship between bending angle and phase rate as well as impact parameter and time:

$$\alpha(a(t)) \propto \dot{\phi}(t) \tag{1}$$

Let Δt be the sample time interval (20 msec), N is the number of points to average [Hajj et al. 2002]:

$$\sigma_\alpha \approx \frac{\lambda}{v} \frac{\sqrt{12}\sigma_\phi}{\Delta t \ N^{1.5}} \tag{2}$$

where v is the vertical tangent point velocity. N is related to the smoothing interval Δz, which determines the vertical resolution:

$$N = \frac{\Delta z}{v \Delta t} \tag{3}$$

Effect of defocusing

Signal magnitude decreases and ray tangent descent slows down as a result of defocusing [Hajj et al. 2002]:

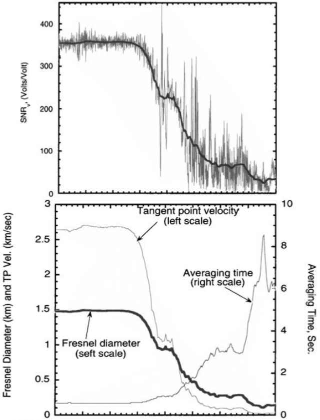
$$\sigma_\phi = \frac{1}{\sqrt{M}} \frac{1}{\mathrm{SNR_o}\sqrt{\Delta t}} \quad (4)$$

$$v = M\ v_o \quad (5)$$

$$M = \left[1 - D\frac{d\alpha}{dz}\right]^{-1} < 1 \quad (6)$$

so that

$$\sigma_\alpha = \frac{\lambda\sqrt{12}}{\mathrm{SNR_o}} \frac{\sqrt{v_o}}{(\Delta z)^{1.5}} \quad (7)$$



Radioholographic retrieval

Radioholographic (RH) retrievals (e.g., FSI, CT) involves Fourier integral transforms of the complex signal $u = A\exp(i\phi)$ from the t-domain to the a-domain:

$$\tilde{u}(a) = \int dt\ u(t) e^{-i\phi_r(a,t)} \tag{8}$$

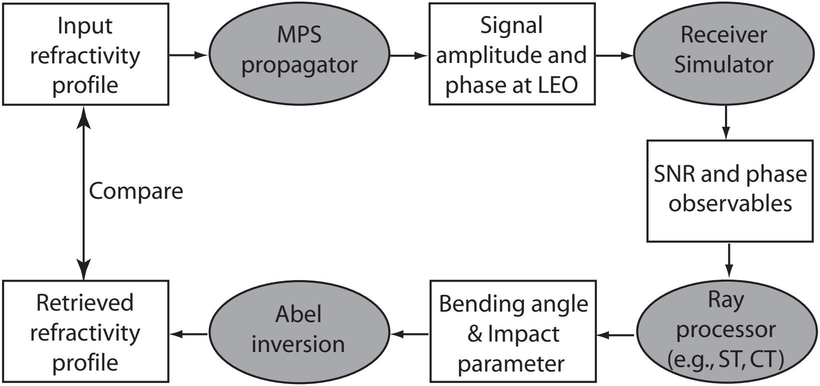
For each a, the main contribution to the integral comes from the stationary phase point (ray).

The bending angle is obtained as the derivative of the connected phase of the transformed signal $\tilde{u}(a)$:

$$\alpha(a) = -\frac{1}{k}\frac{d\tilde{\phi}}{da} \tag{9}$$

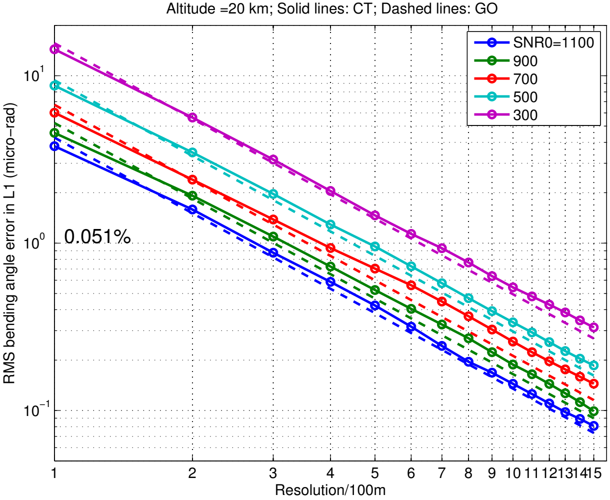
Analytical estimate of the uncertainty estimate is difficult, so use simulations.

Simulation with random additive noise

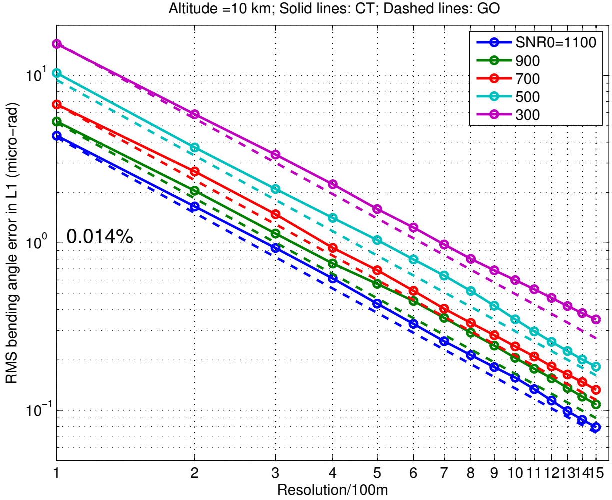


Consider Gaussian random noise of zero mean and stdev corresponding to various $\mathrm{SNR_o}$. Generate 20 realizations and compute the RMS error of the retrieved bending angle.

Accuracy vs vertical resolution (20 km)



Accuracy vs vertical resolution (10 km)



Precision of PBL height

PBL height = height where $-d\alpha/da$ (or $-dN/dz$) is largest.

What is the theoretical limit on how precise the PBL height can be determined?

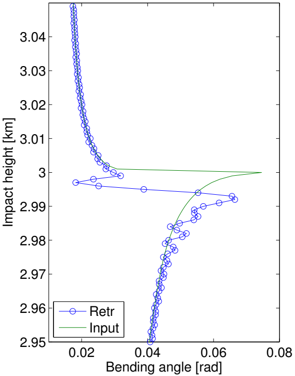
Gorbunov et al. [2004] estimated that the RH vertical resolution is limited by diffraction within the atmosphere.

$$h \sim (\lambda^2 R_e)^{1/3} \approx 60 \text{ m} \tag{10}$$

How does that translate into bending angle/impact parameter?

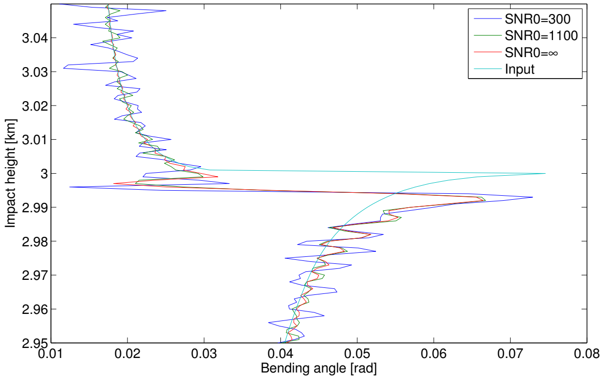
Resolving sharp bending angles

Simulation result (noiseless case)



Diffraction effect blurs the sharp bending by about 10-m in impact height.

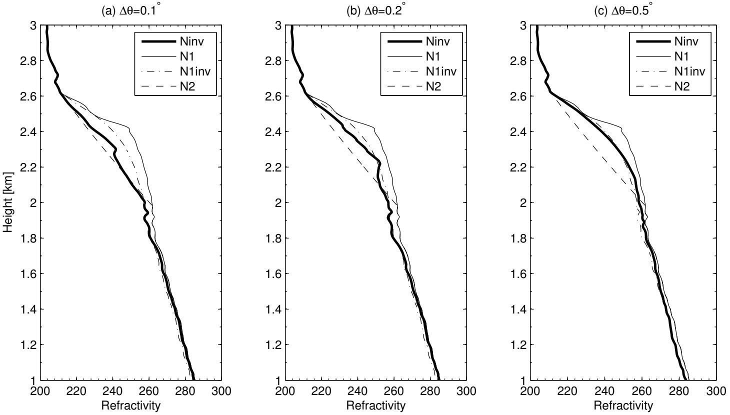
Effect of random noise



- Random noise has only minimal impact on the derived PBL height.
- Tracking errors due to moderate open-loop model offsets also have little impact (not shown).

Effect of horizontal variability (1)

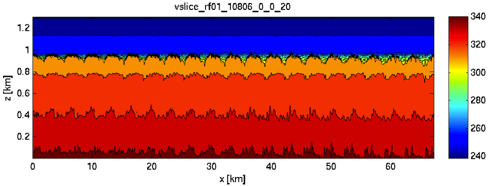
Horizontal resolution: $2\sqrt{2R_e\Delta r} \approx 70$ km for $\Delta r = 100$ m.

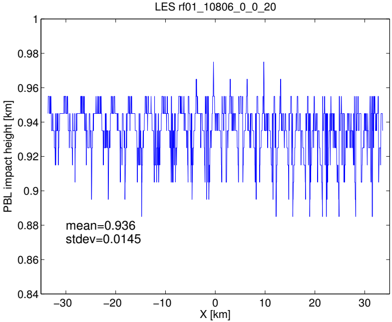


Ao, *Radio Sci*, 2007

Effect of horizontal variability (2)

Large eddy simulations (LES) are useful for performing 2D or 3D RO simulations.





Conclusions

1. Using idealized end-to-end simulations, the relationship between RH bending angle accuracy and vertical resolution is obtained.
   - (Surprisingly) RH has the same noise-resolution characteristics as GO.
   - Simplifies mission planning.
2. PBL height derived from GPS RO has a precision of ≈ 10 m.
   - Limited by diffraction effect.
   - When the bending lapse rate is large (e.g., Sc), the PBL height is best derived without smoothing.
   - Effect of horizontal variability is a key uncertainty and will need to be further modeled and characterized.