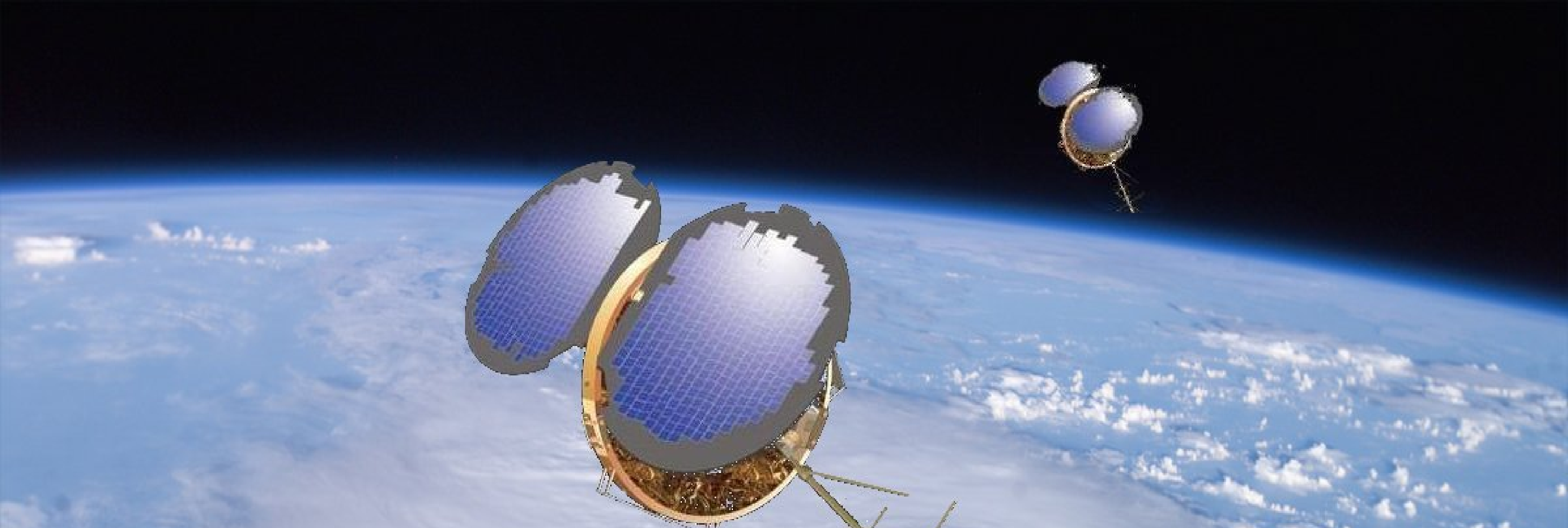

Radio occultation retrieval processing for ionospheric scientists

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UCAR COSMIC Program

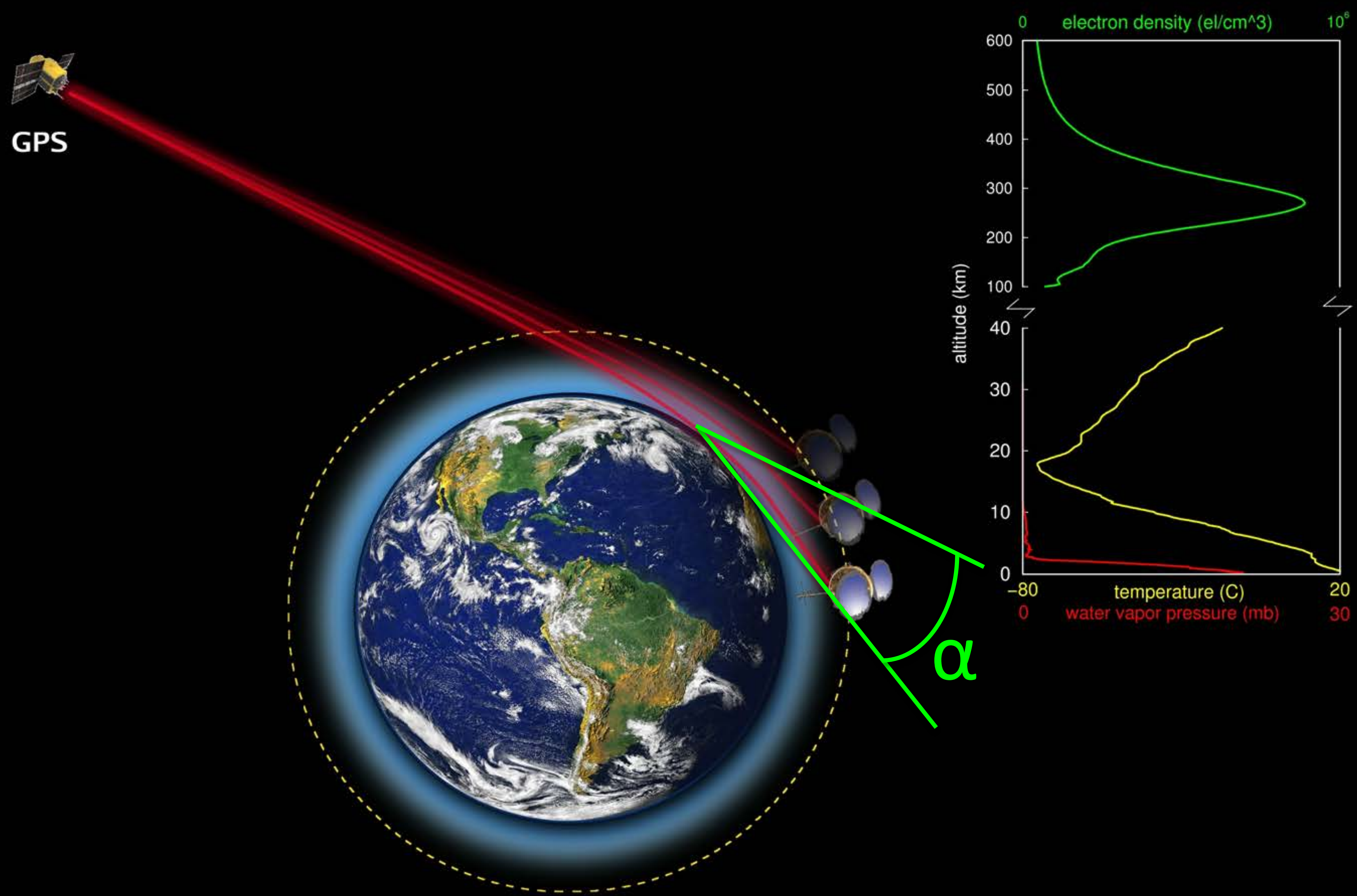
IROWG Ionosphere-Atmosphere Coordination Workshop

Oct 3, 2014

Outline

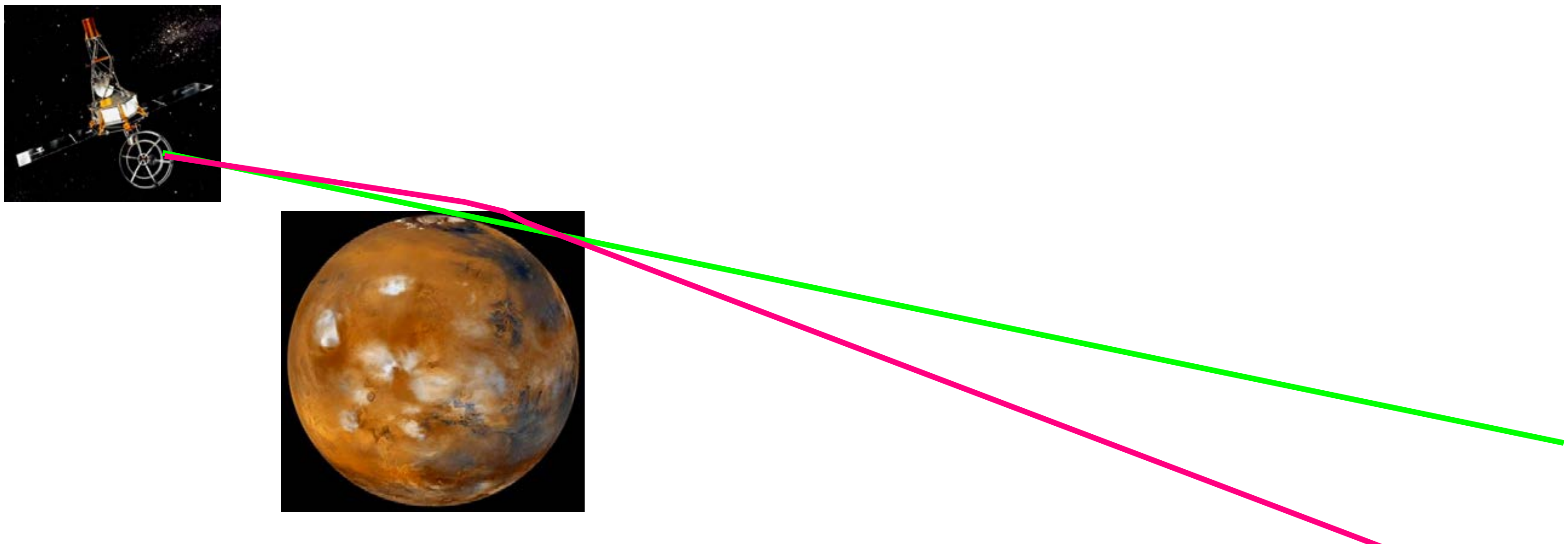
- GPS RO Overview
- Neutral Atmospheric Retrievals
  - Excess Atmospheric phase
  - Bending angle computation
  - Ionospheric correction
  - Extrapolation of ionospheric correction in troposphere

GPS Radio Occultation



But how do we know if the ray is bent?

Measure the Doppler frequency shift of the received radio signal on Earth.



For a straight ray the Doppler shift is caused only by the relative motion of the transmitter relative to the receiver - and can be predicted based on orbital mechanics

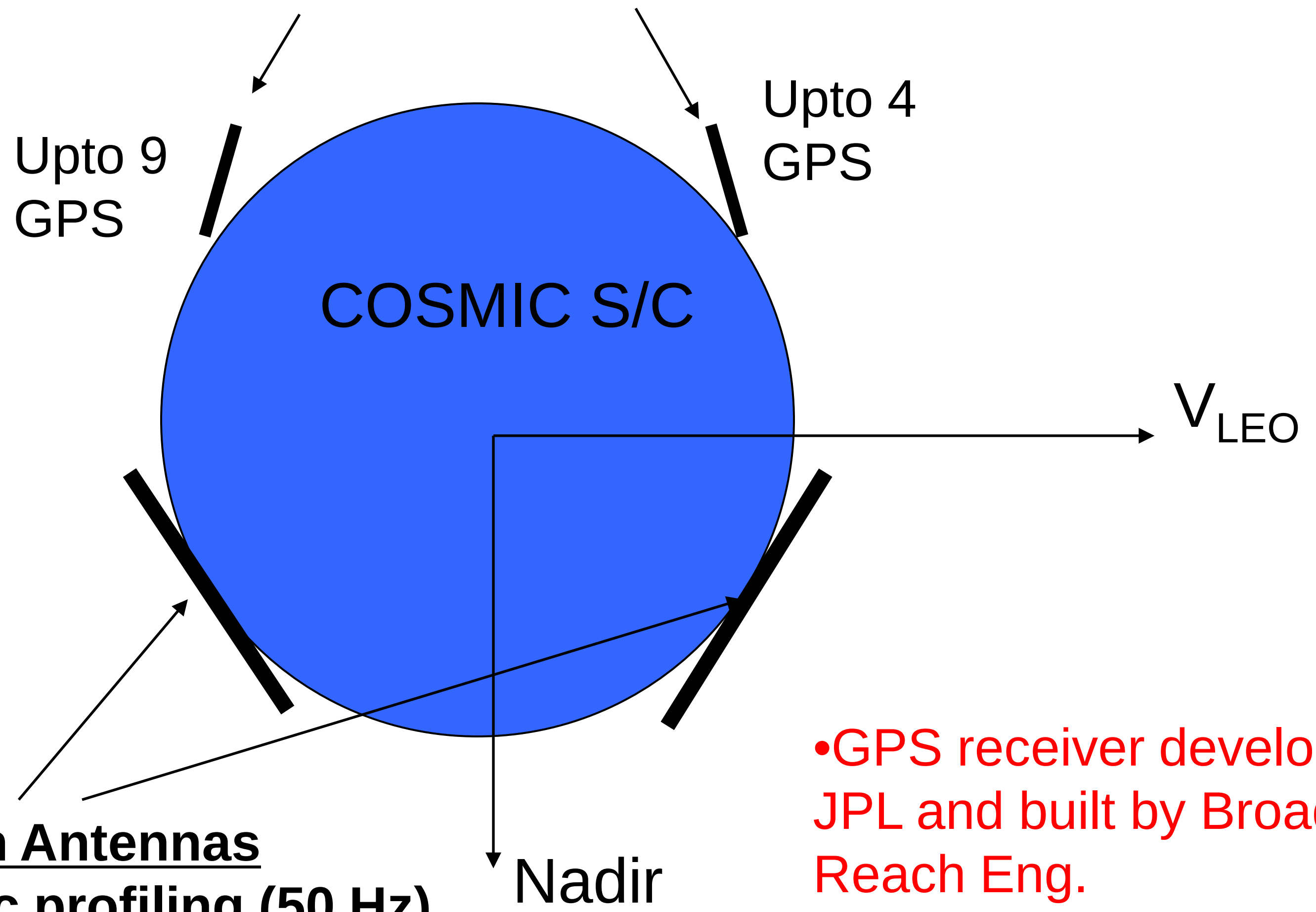
For a bent signal the Doppler shift will noticeably different than predicted based on orbital mechanics only!

GPS Antennas on COSMIC Satellites

<u>2 POD Antennas</u>

- POD, TEC/EDP and S4 (1 Hz)

- clock reference data (50 Hz)

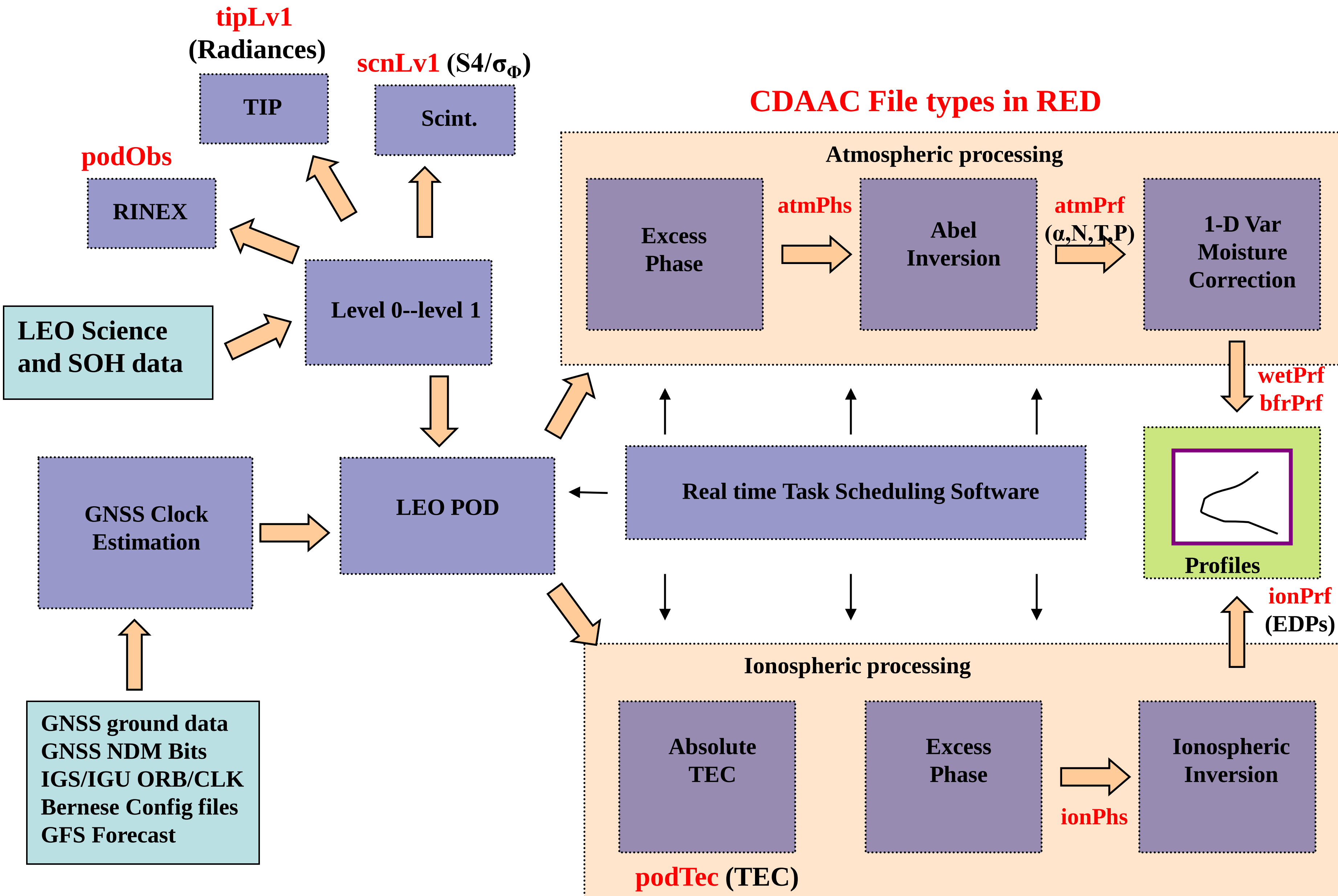


<u>2 Occultation Antennas</u>

- atmospheric profiling (50 Hz)

- GPS receiver developed by JPL and built by Broad Reach Eng.
- Antennas built by Haigh-Farr

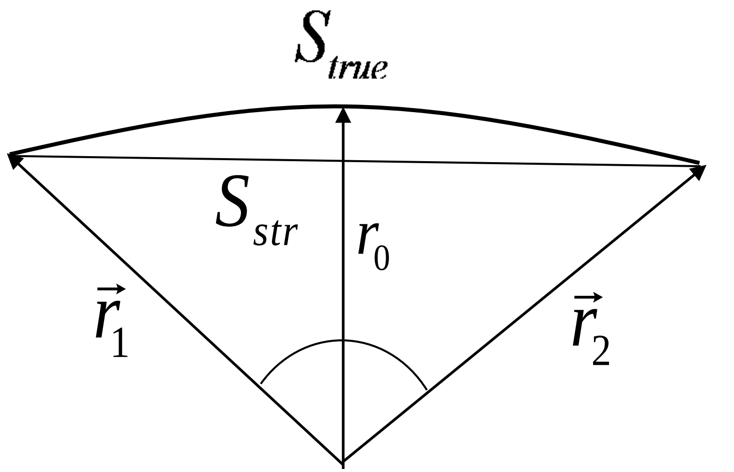
CDAAC Data Flow

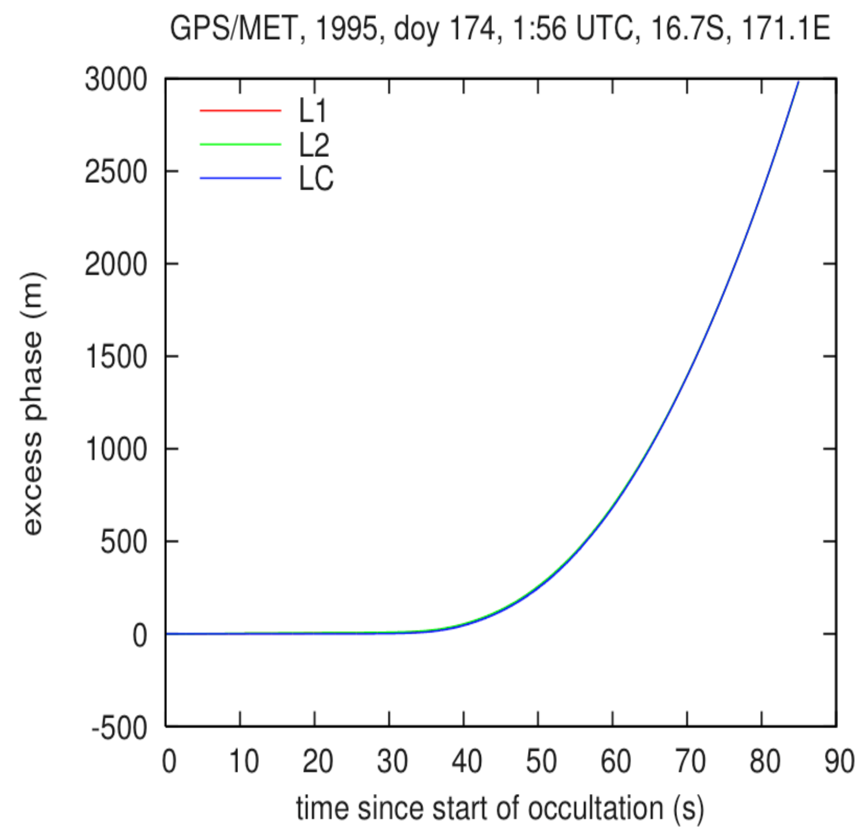


Atmospheric excess phase

- Difference between true phase path between $\vec{r}_1$ *and* $\vec{r}_2$ and straight line (vacuum) path

$$S_{true} - S_{str} = \int n\,dl - \left|\vec{r}_1 - \vec{r}_2\right|$$





GNSS signals that are driven by atomic clocks enable measurement of precise (mm level) carrier phase. Computation of atmospheric excess phase requires knowledge of transmitter/receiver phase centers at the level of 0.1 mm/sec for velocity (allows computation of BA at ~2e-8 rad).

UCAR COMMUNITY PROGRAMS

Measurement Modeling

COSMIC

$$L1_r^s(t_r) = c \cdot \delta t_r(t_r) + c \cdot \delta t_{r,rel}(t_r) + \rho_r^s(t_r) + \delta\rho_{r,rel}^s(t_r) + c \cdot \delta t^s(t_r - \tau_r^s) + c \cdot \delta t_{rel}^s(t_r - \tau_r^s) + \boxed{\delta\rho_{r,ion}^s(t_r) + \delta\rho_{r,trop}^s(t_r)} + \lambda_1 \cdot N_{amb} + \varepsilon \qquad (1)$$

Excess phase

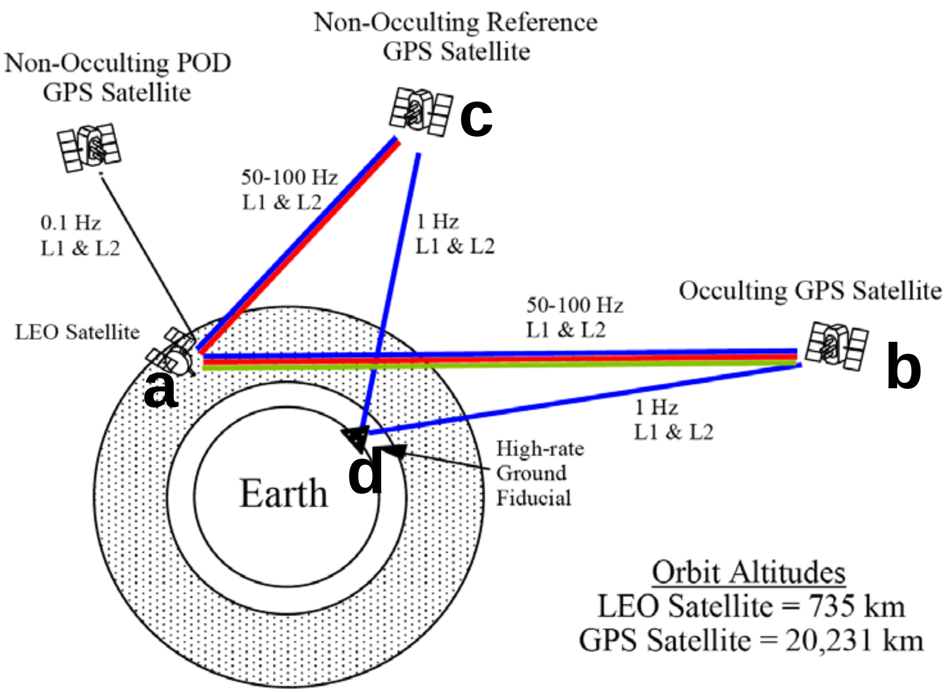
t_r	receive time
c	speed of light in vacuum (m/s)
δt_r	offset between receiver time and proper time at receive time
$\delta t_{r,rel}$	offset between proper time and coordinate time at the receiver due to special and general relativity
ρ_r^s	geometric range at receive time
δt^s	offset between proper time and satellite time at transmit time
δt_{rel}^s	offset between coordinate time and proper time at satellite
$\delta\rho_{r,rel}^s$	gravitational delay between receiver and satellite
τ_r^s	light travel time in vacuum, $\tau_r^s = \rho_r^s(t_r)/c + \delta\rho_{r,rel}^s(t_r)$
$\delta\rho_{r,ion}^s$	ionospheric delay between receiver and satellite
$\delta\rho_{r,trop}^s$	tropospheric delay between receiver and satellite
λ_1	wavelength of L1 signal (m)
N_{amb}	phase ambiguity
ε	phase noise

+ System delays
+ Local spacecraft multipath
+ Antenna phase center offsets and variations
+ Carrier phase wind-up

(Schreiner et al., 2009)

Removing Oscillator Fluctuations

- Zero-Difference
  - Assume LEO/USO clock perfect
  - Use solved-for GPS clocks
  - Minimal noise
- Single-Difference
  - LEO clock fluctuations removed
  - Use solved-for GPS clocks
  - Noise from reference link
- Double-Difference
  - Ground/LEO clock fluctuations removed
  - Noise from reference link and ground link (multipath, atmos. noise, thermal noise)



See: Hajj et al., 2002, Wickert et al., 2002, Beyerle et al., 2005, Schreiner et al., 2009

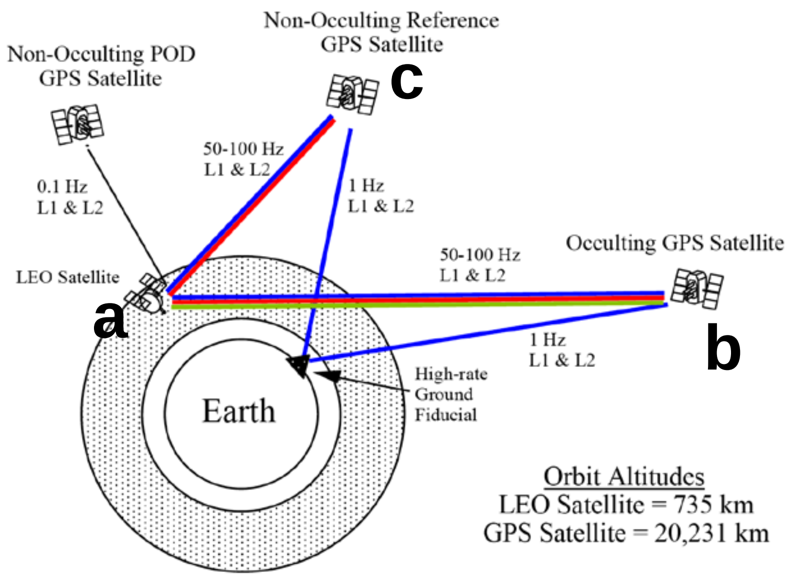
Single-Difference details

$$L1_a^b(t_r) = \boxed{c\cdot\delta t_a(t_r) + c\cdot\delta t_{a,rel}(t_r)} + \rho_a^b(t_r) + c\cdot\delta t^b(t_r - \tau_a^b) + c\cdot\delta t_{rel}^b(t_r - \tau_a^b) + \delta\rho_{a,rel}^b(t_r) +$$
$$\boxed{\delta\rho_{a,ion}^b(t_r) + \delta\rho_{a,trop}^b(t_r)}$$

Subtract ionosphere-free reference link phase, and eliminate other terms to get:

$$L1_a^b(t_r) - L3_a^c(t_r) = \delta\rho_{a,ion}^b(t_r) + \delta\rho_{a,trop}^b(t_r)$$

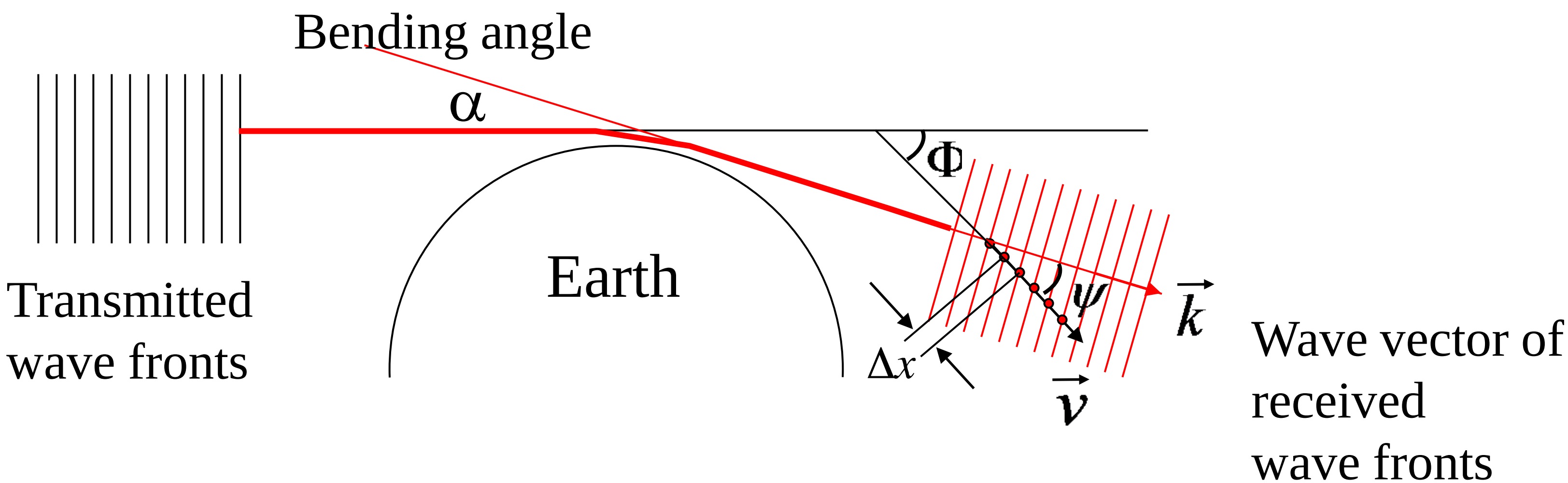
Smooth reference link L1-L2 to reduce L2 noise, but increases the uncorrected small-scale ionospheric effects (Rocken et al., 1997, Schreiner et al., 1998, Beyerle et al., 2005)



$$L3_a^c(t_r) = L1_a^c(t_r) + c_2\left\langle L1_a^c(t_r) - L2_a^c(t_r)\right\rangle$$

$\langle\ \rangle$ denotes smoothing with a 2 sec window

Determining Bending from observed Doppler



From orbit determination we know the location of source and we know the receiver orbit $\vec{v}$. Thus we know Φ

We measure Doppler frequency shift: $f_d = \dfrac{1}{\Delta t} = \dfrac{v}{\Delta x} = \dfrac{v}{\lambda}\cos\psi = f_T \dfrac{v}{c}\cos\psi$

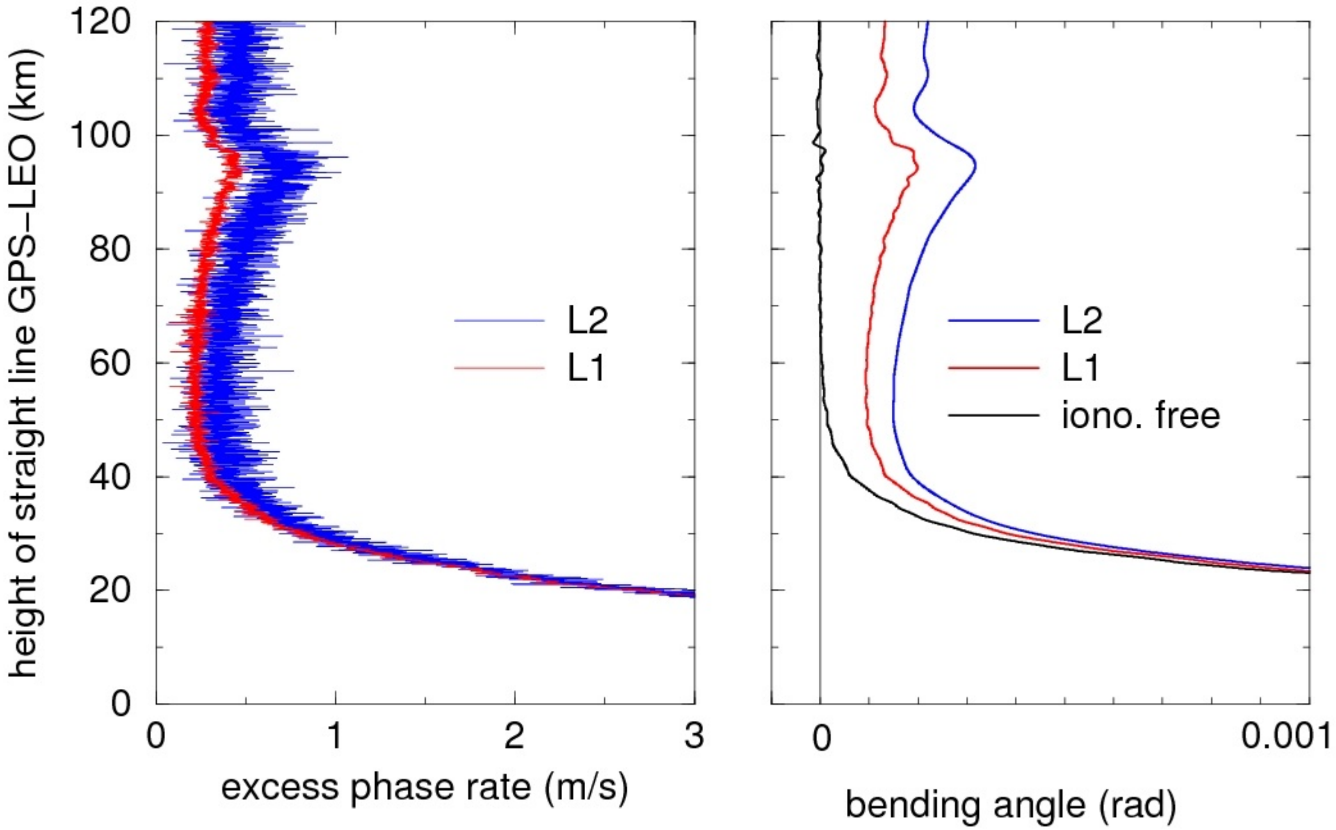
Thus we know ψ. And compute the bending angle $\alpha = \Phi - \psi$

Ionospheric correction of bending angles

Ionospheric correction is performed on L1 and L2 bending angles by taking them at the same impact parameter (Vorob'ev and Krasil'nikova, 1994)

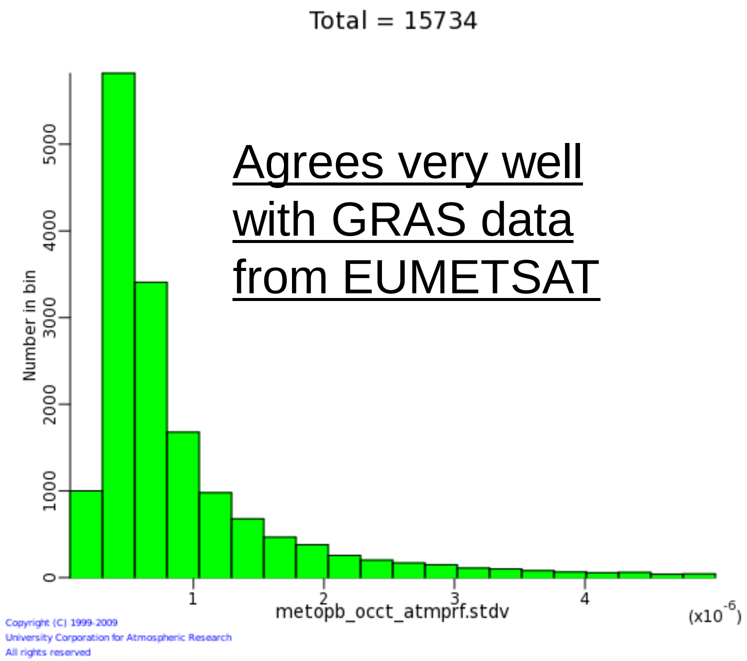
$$\alpha(a) = c_1\alpha_1(a) - c_2\alpha_2(a); \quad c_1 = f_1^2/(f_1^2 - f_2^2); \quad c_2 = f_2^2/(f_1^2 - f_2^2)$$

Alternatively, it can be performed: $\alpha(a) = \alpha_1(a) - c_2 < \alpha_4(a) >; \alpha_4 = \alpha_1 - \alpha_2$
The additional smoothing <> reduces the effect of larger noise on L2 (but increases the uncorrected small-scale ionospheric effects).



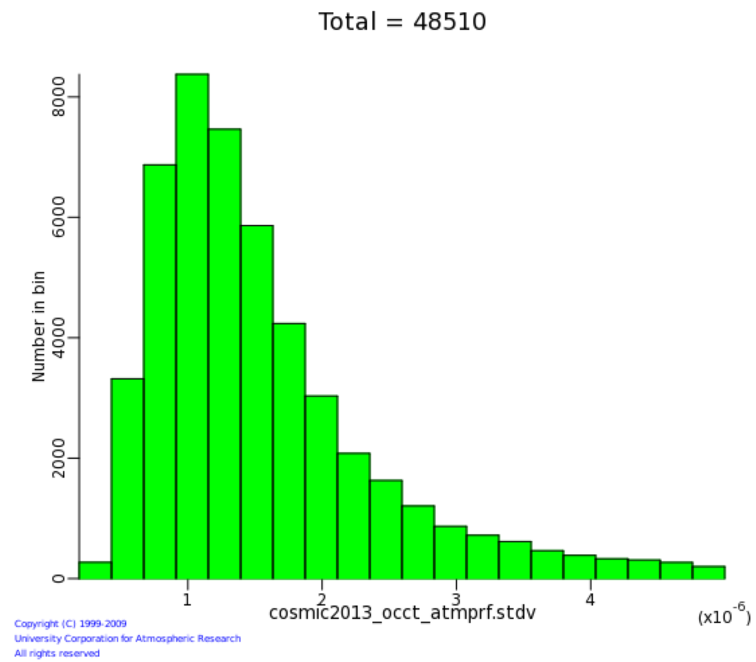
COSMIC and Metop-B Bending Angle noise between 60-80 km June 2013

Metop-A/GRAS – Zero Diff.



Agrees very well with GRAS data from EUMETSAT

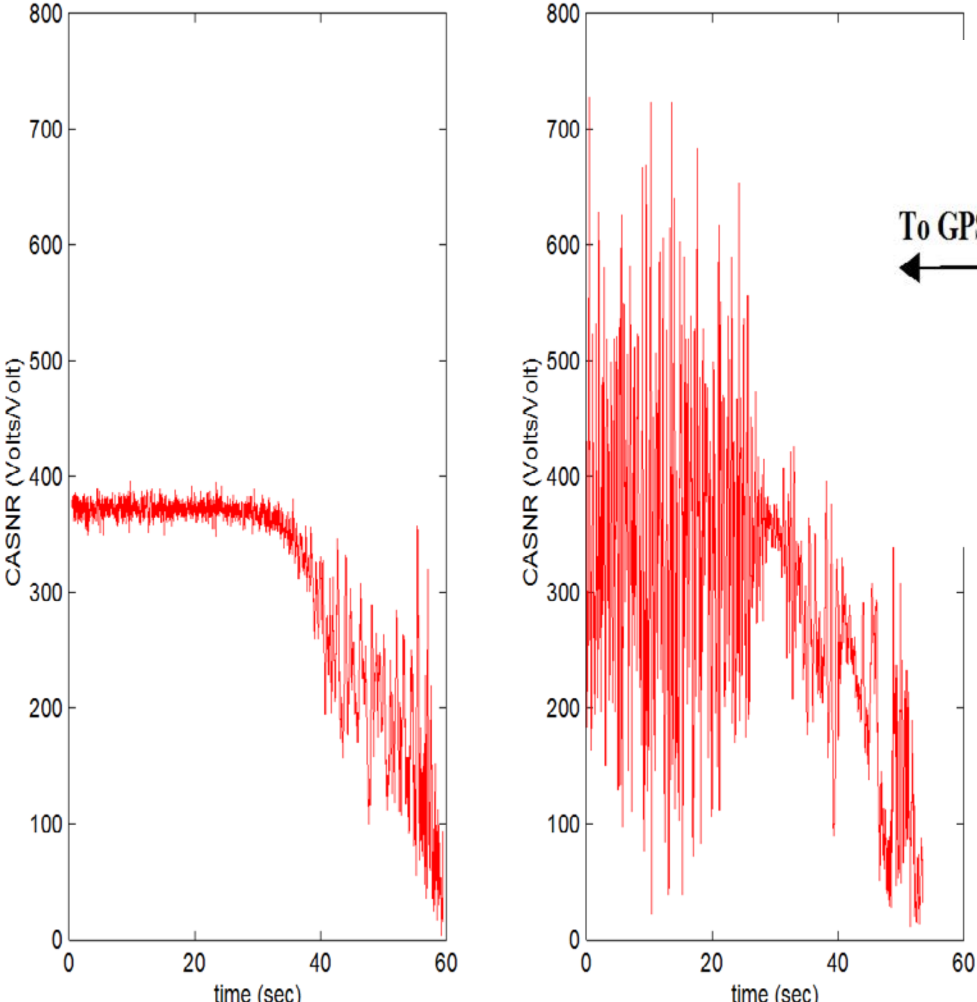
COSMIC – Single Diff.



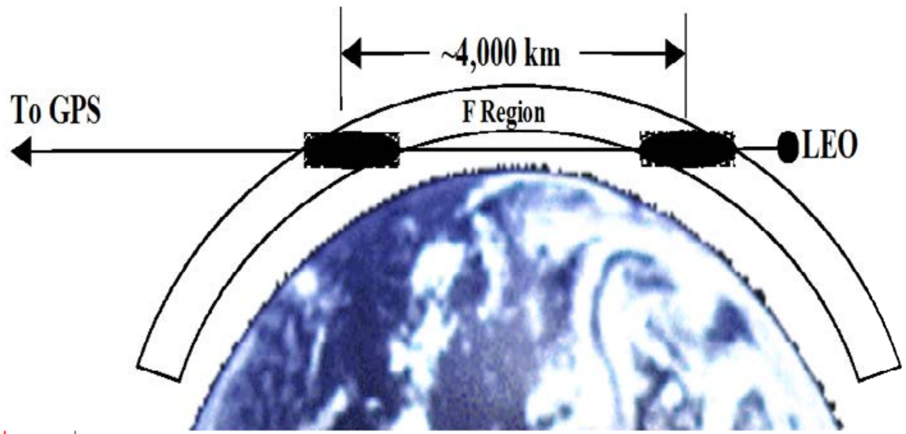
Impact of Scintillation on Retrievals

No scintillation
S4=0.005

Scintillation
S4=0.113



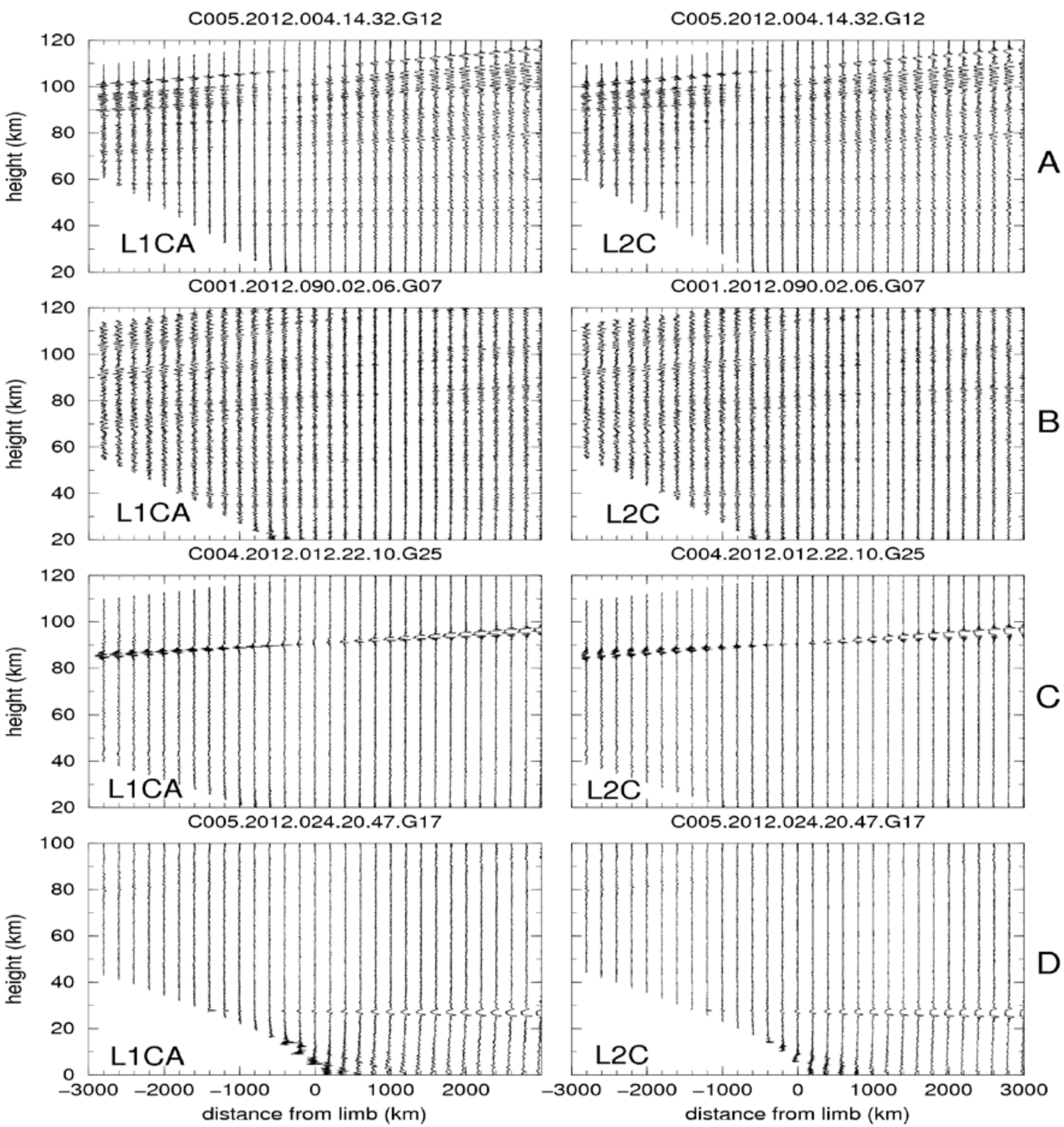
GPS/MET SNR data



Where is the source
Region of the scintillation?

Localize irregularities: see
(Sokolovskiy et al., 2002)

Back propagation of L1 and L2C complex signals solves for effects of diffraction in a vacuum. Ionospheric correction of L1 and L2C BA applied at locations of minimum amplitude fluctuation reduces the residual errors caused by diffraction (next slide).



Scintillation from F2 layer

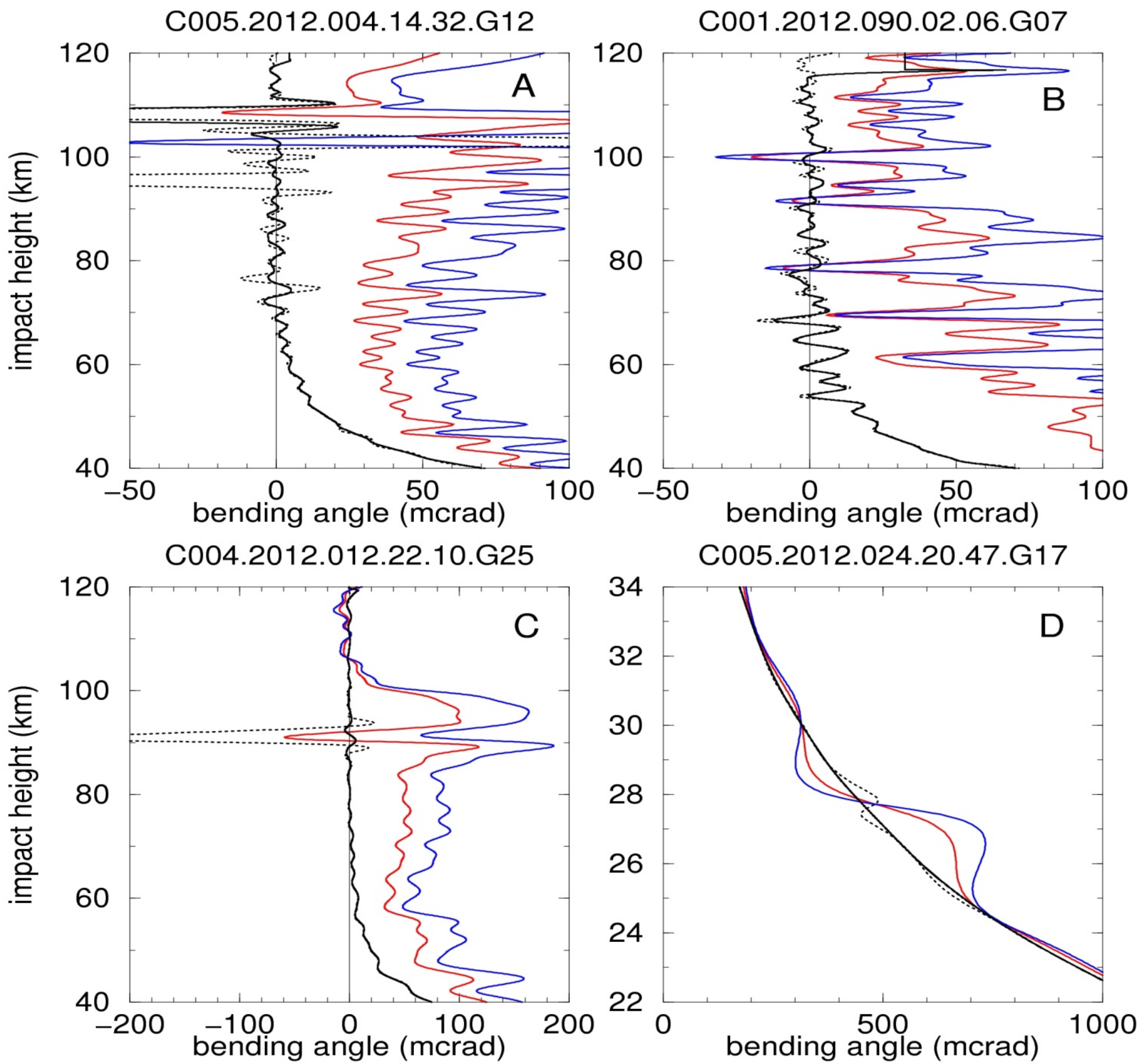
Scintillation from F2 layer

Scintillation from Es layer

Scintillation from Es layer

Sokolovskiy et al., 2013

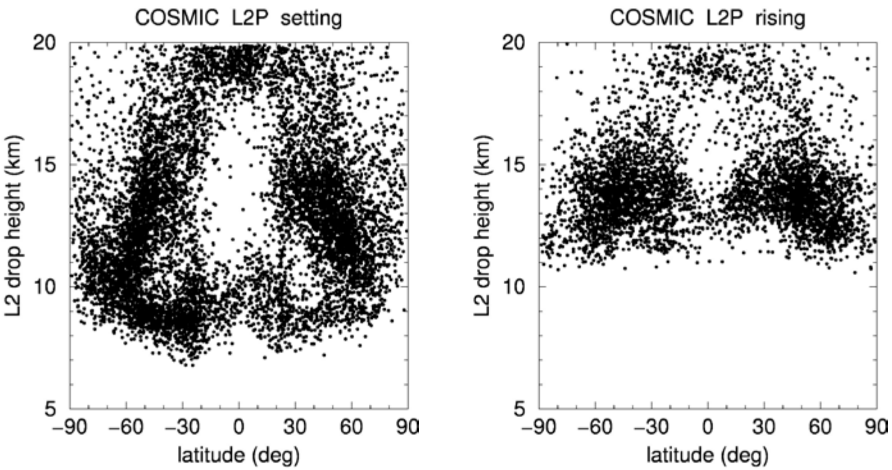
Reduction of the errors of ionospheric correction caused by diffraction after applying back propagation (previous slide)



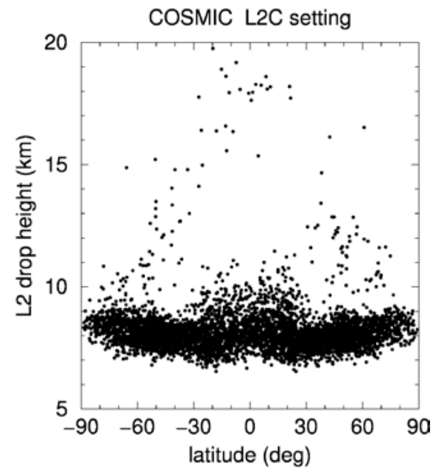
Old processing: not all occultations are processed.

Below the height where raw |L1-L2| Dopplers > threshold (6 cm / samp) at < 40 km
(after full and half cycle slip correction of L1):
Ionospheric correction is replaced by extrapolation of L1-L2 BA, GO is replaced by WO;
If this height > 20 km, the occultation is not processed.

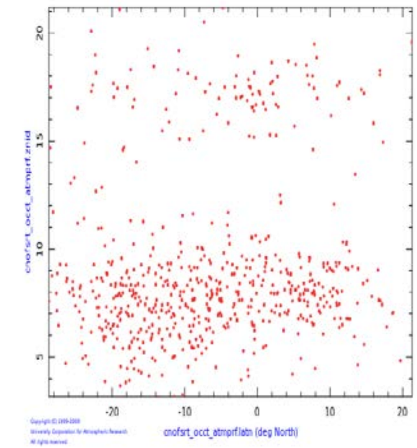
COSMIC L2P



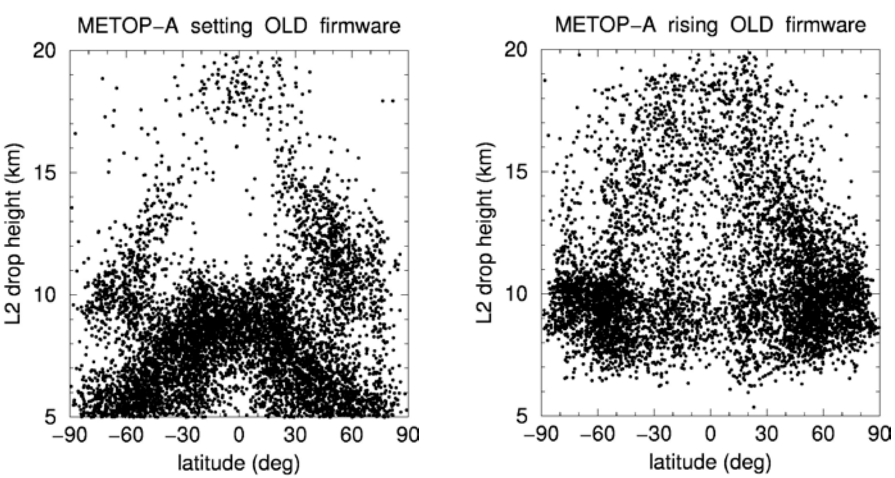
COSMIC L2C



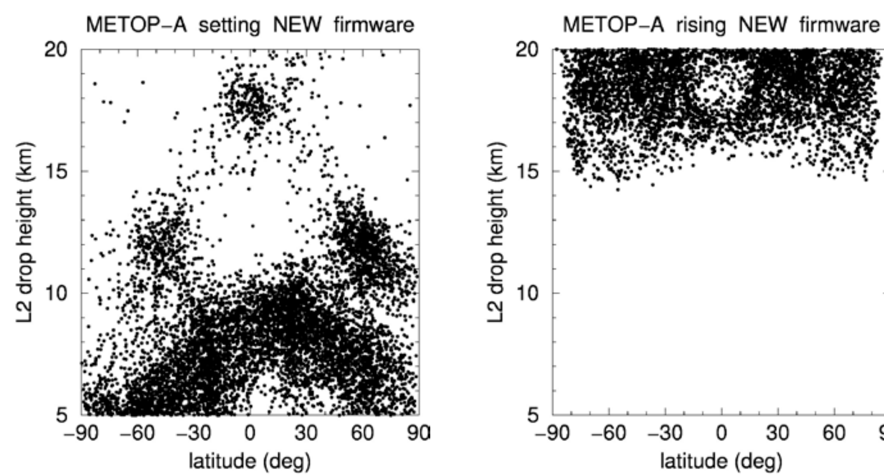
C/NOFS L2P



METOP-A before 2013 firmware update

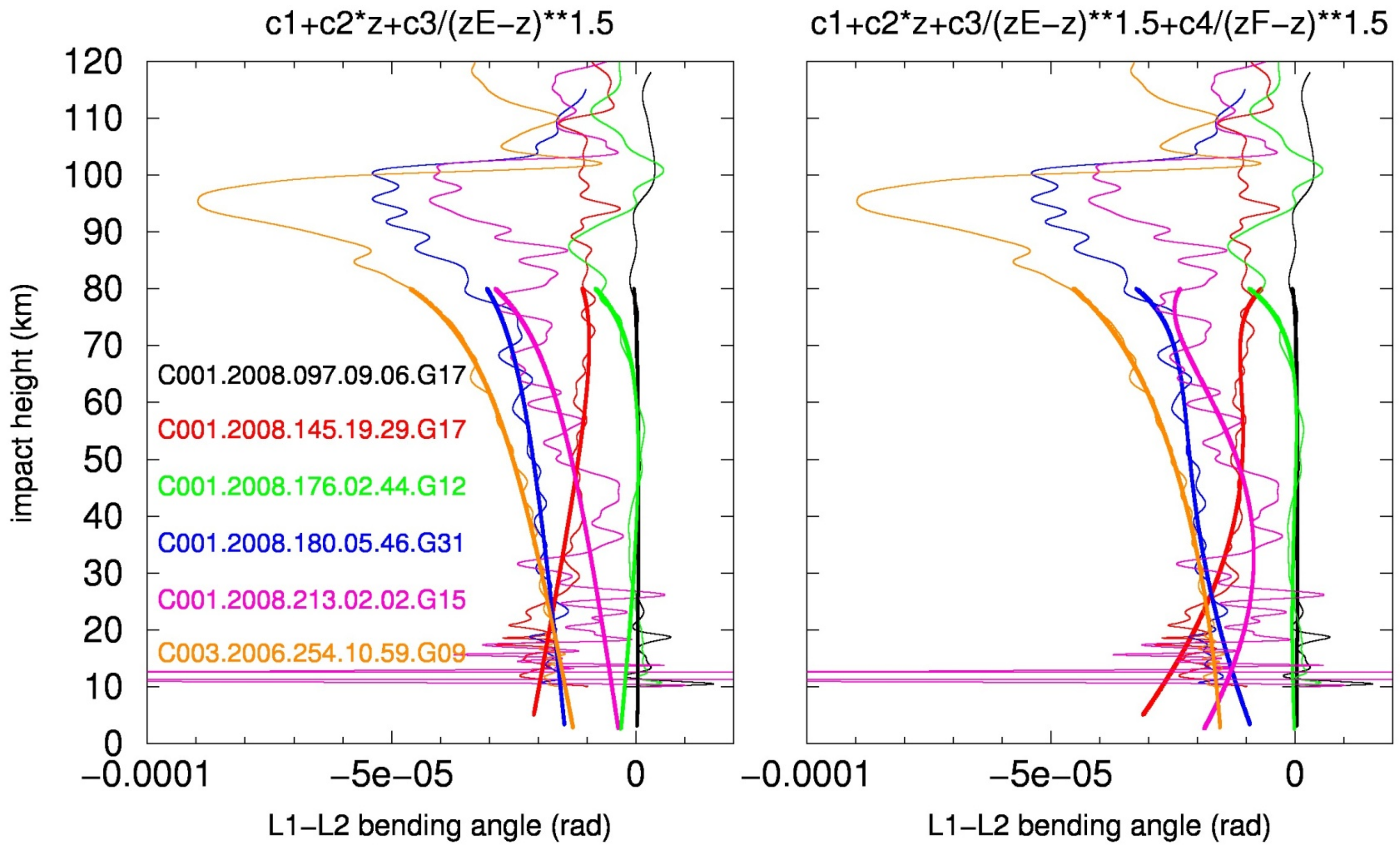


METOP-A after 2013 firmware update



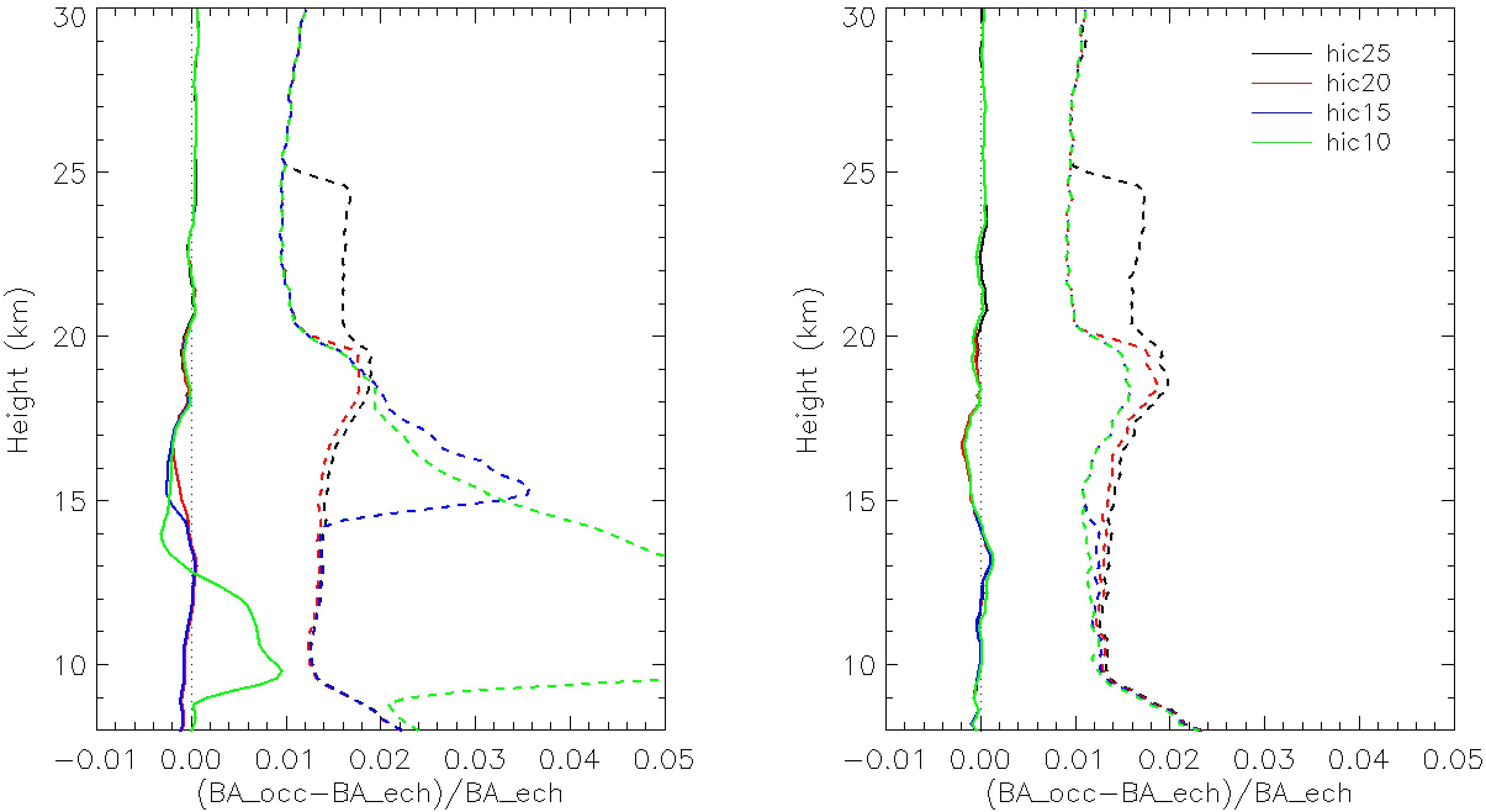
Extrapolation of the ionospheric correction of BA into the troposphere

In the troposphere, L2 either is not available or, when available, LC is noisy.
L1 is corrected by extrapolated L1-L2: this reduces the noise at the expense of un-corrected small-scale ionospheric effects on L1.
Approximation of L1-L2 BA at 20-80 km by linear function + response from E layer or E and F layers (zE=100km, zF=300km).
Including F layer causes instability of extrapolated L1-L2.



Effect of Extrapolation Height of Iono. Corr. for COSMIC L2P v.s. L2C signal

- L2P: semi-codeless tracking, not available in OL tracking mode;
  L2C: pilot-aided tracking, as stable as L1CA (or even better), available in OL (setting occs.)
- Optimal **hic** for COSMIC L1CA&L2P RO is near 20 km;
- For L2C, **hic** = 10 km results in smallest stdv of RO retrievals from ECMWF analyses.



Effect of Extrapolation Height of Iono. Corr. for COSMIC L2C signal in Lower Troposphere

- Ionospheric correction of L1CA by using partially uncorrected L2C in LT results in larger noise.