A LEO-LEO Occultation Observing System for Characterizing Humidity, Ozone, Temperature, Geopotential and Clouds

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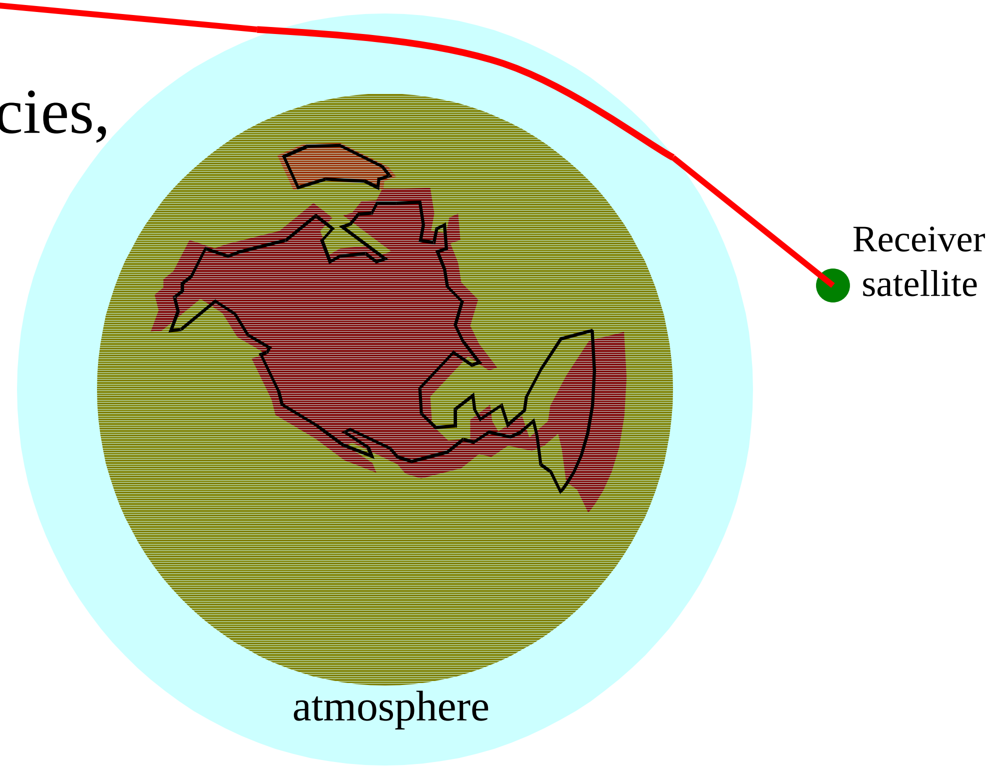
Outline

- **Retrieval Theory Overview**
- Accuracy of retrievals
  - Sources of Error
  - Clear sky
  - Cloudy conditions
- Summary & Conclusion

Geometry of the Active Microwave Occultation

An occultation occurs between 2 satellites connected with the solid red radio link.



With proper choice of frequencies, yields very accurate and high vertical resolution profiles of

- refractivity,
- density,
- pressure,
- temperature,
- constituents (H_2O, O_3)
- clouds

vs. height

ATOMS’ Cross-Link Frequencies

Below 200 GHz, there are 2 water vapor absorption lines at 22.23 and 183.31GHz and a strong ozone line at 195.43 GHz.

(1) For water vapor

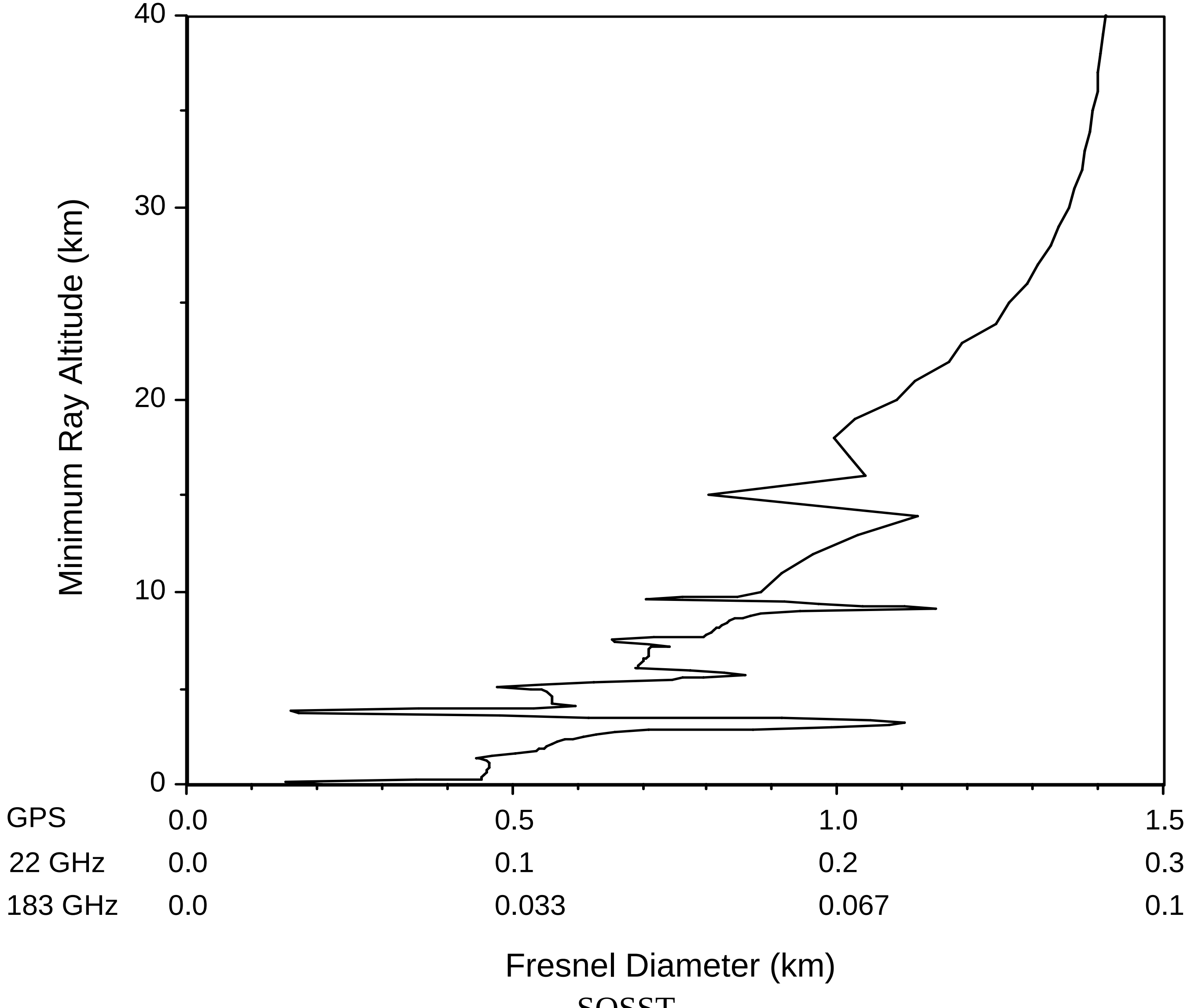
22.23 GHz line (low band)

183.31 GHz line (high band)

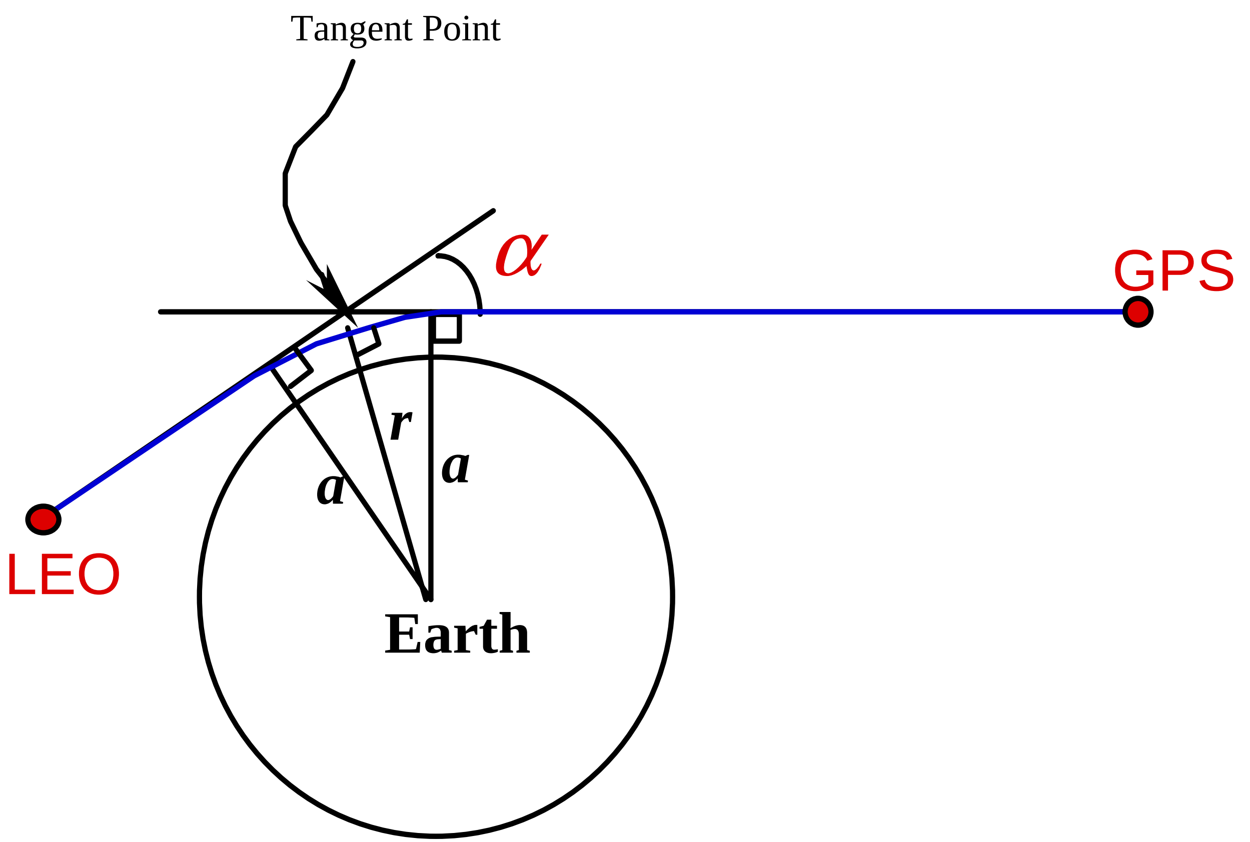
(2) For ozone

195.43 GHz line (high band)

Diffraction limited vertical resolution



Retrieval Overview: Derivation of Index of Refraction (n)



$$\alpha(a) = 2a \int_{r_t}^{\infty} \frac{1}{\sqrt{r^2 n^2 - a^2}} \frac{d\ln(n)}{dr} dr \quad \Leftrightarrow \quad n(r) = \exp\left[\frac{1}{\pi} \int_{a_1}^{\infty} \frac{\alpha}{\sqrt{a^2 - a_1^2}} da \right]$$

Retrieval Overview: Deriving extinction coefficient profiles

- Signal intensity is reduced by absorption along the signal path as

$$\mathrm{d}I = -I \; k \; \mathrm{d}l$$

where k is the volume absorption coefficient.

- For each wavelength, the observed intensity, I, equals the vacuum intensity (signal intensity with no atmosphere), I_0, times $e^{-\tau}$ where τ is the optical depth.

$$I = I_o \exp(-\tau) \quad or \quad \tau = \ln\left(\frac{I}{I_o}\right)$$

- The measured optical depth is along the signal path whereas we want a ***radial*** profile of the extinction coefficient
- The simplest solution is an abel integral transform pair for opacity and extinction coefficient: (Note: $x = nr$)

$$\tau(a) = \int k \; dl = 2\int_{x=a}^{x=\infty} k \frac{x \, {dr}/{dx} \, dx}{\sqrt{x^2 - a^2}} \Leftrightarrow k = -\frac{1}{\pi}\frac{da}{dr}\bigg|_{a=a_0} \int_{a=a_0}^{a=\infty} \frac{d\tau}{da} \frac{da}{\left(a^2 - a_0^2\right)^{1/2}}$$

Deriving water vapor, temperature and pressure (clear sky)

Water vapor retrievals:

Using frequency pairs (frequencies #1, #2) close to the water vapor absorption lines

$$\textit{absorption equation} \quad k_1 - k_2 = F(T,\, P_d,\, P_w)$$

$$\textit{refractivity equation} \quad N = 77.6\frac{P_d}{T} + 71.7\frac{P_w}{T} + 3.75\times10^5\frac{P_w}{T^2}$$

$$\textit{hydrostatic equation} \quad \frac{d(P_d + P_w)}{P_d + P_w} = -\frac{g\,dz}{R\,T}$$

At each altitude, solve these 3 closed, non-linear equations for 3 unknowns, T, P_d, and P_w. (P_d – dry pressure; P_w – water vapor pressure)

Deriving water vapor, temperature, pressure & clouds

Lower Troposphere Water vapor retrievals:

For lower and middle troposphere where liquid water clouds are likely present,

Use the 22 GHz water vapor line and add 2 absorption equations at frequencies #1, #2 and #2, #3,

$$absorption\ equation\ \#1\quad k_1 - k_2 = F_{12}(T, P_d, P_w, L_c)$$

$$absorption\ equation\ \#2\quad k_2 - k_3 = F_{23}(T, P_d, P_w, L_c)$$

Solve these 4 closed, non-linear equations (the 2 absorption equations above, the refractivity equation, and the hydrostatic equilibrium equation) for 4 unknowns, T, P_d, P_w, and cloud liquid water content, L_c.

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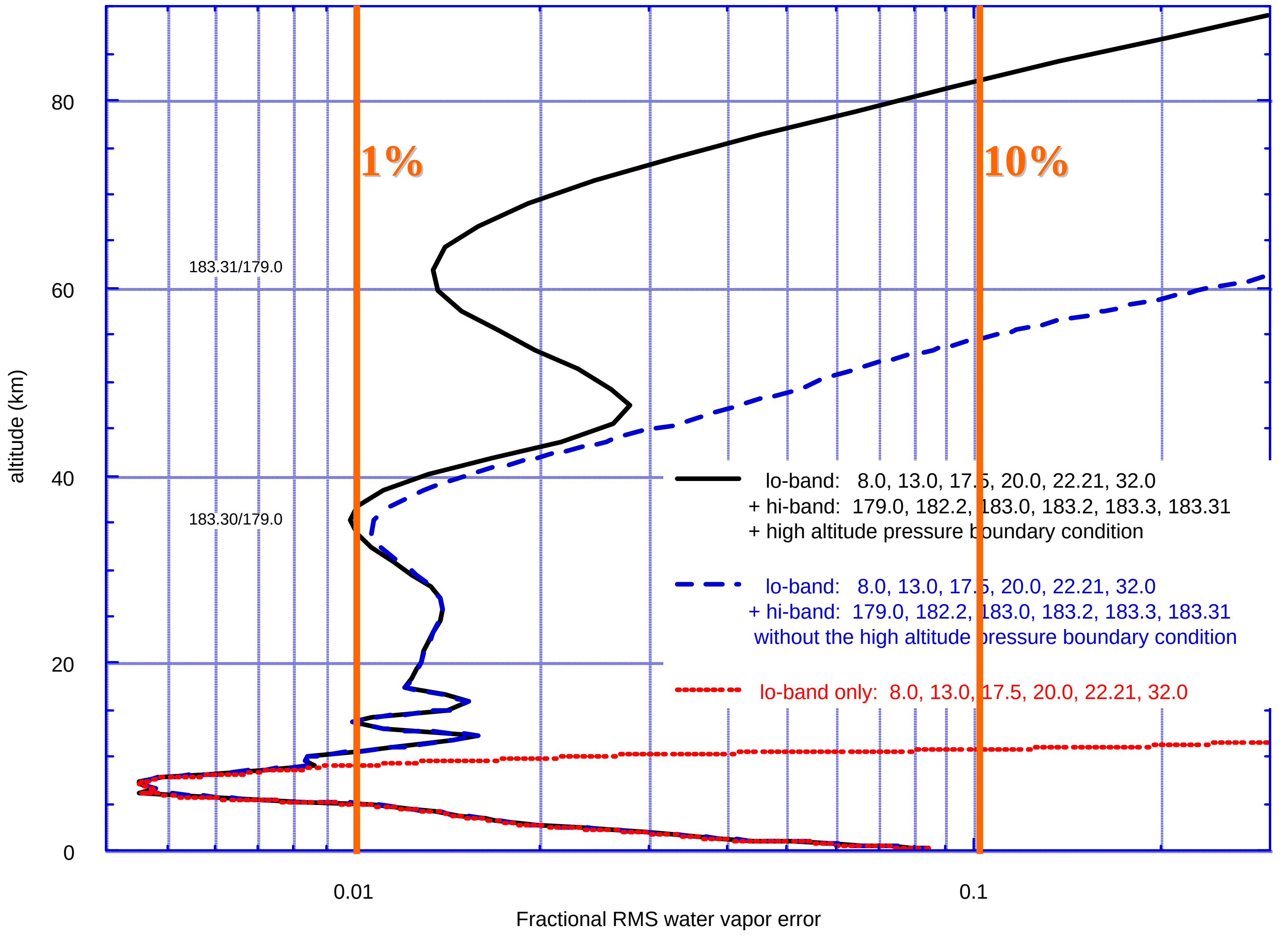
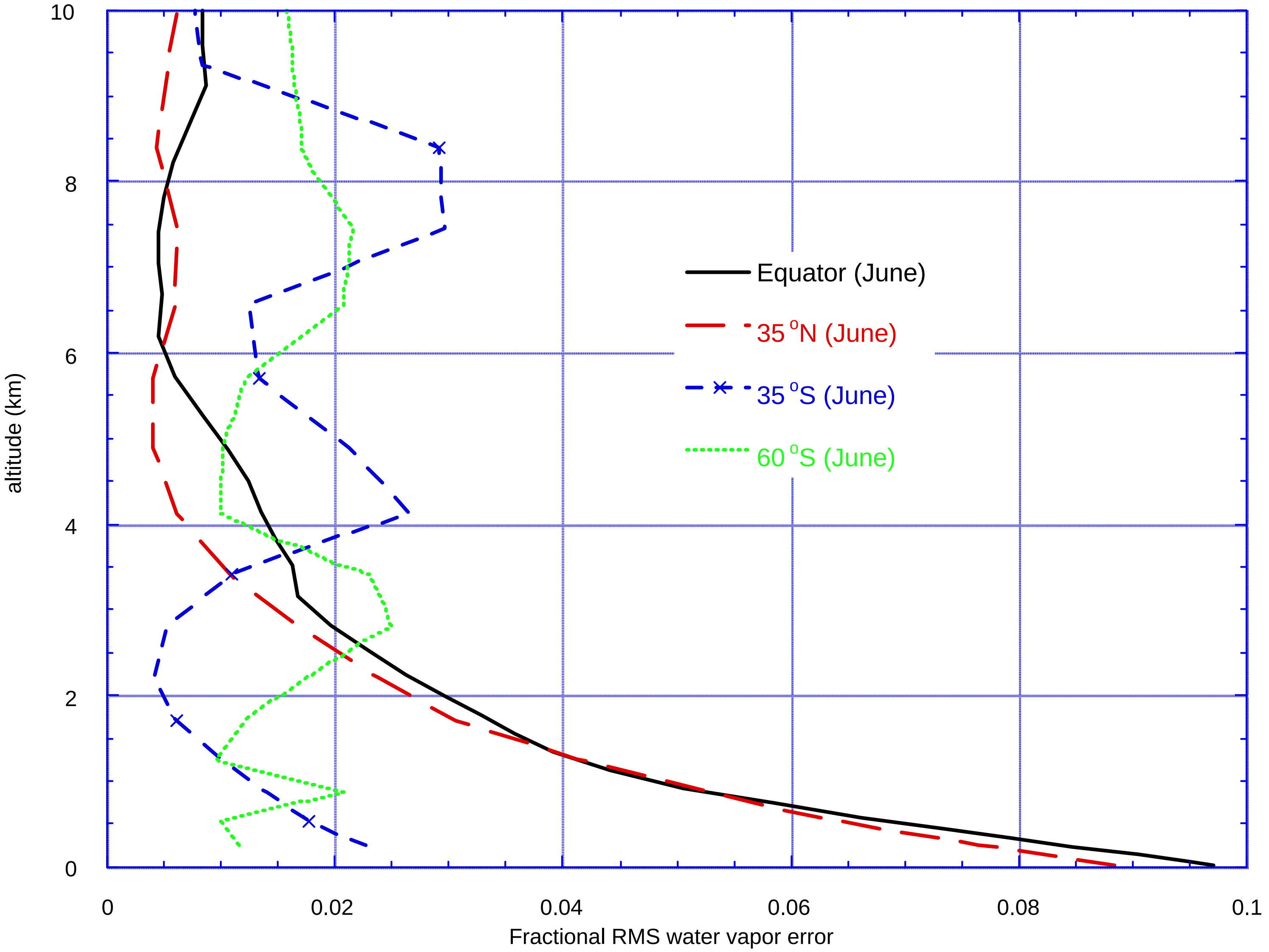
Sources and Mitigation of Error

Instrumental effects:	Finite signal to noise ratio,	Directional antenna
	Antenna gain and pointing,	Calibration tone
	Transmitter power fluctuations,	Monitor/Cal. tone
	Receiver gain fluctuations,	Cal. tone
	Local multipath	Directional antenna
Atmospheric effects:	Molecular oxygen absorption	Est. from T & P
	Defocusing	Cal.tone/Can. Xfm
	Diffraction from layering	Cal.tone/Can. Xfm
	Scintillations from turbulence	Cal.tone/Can. Xfm
	Atmospheric multipath	Canonical Xfm
Retrieval errors:	Non-spherical distributions	Horiz. average
	Uncertainty in line parameters	Spectr. cal. in space
	Correlation between vapor and liquid frequency dependence	Additional tones

Precision of Individual Water Vapor Profiles (Tropics)



Latitudinal/Seasonal Dependence of Water Vapor Precision



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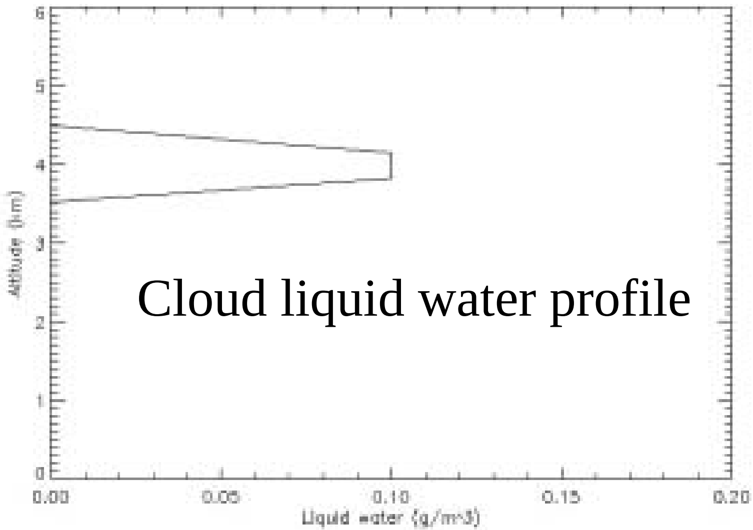
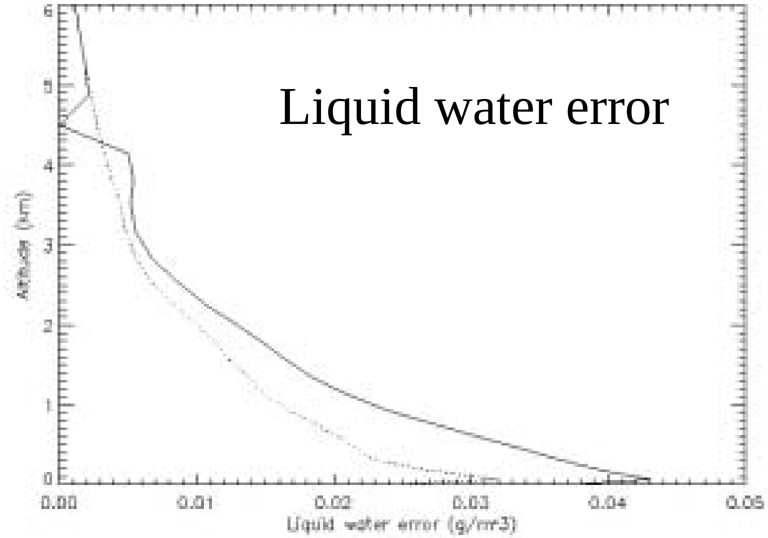
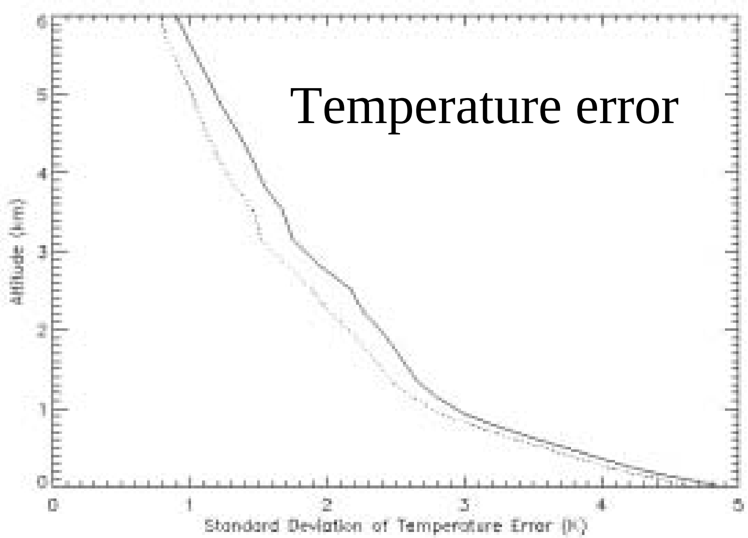
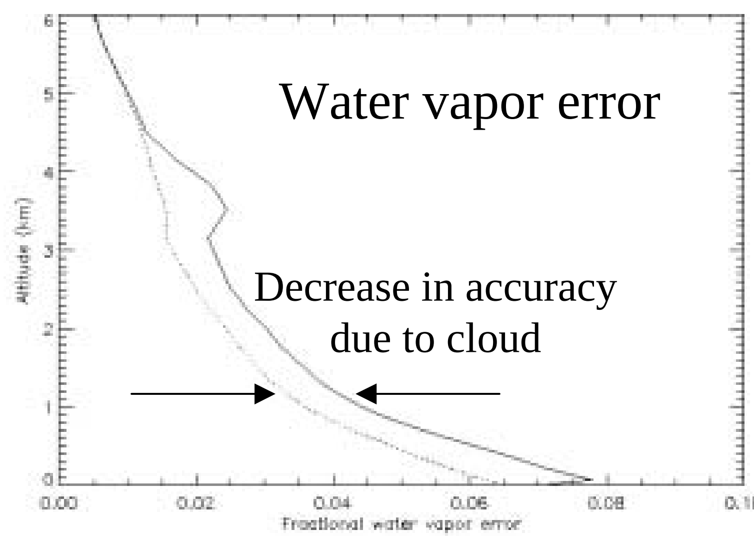
Tropical Retrieval Precision (with cloud near 4 km)



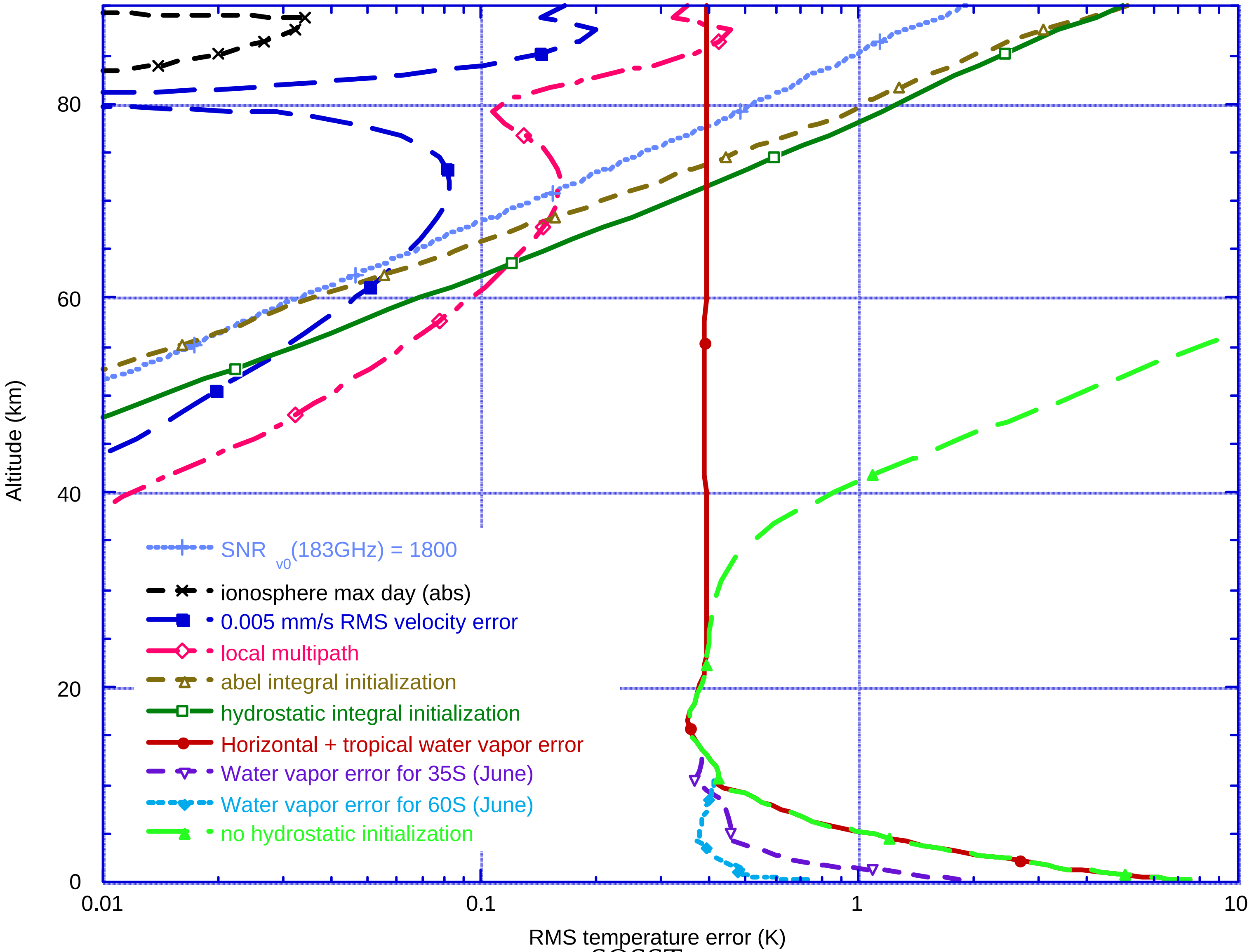




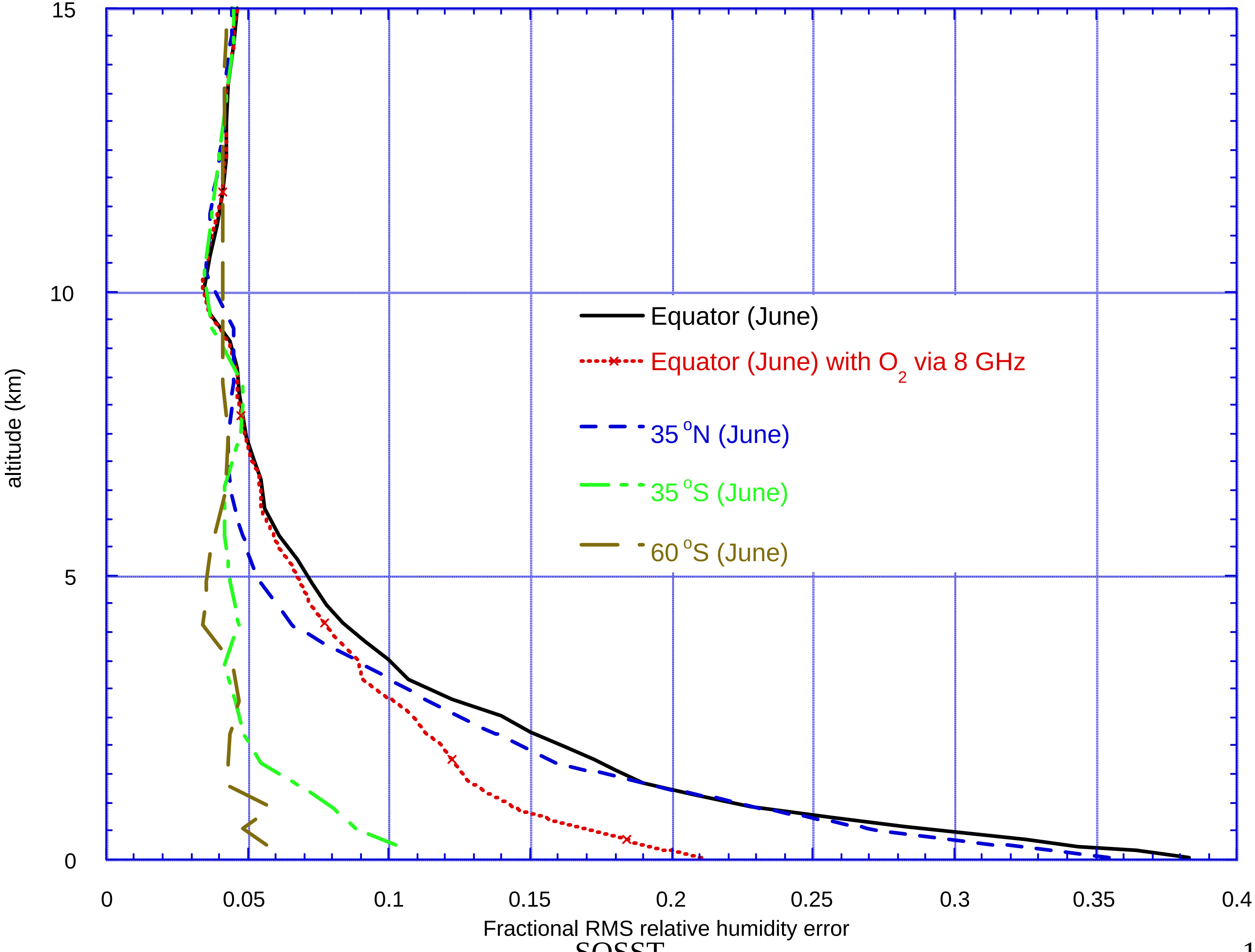


Solid line is retrieval with cloud. Dotted line is clear sky retrieval

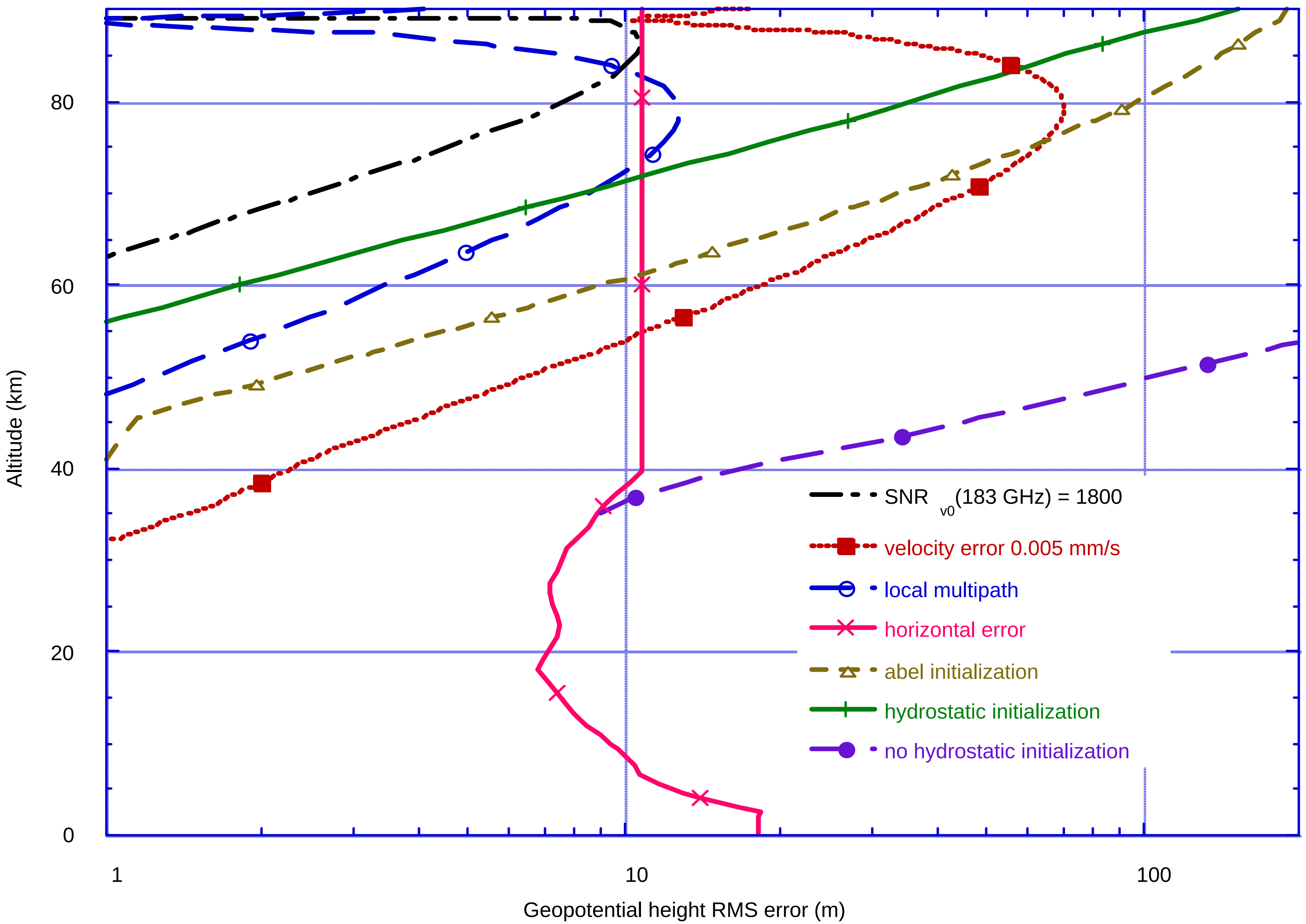
Precision of Individual Temperature Profiles



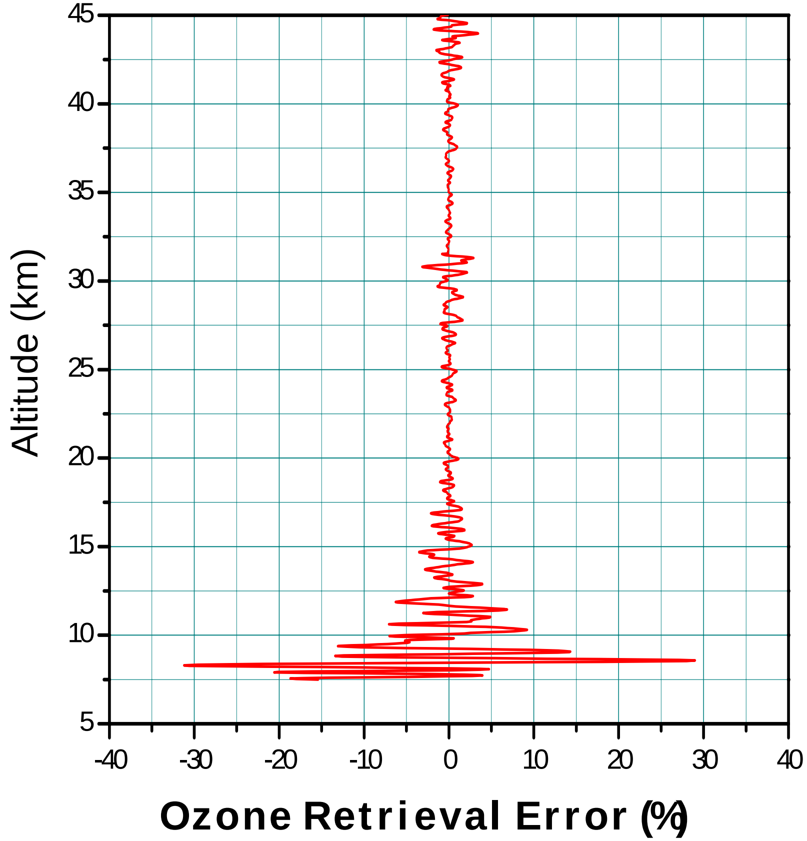
Precision of Individual Relative Humidity Profiles

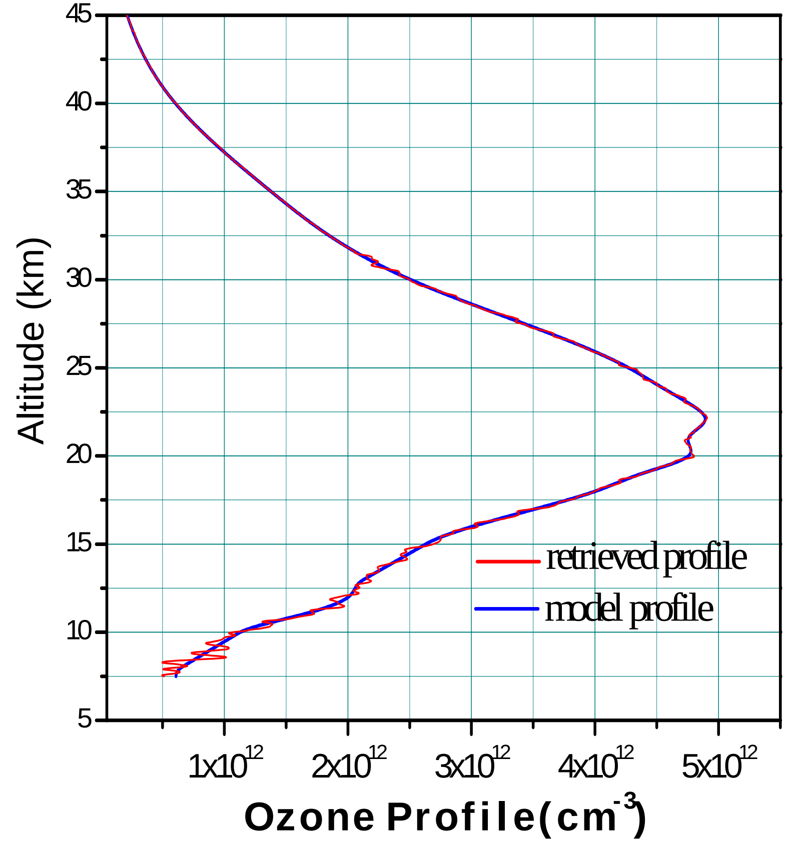


Precision of Geopotential Height of Pressure Profiles



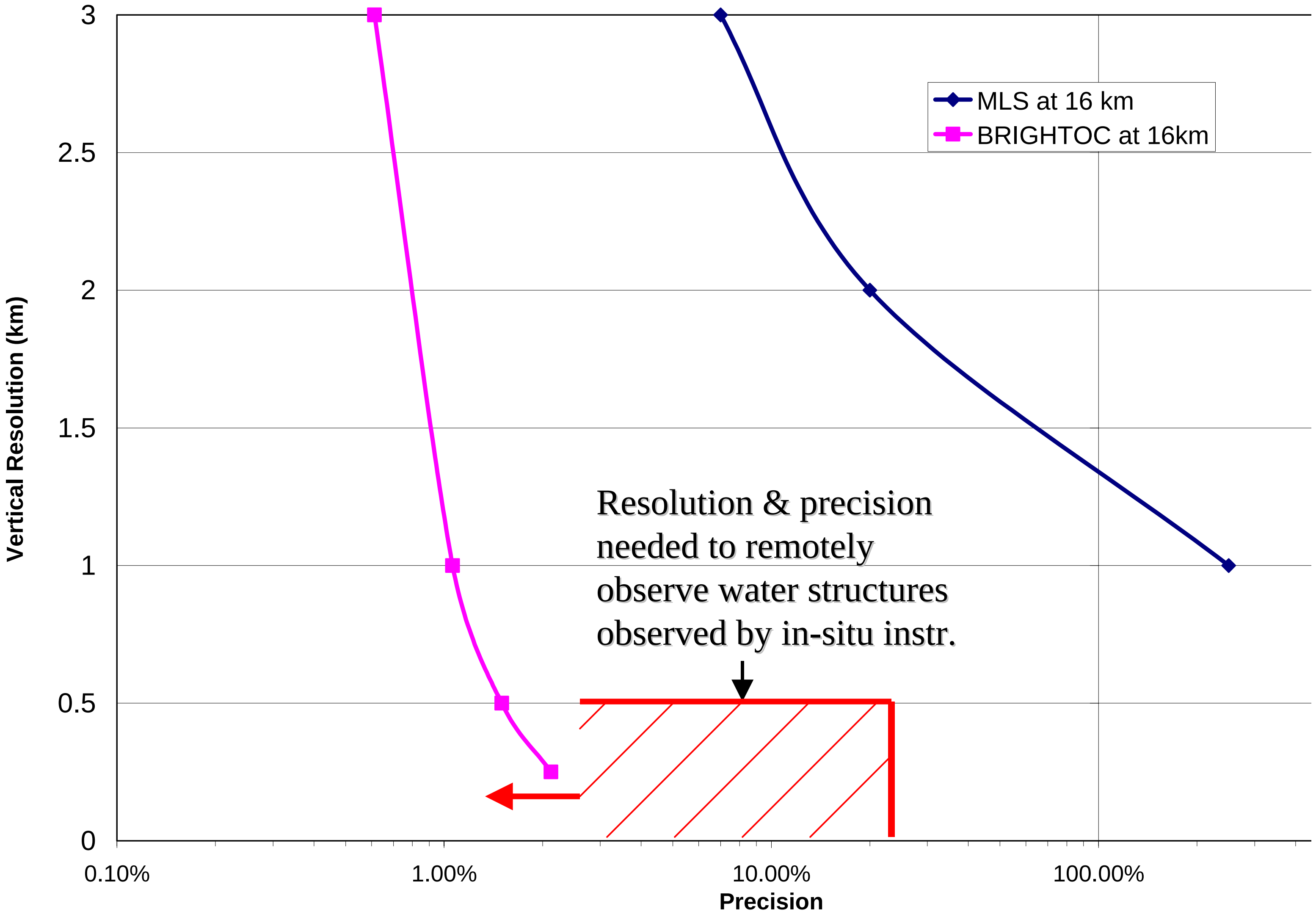
Ozone Retrieval Precision





- Ozone r.m.s. retrieval error ~ 2 % (15- 40 km)
- Below 10 km, the ozone retrieval error quickly increases because the ratio of ozone absorption to air absorption becomes very small

BRIGHTOC & MLS Upper Troposphere Moisture
Vertical Resolution vs. Precision



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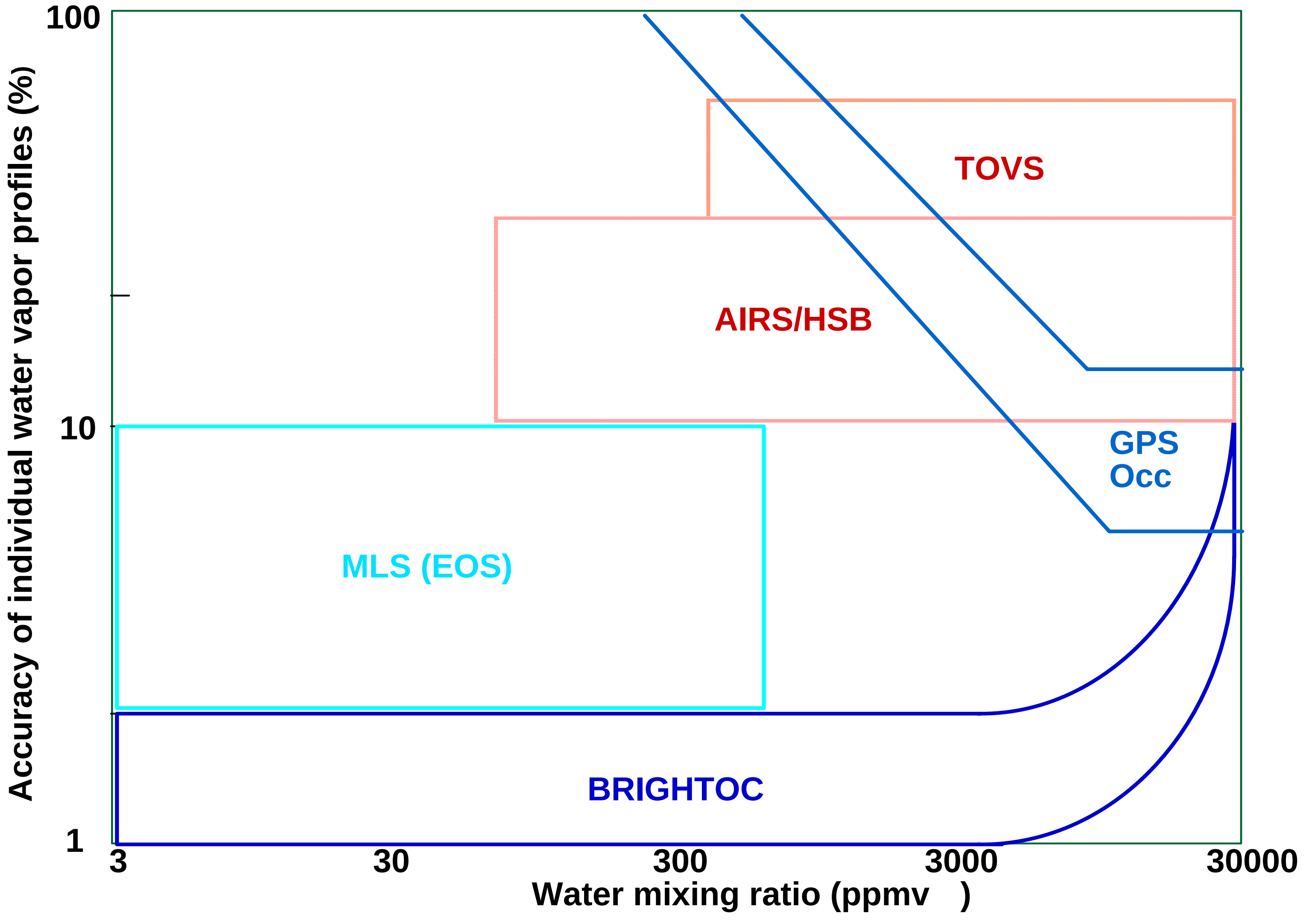
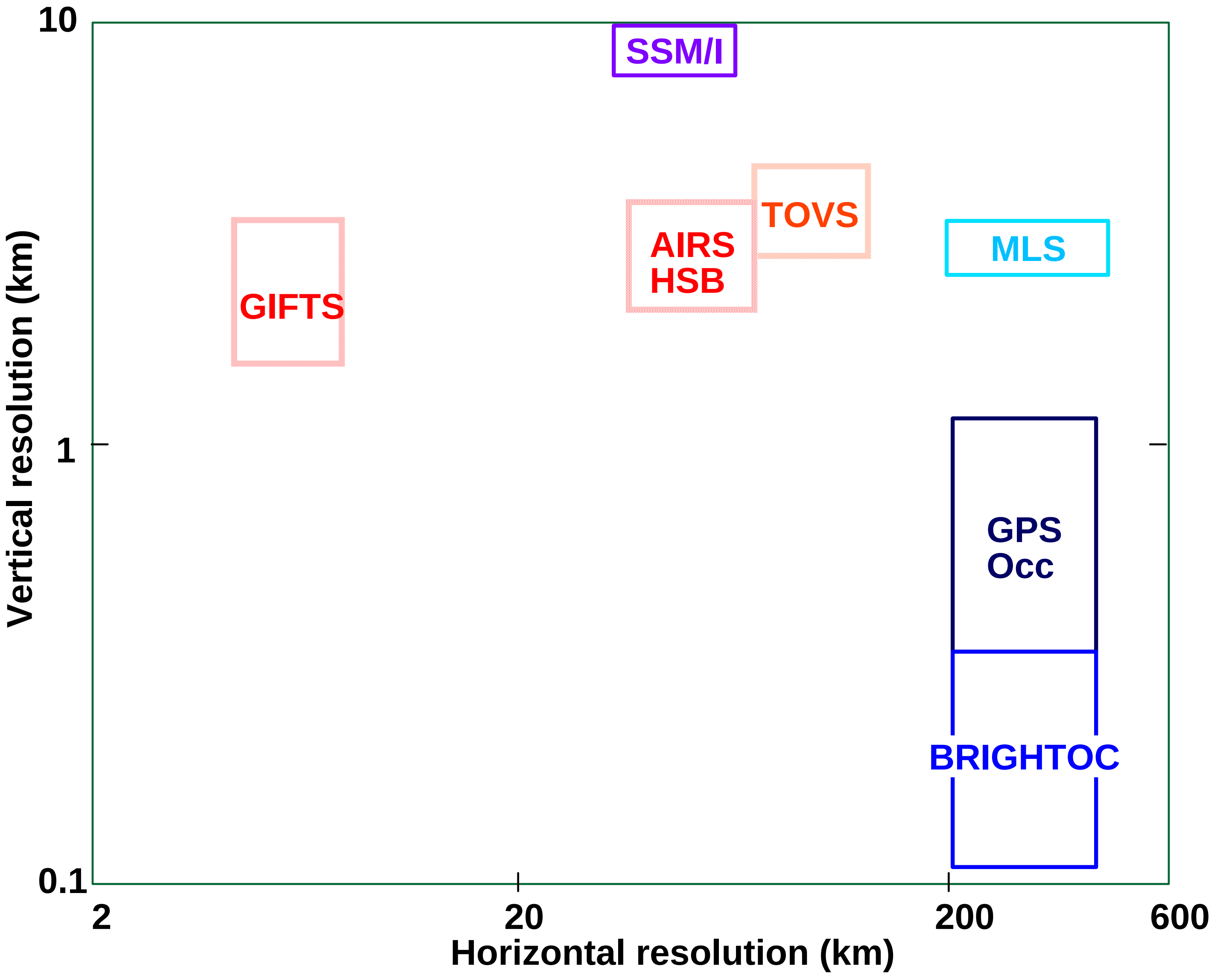
Occultation Features



Occultation Features



Science Issues in Upper Trop/Lower Strat.

- Upper troposphere/lower stratosphere is VERY important regime for climate
  - Water vapor and ozone are very important radiatively in this regime
  - Water vapor and ozone are poorly observed
  - Fundamental questions exist on basic behavior and trends of water and ozone in this regime
  - Solar variability and Earth are potentially connected through ozone
- We need precise and high vertical resolution observations to understand
  - The origin and distribution of upper trop/stratospheric water and its impact on the radiative forcing
  - Processes responsible for exchange between stratosphere and troposphere

Occultation Features

Occultation signal is a point source

⇒ Fresnel Diffraction limited vertical resolution

⇒ Very high vertical resolution

We control the signal strength and therefore have much more control over the SNR than passive systems

⇒ Very high precision at high vertical resolution

Self calibrating technique

⇒ Source frequency and amplitude are measured immediately before or after each occultation so there is no long term drift

⇒ Very high accuracy

Occultation Features

Calibration tones allow

⇒ Removal of antenna and electronic gain variations during each occultation

⇒ Removal of unwanted diffraction effects

Simple and direct retrieval concept

⇒ Known point source rather than unknown distributed source that must be solved for

⇒ Unique relation between variables of interest and observations (unlike passive observations)

⇒ Retrievals are independent of models and initial guesses

Occultation Features

Height is independent variable

⇒ Recovers geopotential height of pressure surfaces remotely completely independent of radiosondes

⇒ Spans mesosphere to the surface

Microwave system

⇒ Can see into and below clouds, see cloud base and multiple cloud layers

⇒ Retrievals only slightly degraded in cloudy conditions

⇒ Allows all weather global coverage with high accuracy and vertical resolution