Error Estimate of Bending Angles in the Presence of Strong Horizontal Gradients

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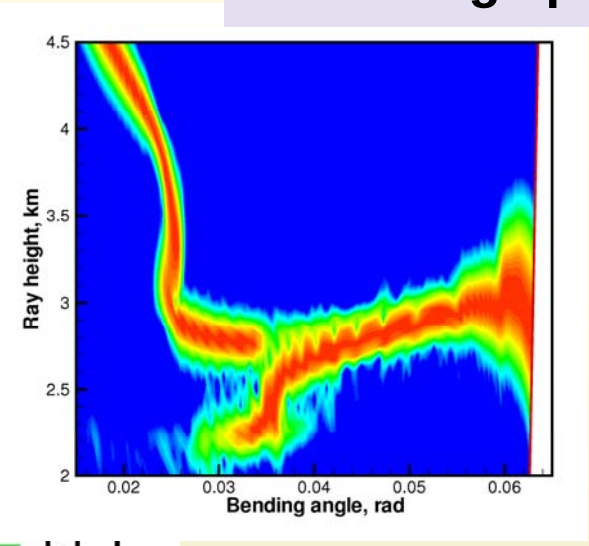
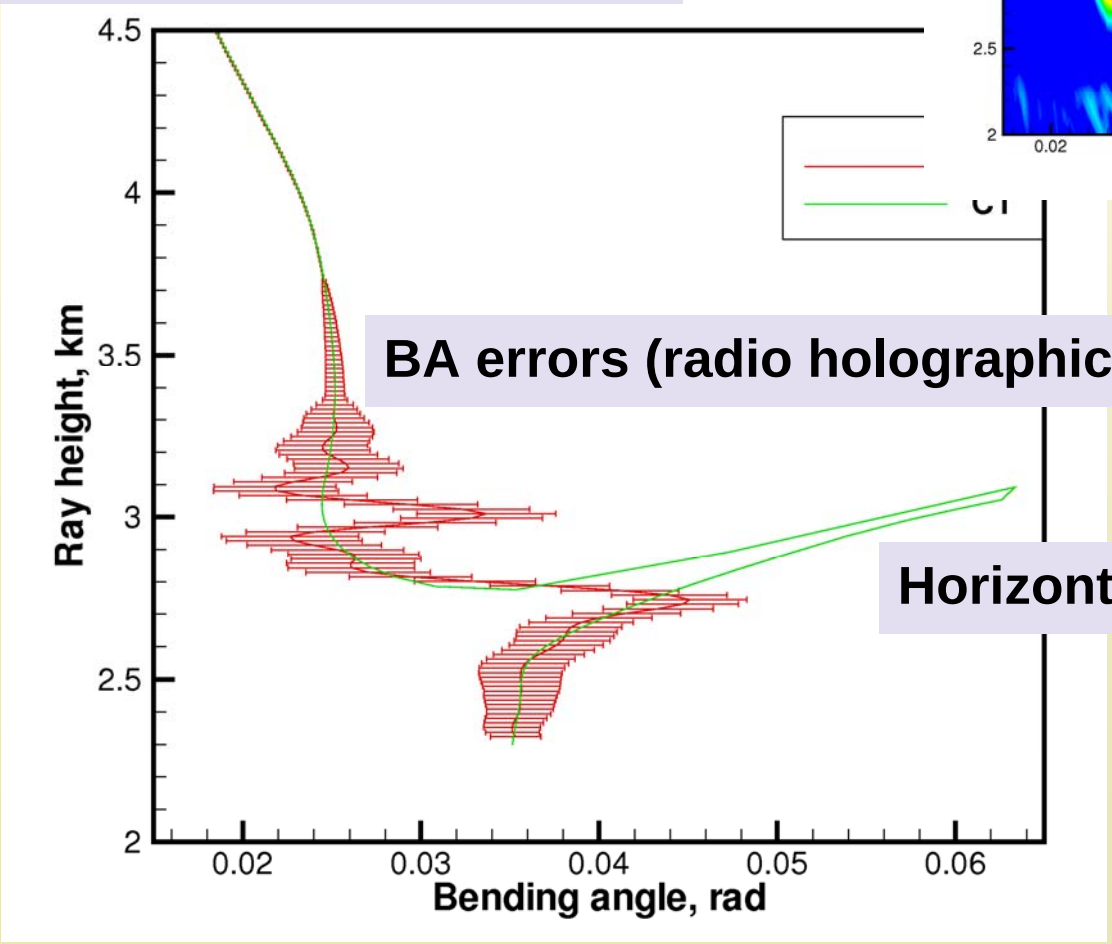
CT sliding spectrum



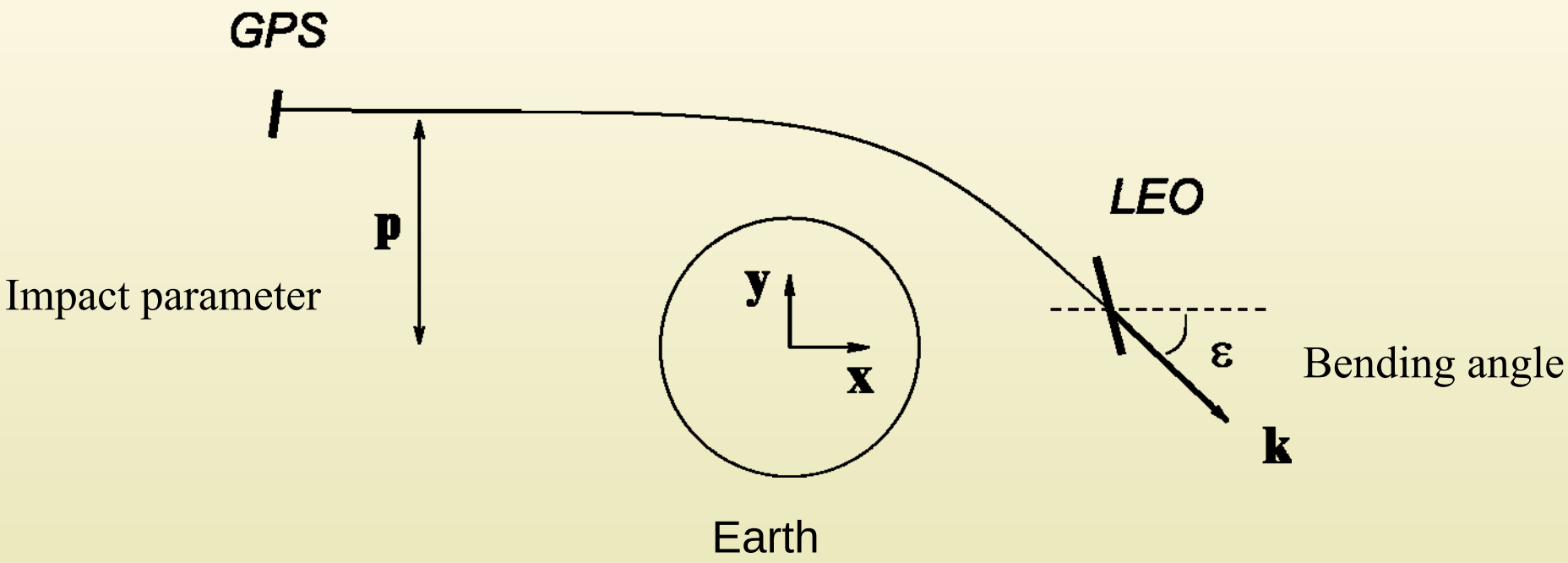
Inversion of bending angles (BA)



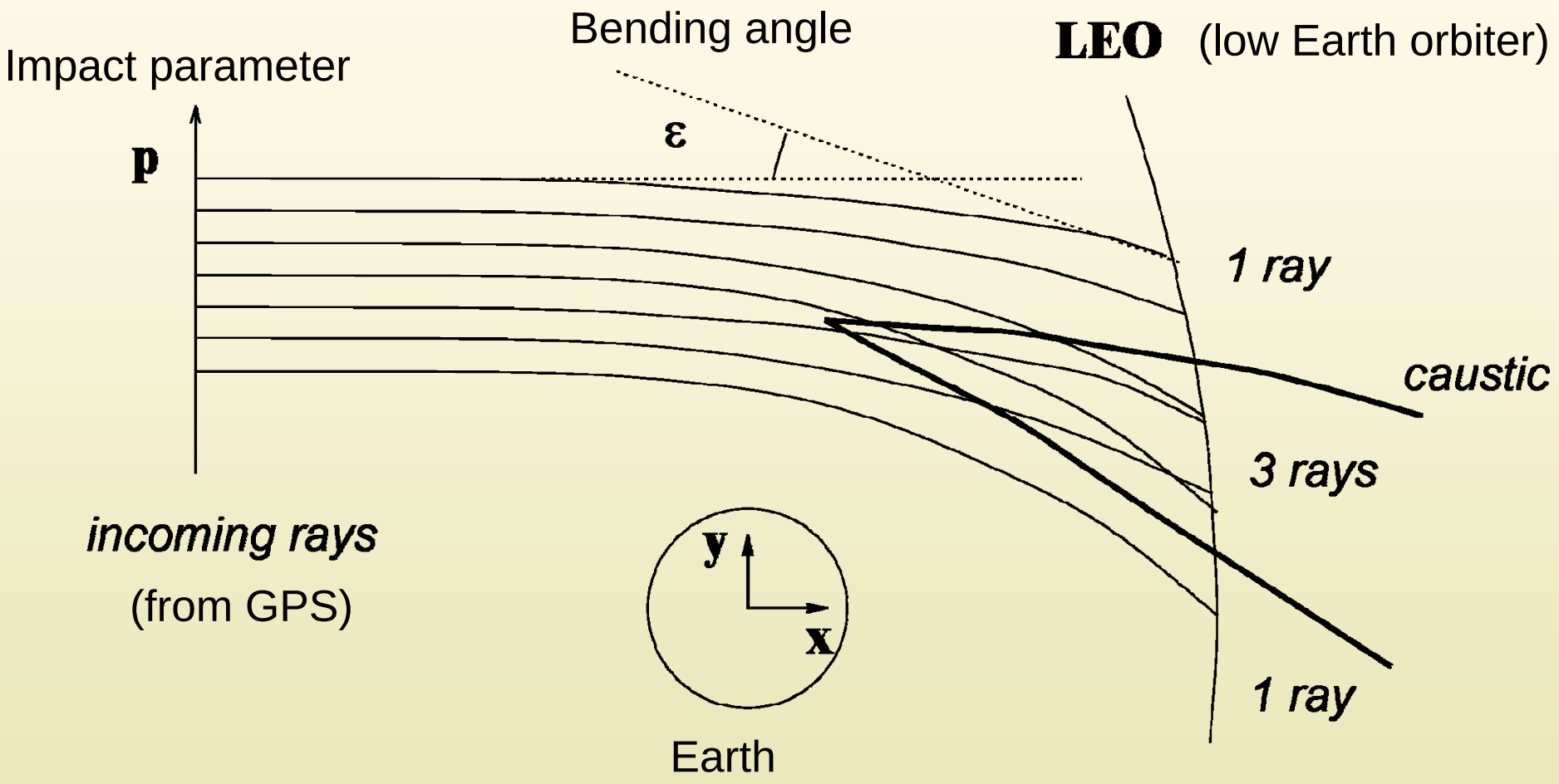
BA errors (radio holographic errors)

Horizontal gradients

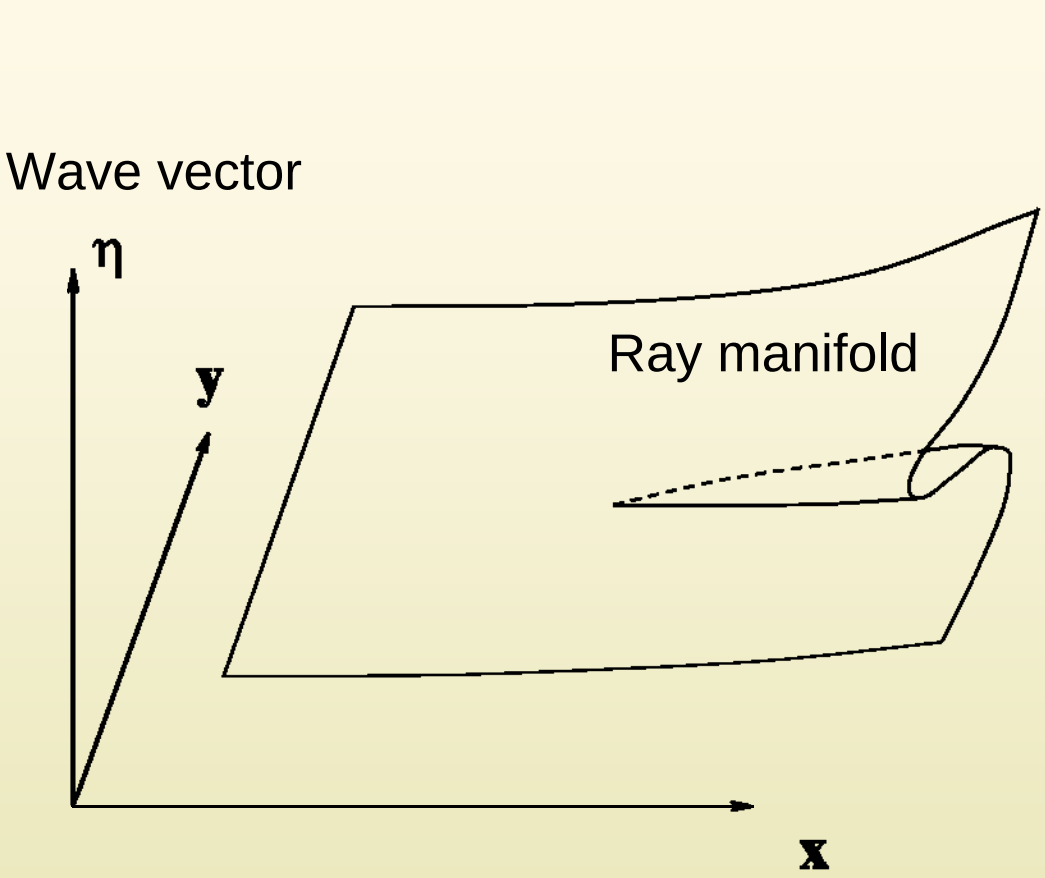
Radio Occultation Geometry

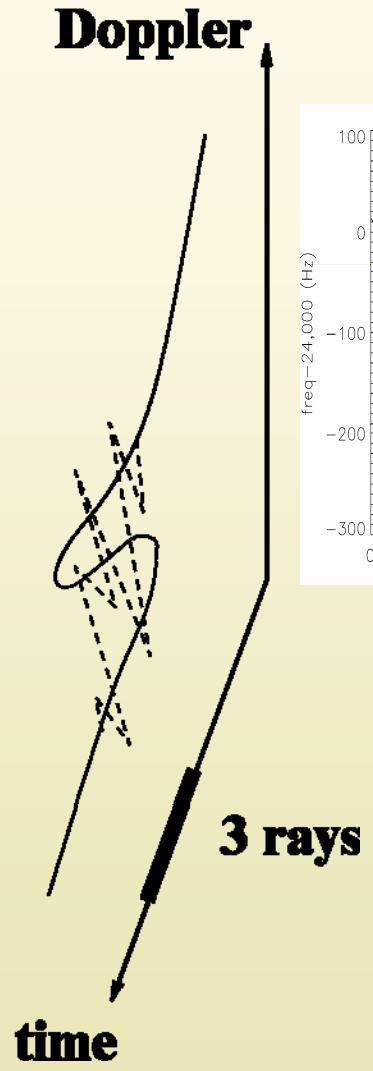


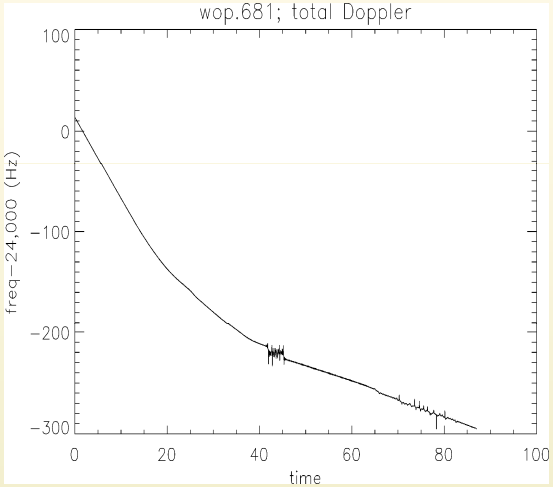
Multipath Example



Schematic Ray Manifold

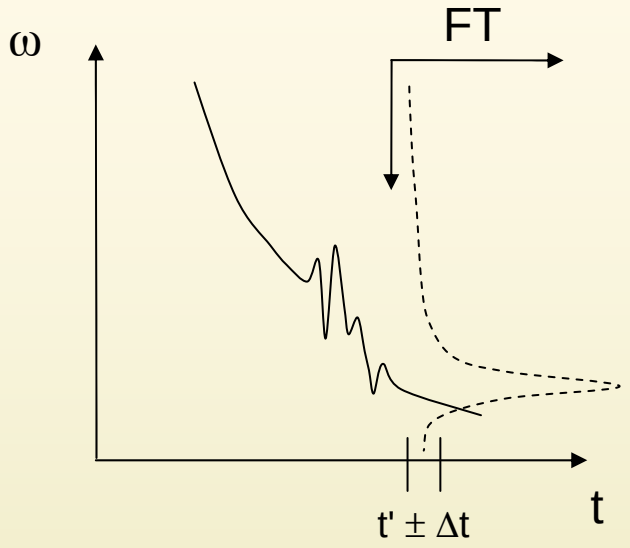




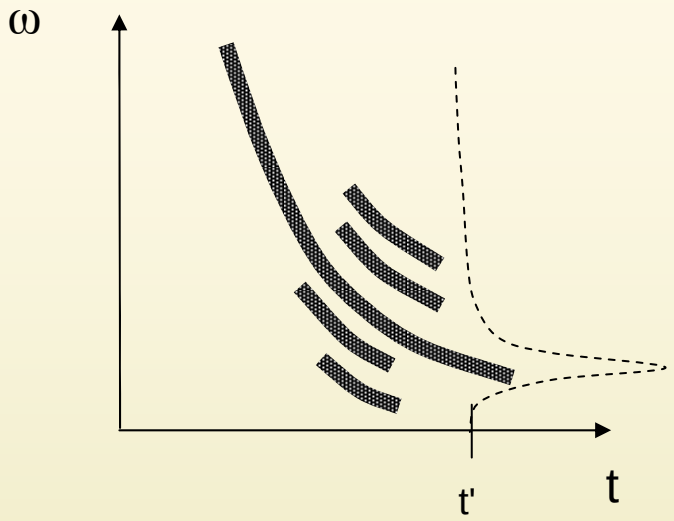


Sliding Spectrum (FT in sliding window)

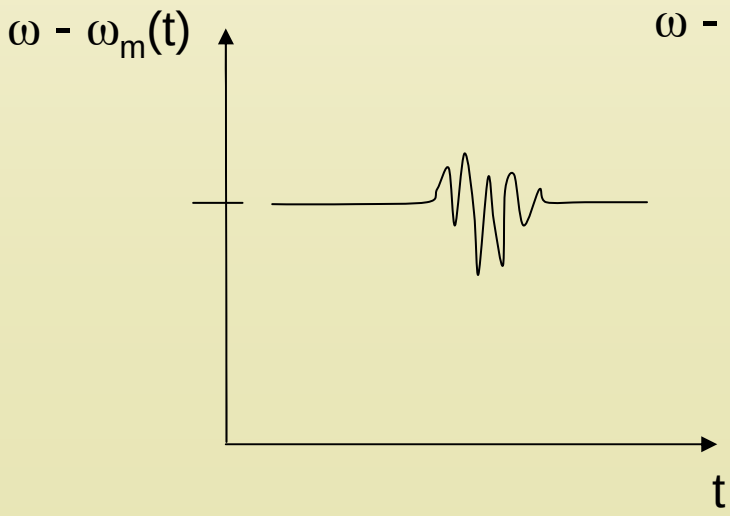
Doppler

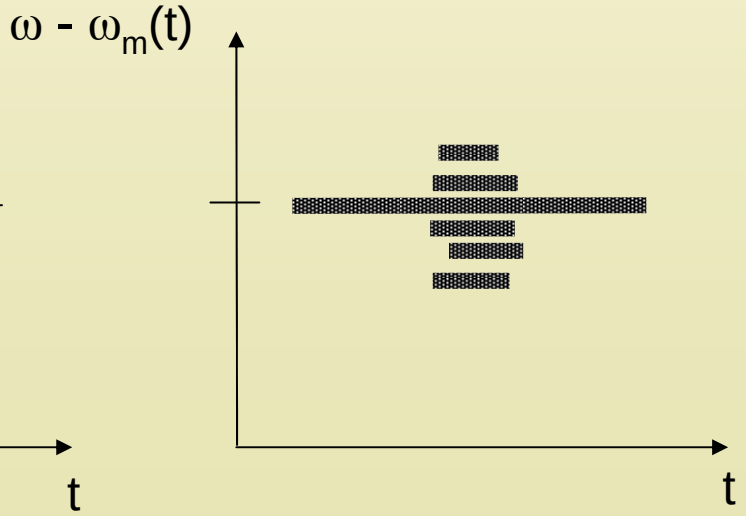


Sliding spectrum



Subtract smooth phase model:





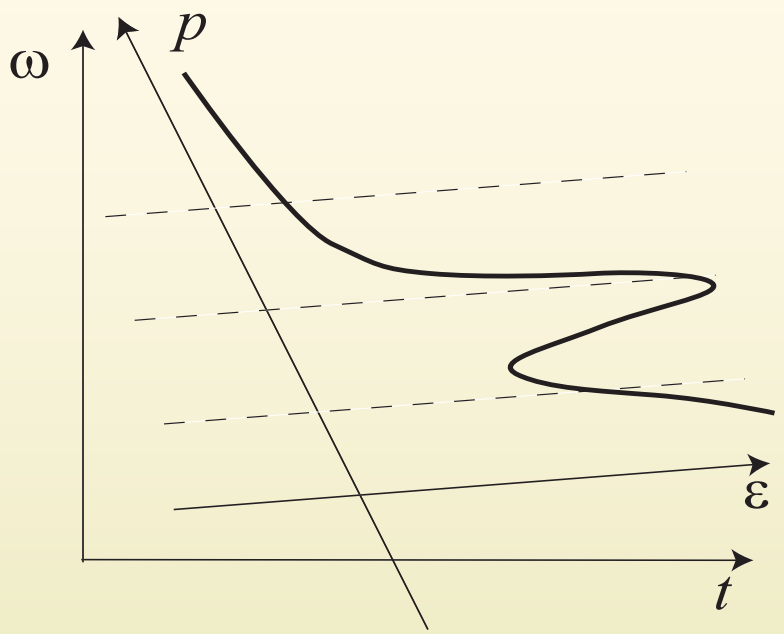
Canonical Transform (CT) Algorithm

Mapping:

$$u(t) = A(t)\exp\left(ik\Psi(t)\right), \quad \omega = \frac{d\Psi(t)}{dt}$$

$$w(p) = \sqrt{\frac{-ik}{2\pi}}\int a_2(p,t)\exp(ikS_2(p,t))u(t)\,dt;$$

$$w(p) = A'(p)\exp\left(ik\Psi'(p)\right), \quad \varepsilon = \frac{d\Psi'(p)}{dp}$$

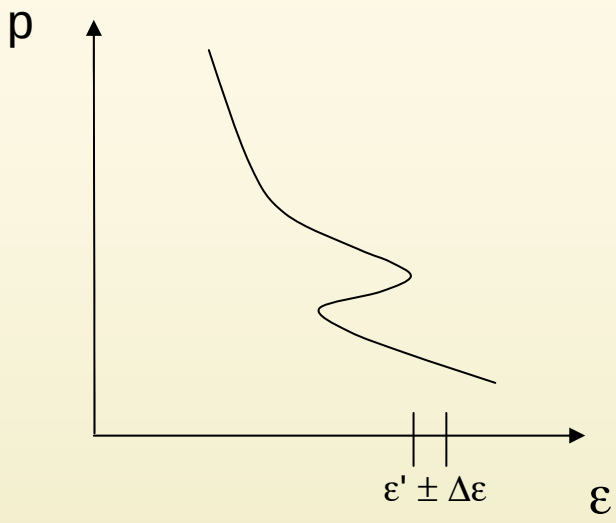


Smooth reference model in p-domain:

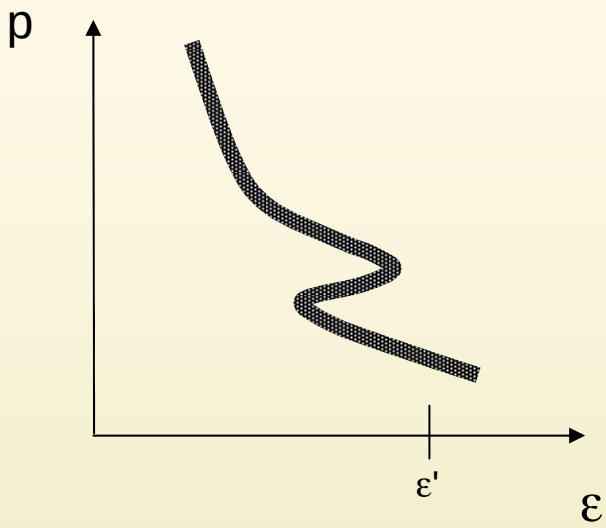
$$w_m(p) = \exp\left(ik\Psi'_m(p)\right)$$

CT Sliding Spectrum & BA Errorbars

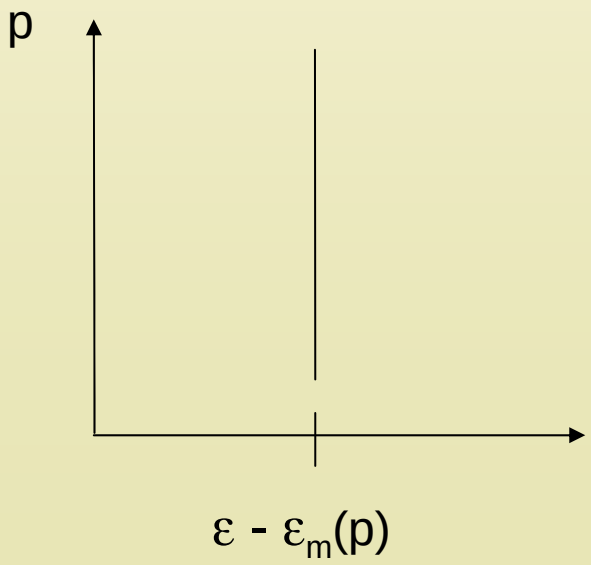
CT Bending angle

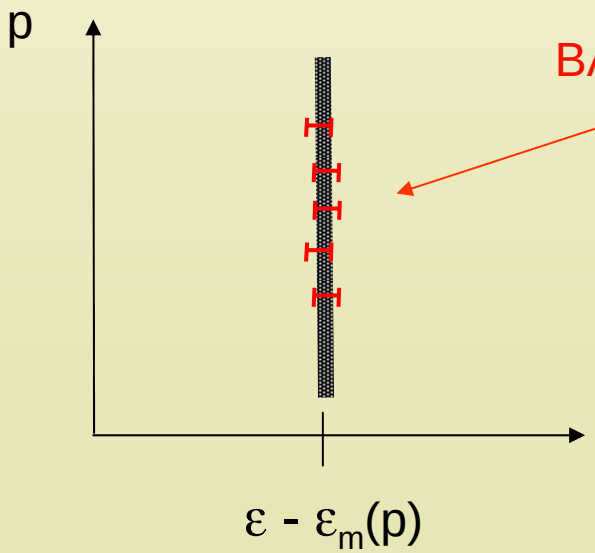


Sliding spectrum



Subtract smooth BA phase model:





BA errorbars

- calculated from weighted average of the spectrum (=radio holographic errors)

Radio Holographic Errors

Sliding spectrum in p-domain:

$$w(p,\xi) = \int_{p-\frac{\Delta p}{2}}^{p+\frac{\Delta p}{2}} \frac{w(p')\cos\dfrac{\pi(p'-p)}{\Delta p}\exp(-ik\xi p')}{\exp\left(ik\Psi'_m(p')\right)}dp'$$

Bending angle error:

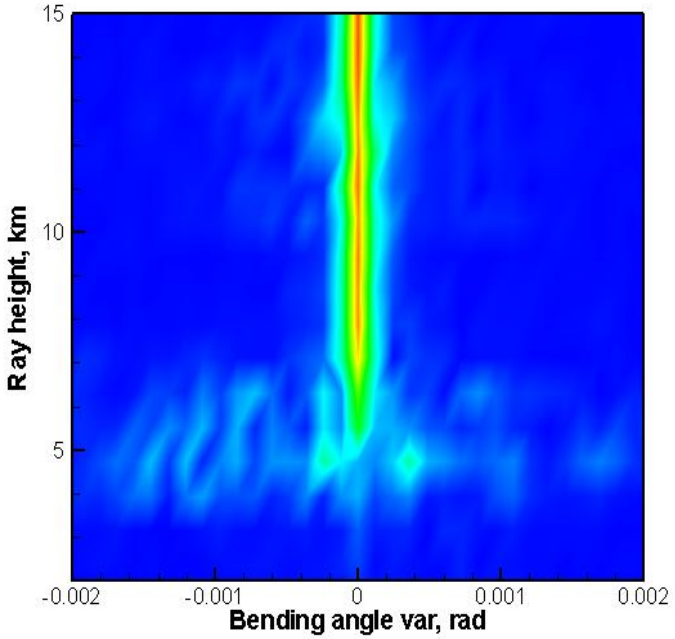
$$\delta\varepsilon_T(p) = \left(\frac{\int|w(p,\xi)|^2\,\xi^2 d\xi}{\int|w(p,\xi)|^2\,d\xi}\right)^{1/2}$$

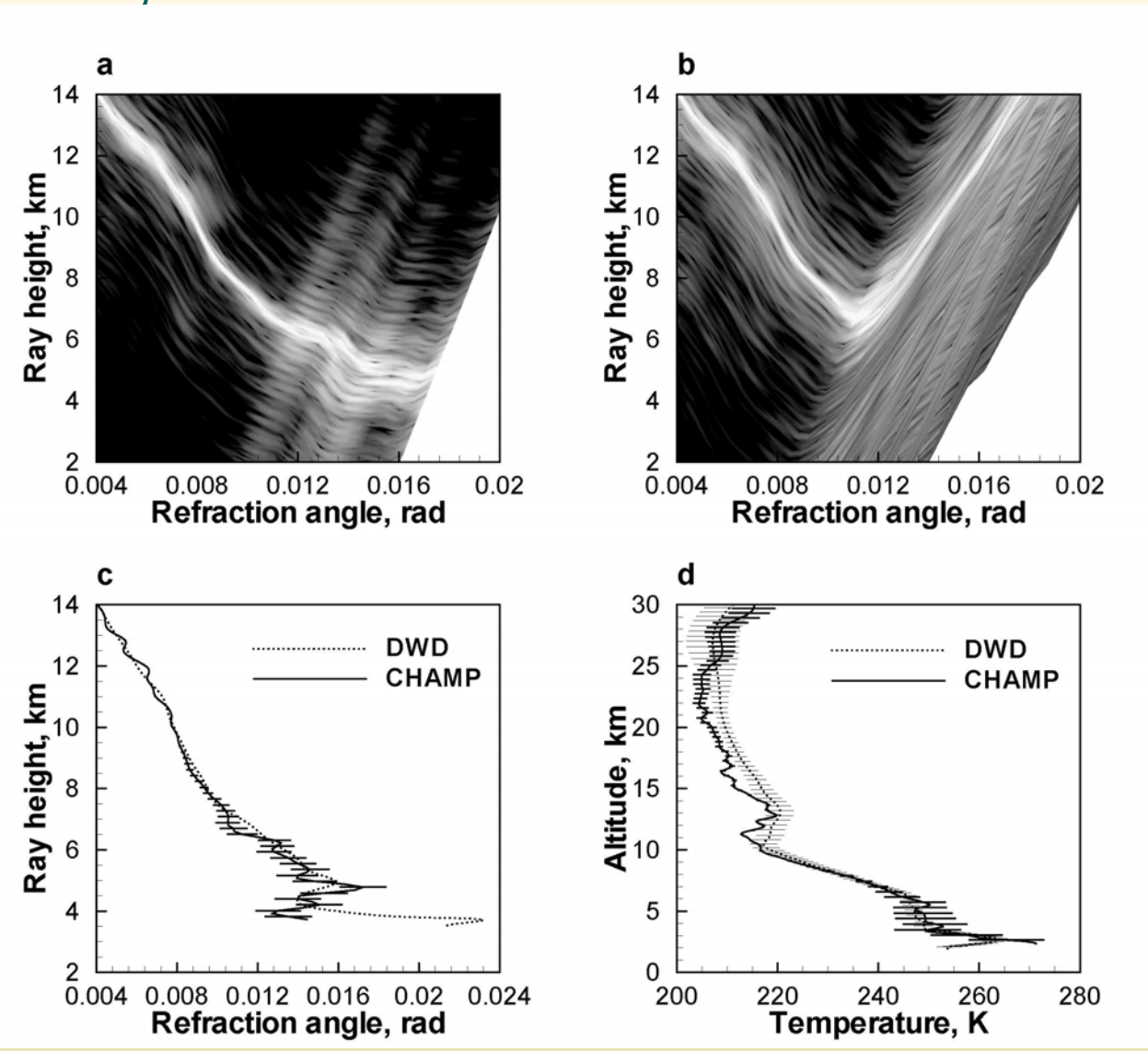
(bending angle spectral width in p-domain)

ξ: momentum conjugated to impact parameter (= bending angle variation)

CHAMP occultation 0004, 2004.01.18

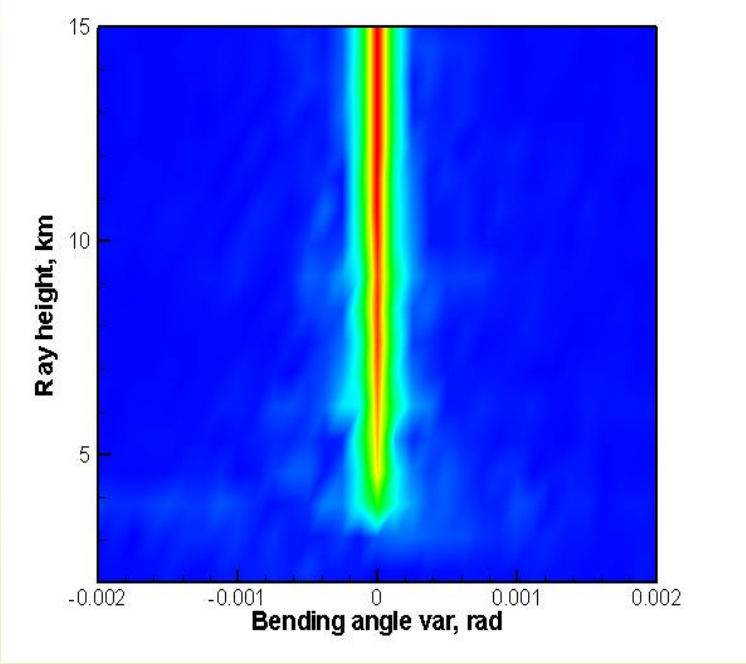
UTC 00:24, 50.4N 116.1W

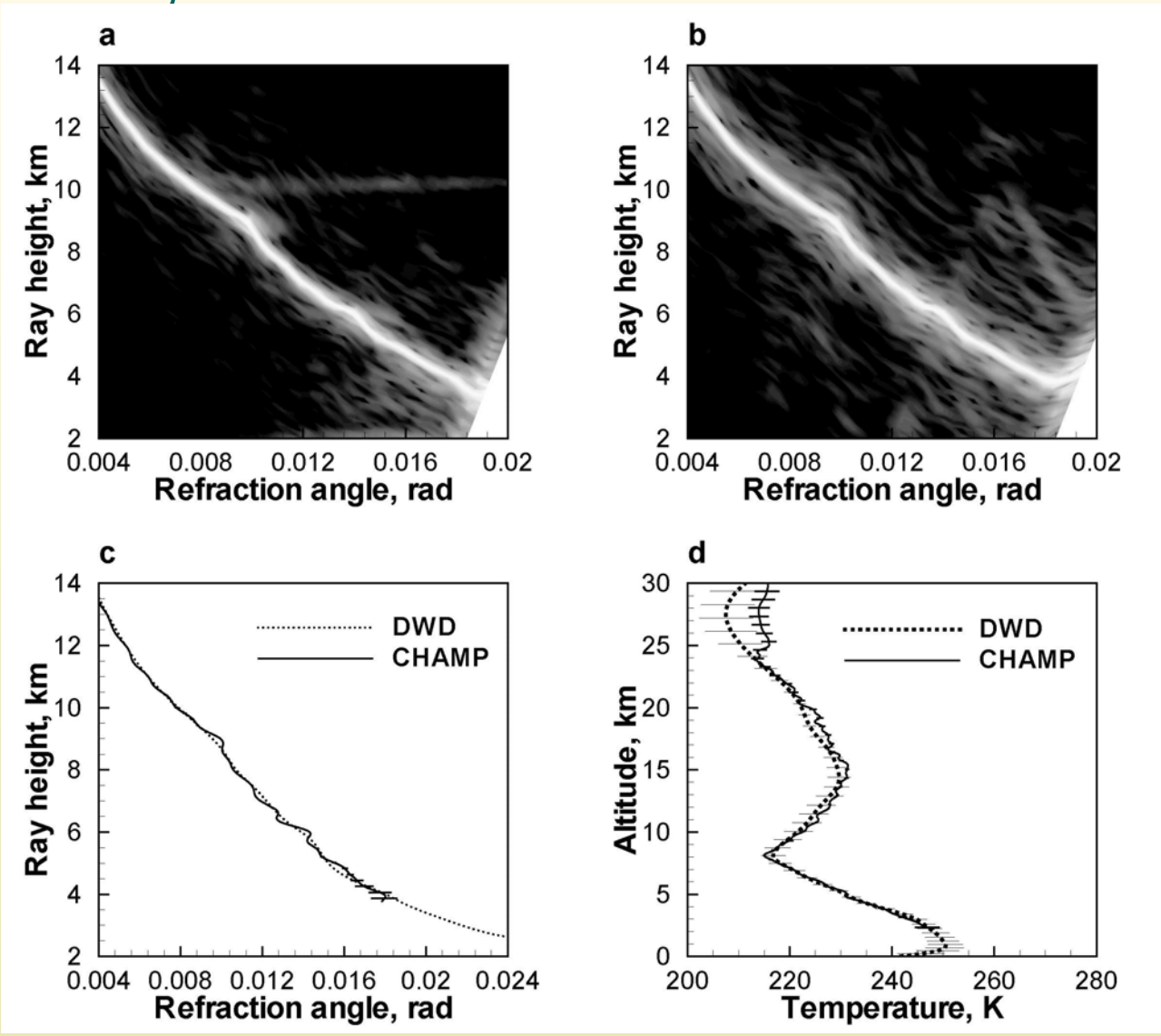




CHAMP occultation 0097, 2004.01.18

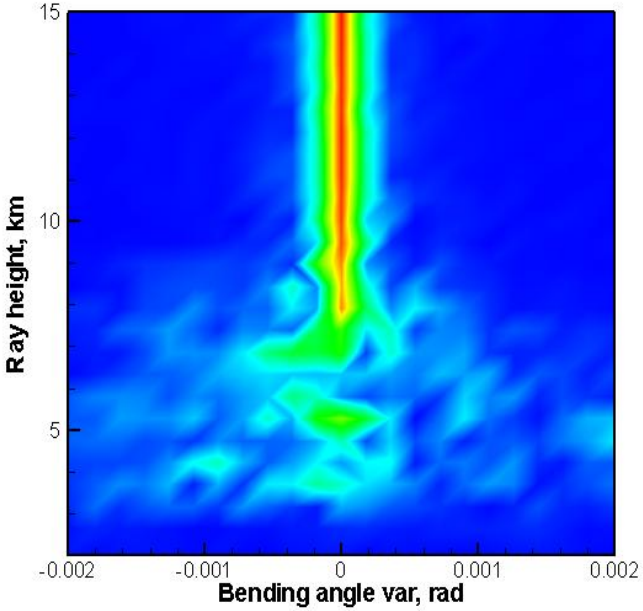
UTC 09:50, 78.8N 125.6W

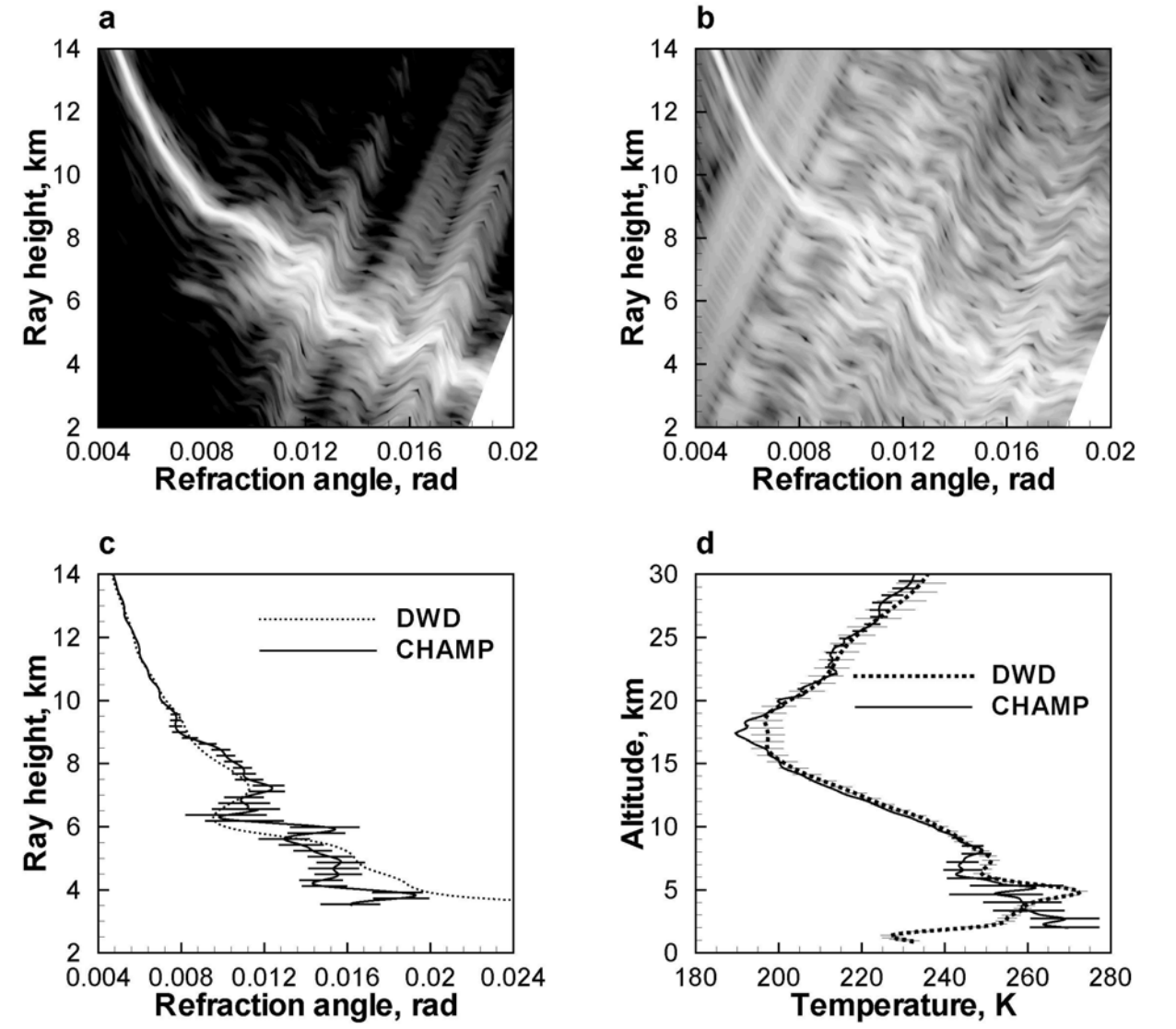




CHAMP occultation 0041, 2004.01.18

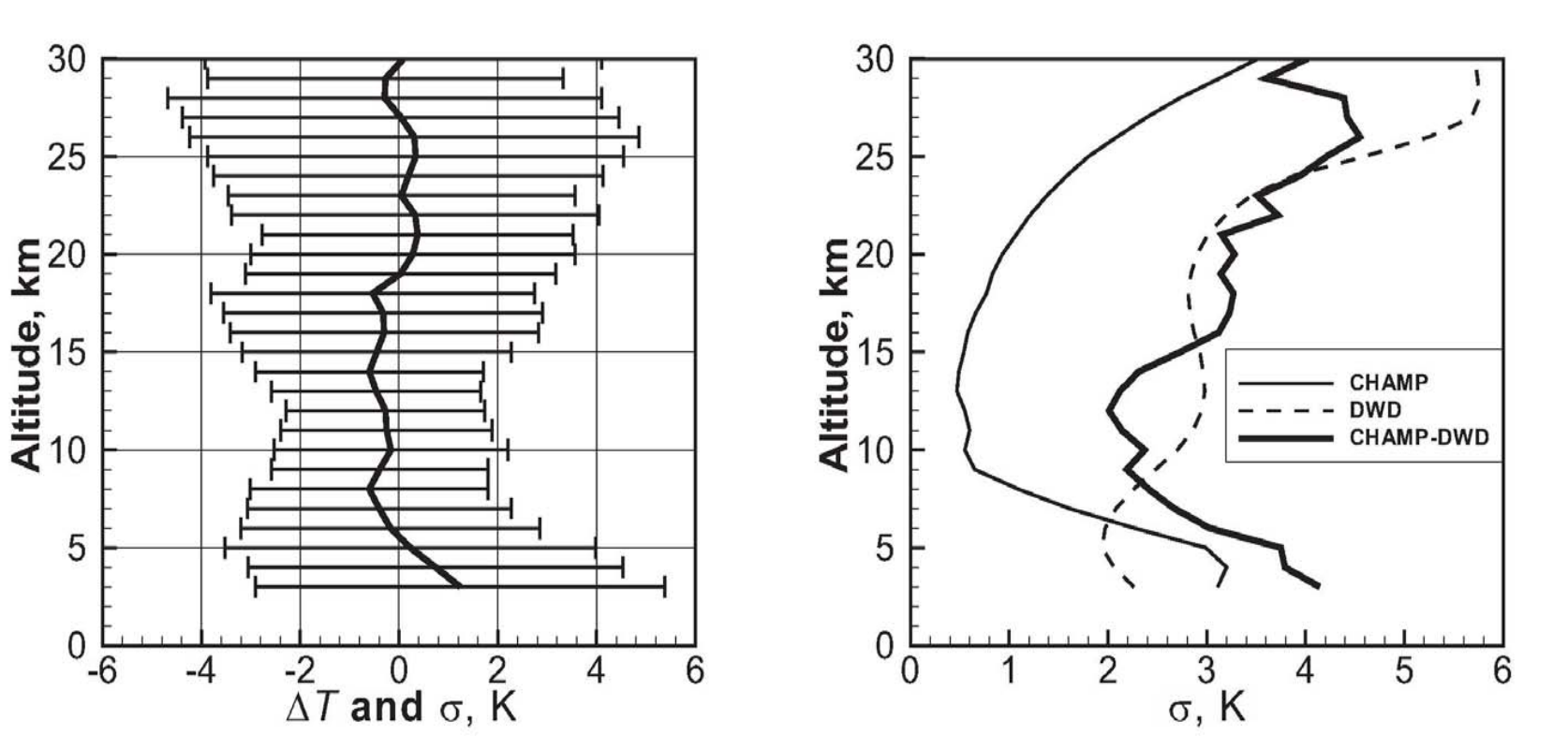
UTC 04:09, 26.0S 19.4E





Statistical Analysis of CHAMP Data

2004.01.18



Radio holographic error estimation of CHAMP data and DWD errors are consistent with observed CHAMP-DWD differences

[Ref: Gorbunov, Lauritsen, Rhodin, Tomassini, Kornblueh;
JGR, 111, D10105, doi:10.1029/2005JD006427 (2006)]

Horizontal Gradients

The typical atmosphere will posses horizontal gradients.

Some typical values are:

$\delta N/\delta x$ ~ 5-20 N-units/300 km ($\delta N/\delta h|_{h=2\ km}$ ~ 40 N-units/1000 m)

(the dry component of N varies much less)

$\delta T/\delta x$ ~ 3-5 K/300 km (or: 3 K/50 km) ($\delta T/\delta h|_{h=2\ km}$ ~ 5-7 K/1000 m)

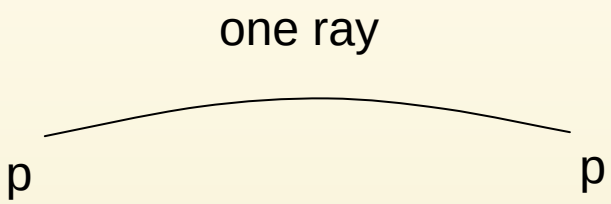
$\delta p/\delta x$ ~ 100 m / 300 km (but p_{GPS} and p_{LEO} may be nearly identical)

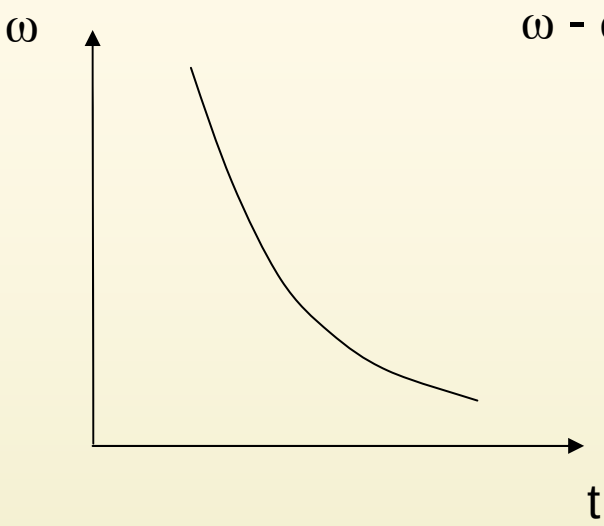
$\delta \varepsilon/\delta x$ ~ 0.005-0.02 rad (near the surface)

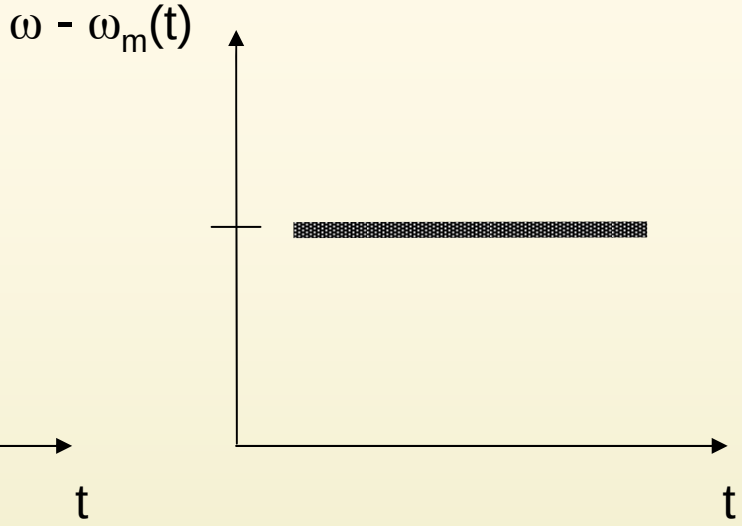
Spherical Symmetry

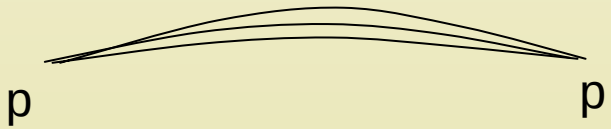
Doppler (GO)

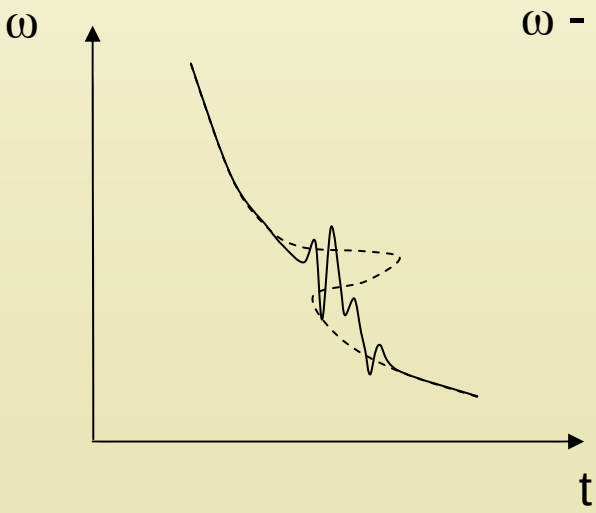
Sliding spectrum

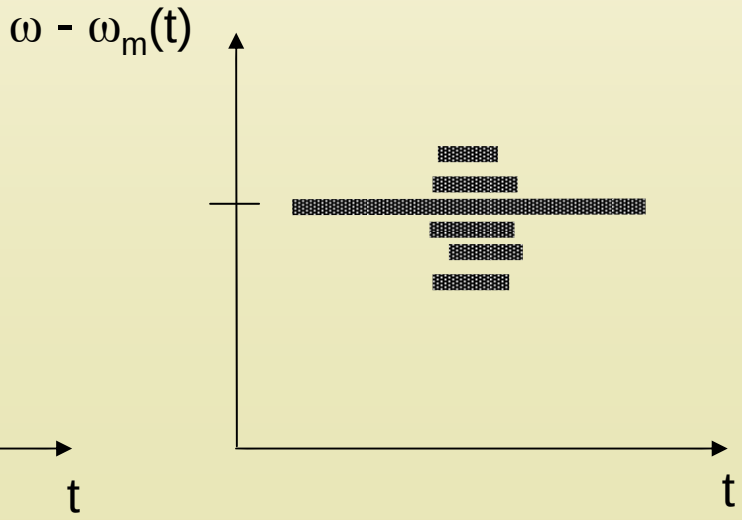








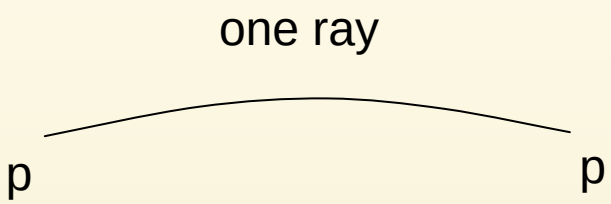


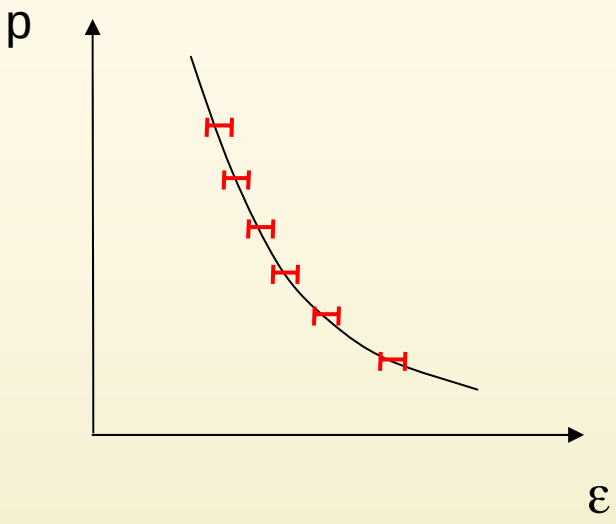


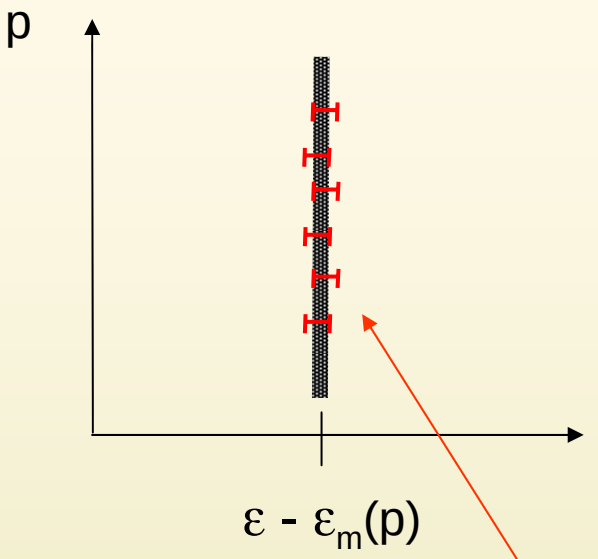
Spherical Symmetry

CT Bending angle

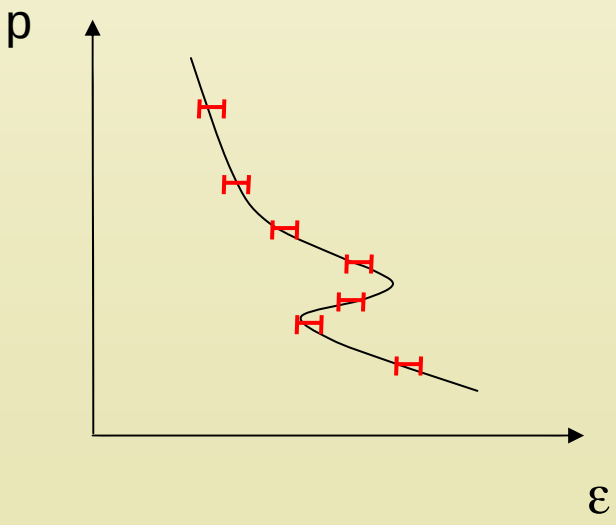
Sliding spectrum

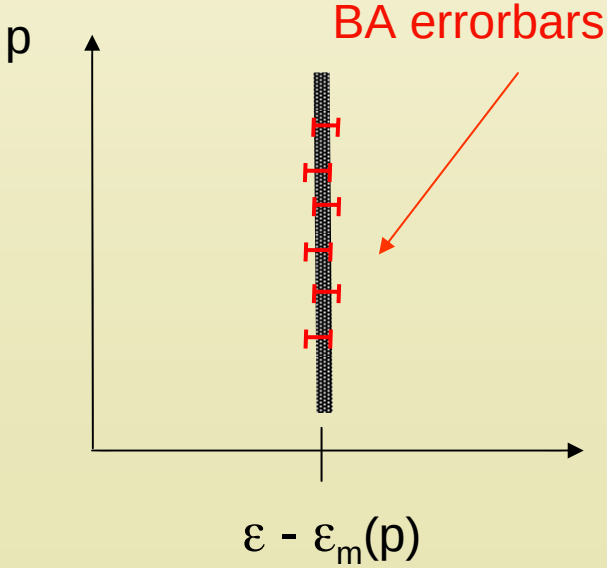






BA errorbars

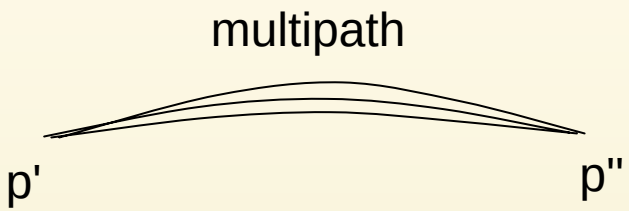


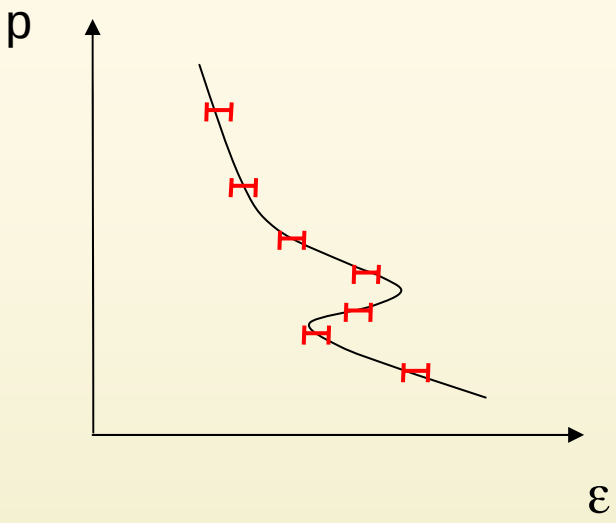


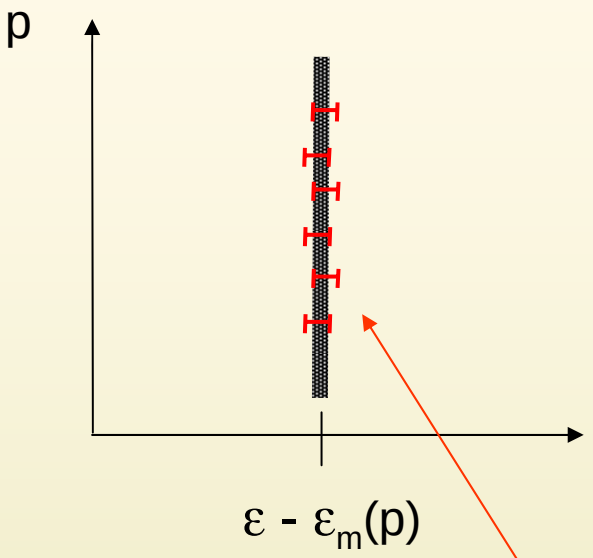
Horizontal Gradients

CT Bending angle

Sliding spectrum

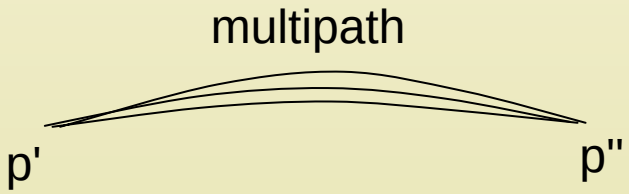


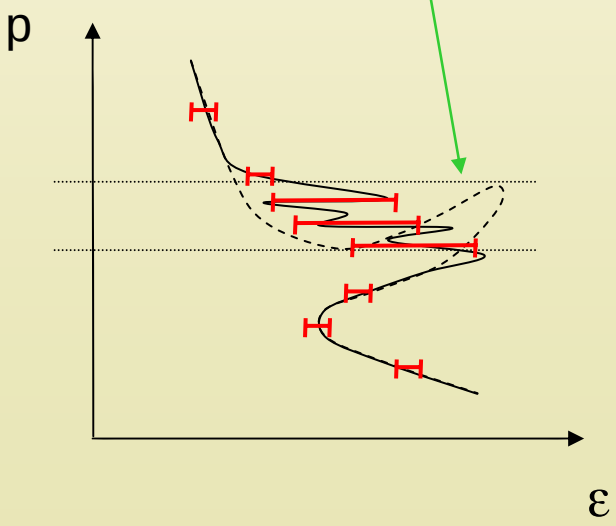


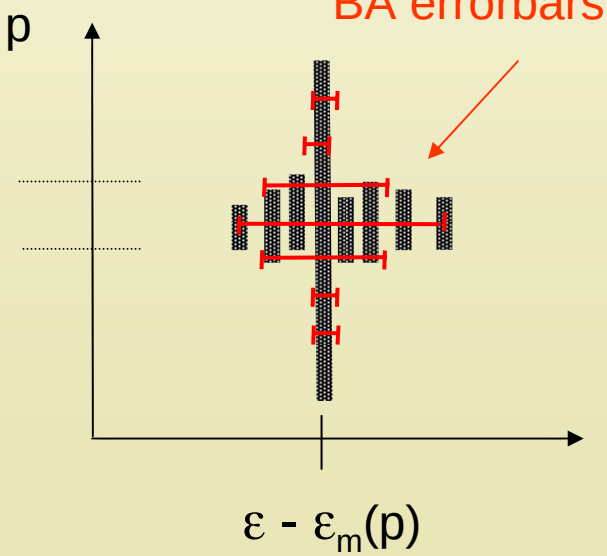


ε(p) non-unique!

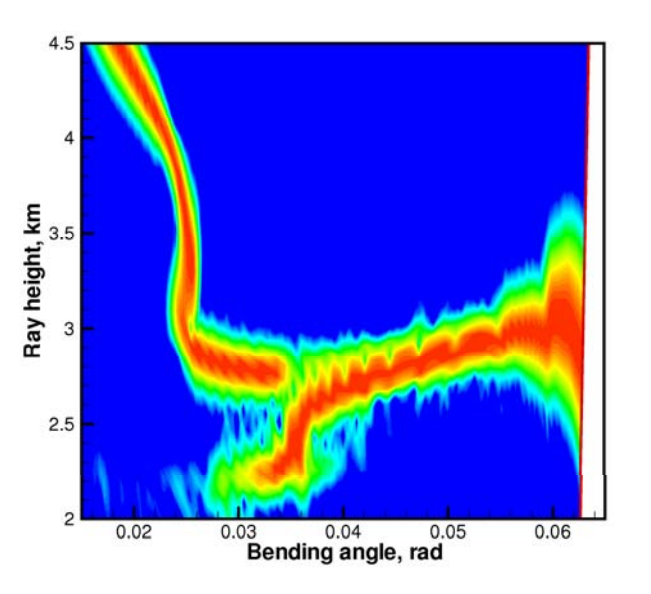
BA errorbars

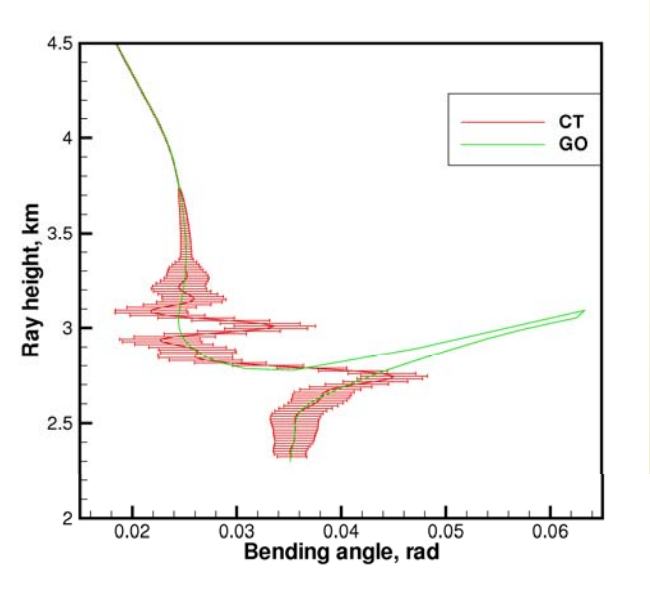


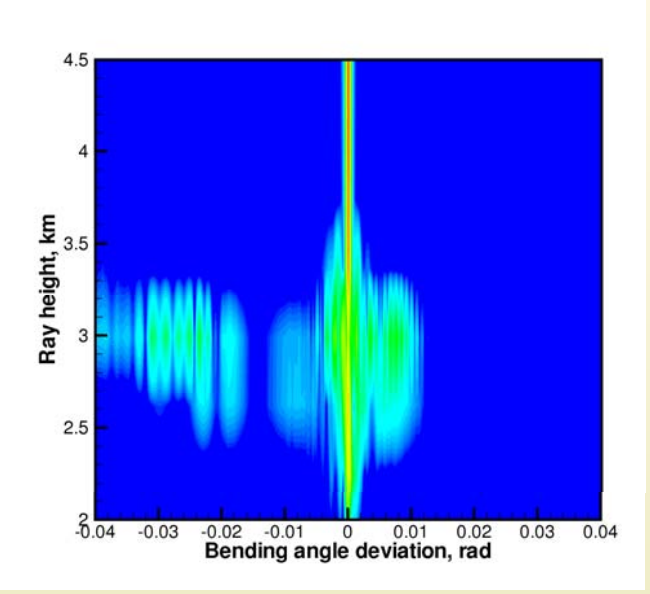




Example: BA

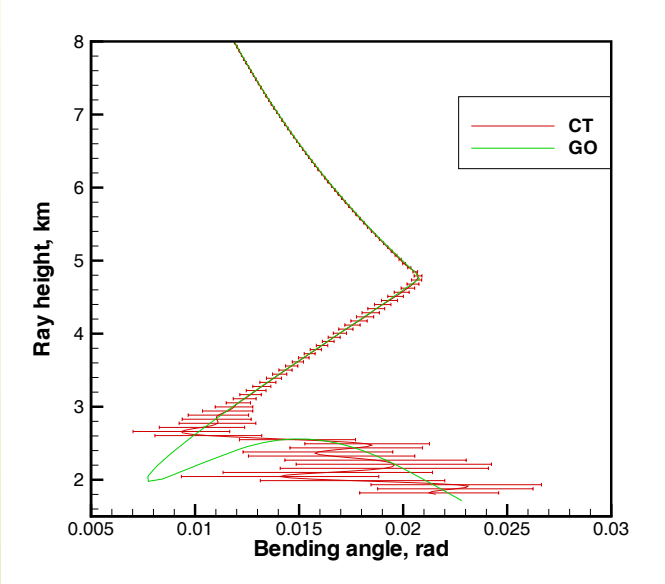


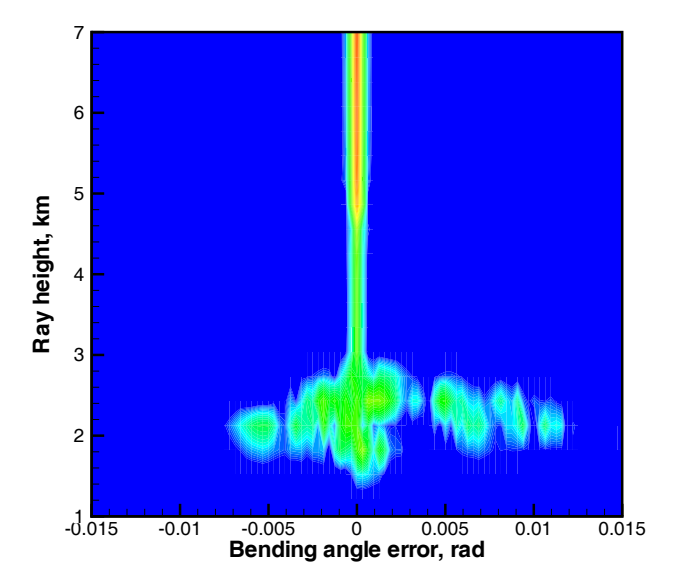




Simulations based on fixed ECMWF field: 5 Feb 1997, UTC 00:00

Example: Sokolovskiy front





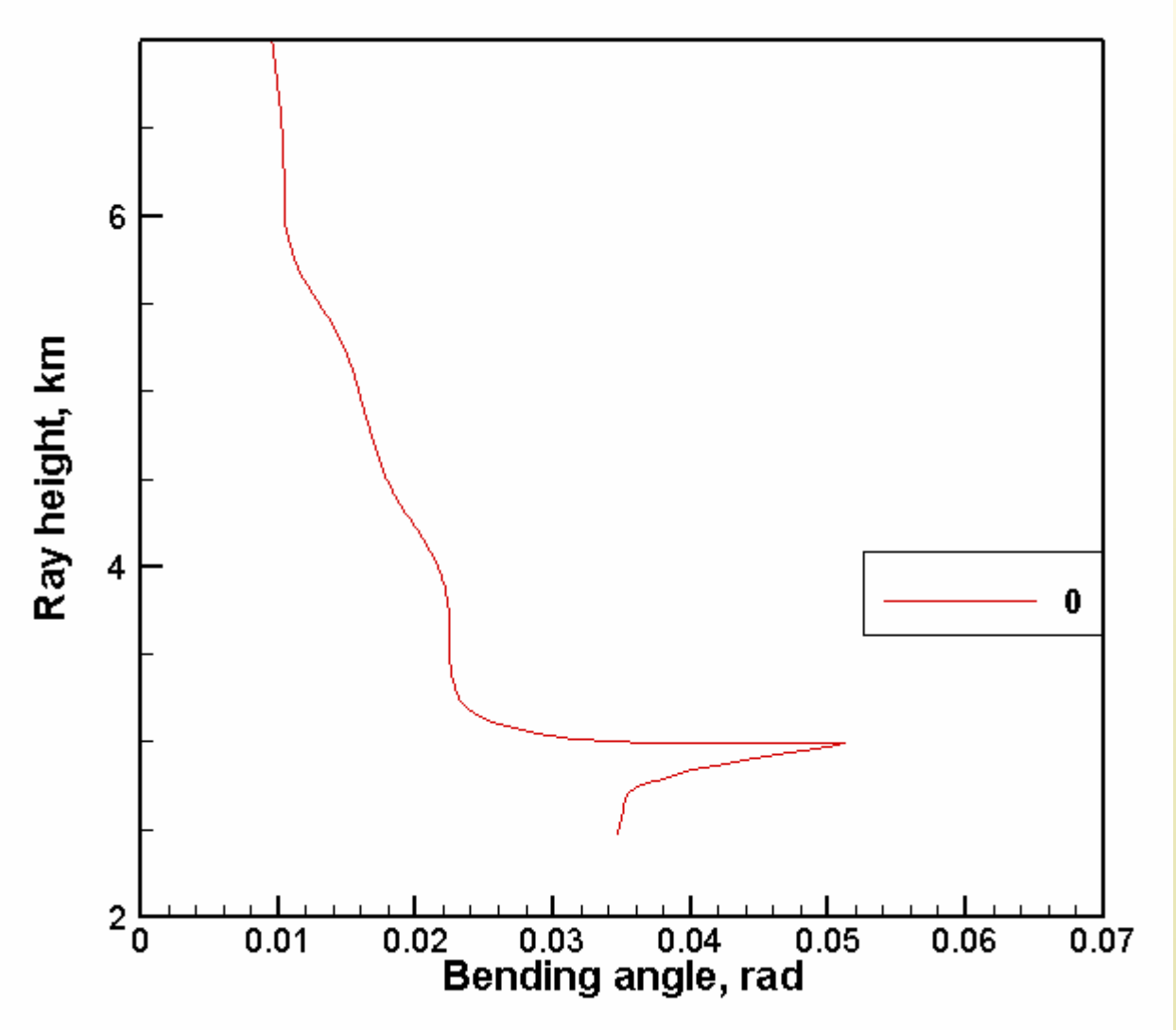
Sokolovskiy front: MWR 133, 2200 (2005):

$N(z,\theta) = N_0 \exp(-z/H) [1+\mu f(z/\varepsilon - r_e\theta/d)]$, $f(\xi) = \sin(\pi\xi/2)$ for $-1<\xi<+1$

N_0=340, H=7.5 km, μ=0.15, ε=0.025, d=15.0 km, $z=r-r_e$

Sequence of BA profiles through fixed ECMWF field

Occultation point is fixed whereas the GPS-LEO system is “rotated” in steps (total of 360 degrees) around it



Retrieved BA profiles with CT errorbars

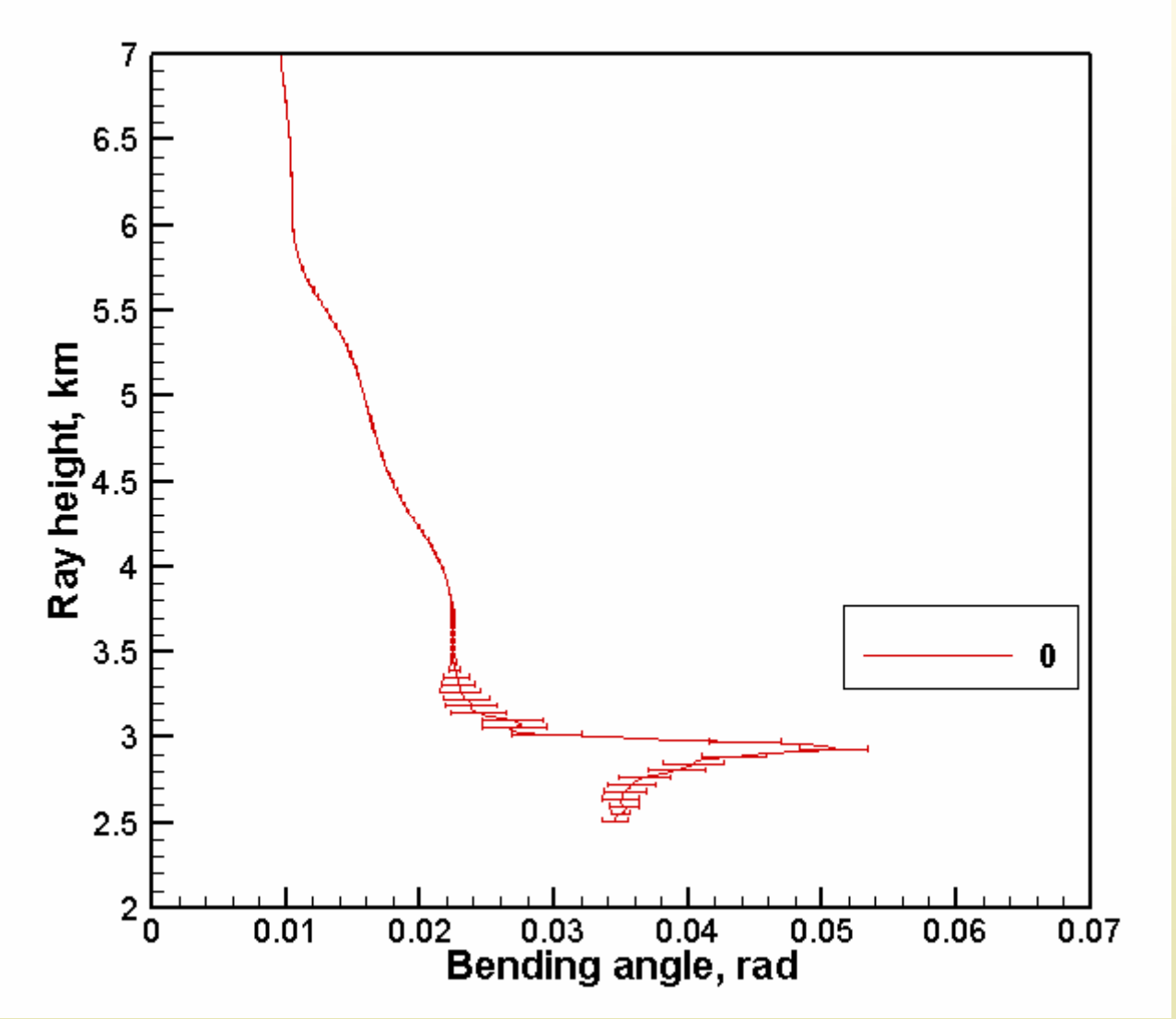
Occultation point is fixed whereas the GPS-LEO system is “rotated” in steps (total of 360 degrees) around it

Exact ε(p) behavior:

0 – 90°: unique

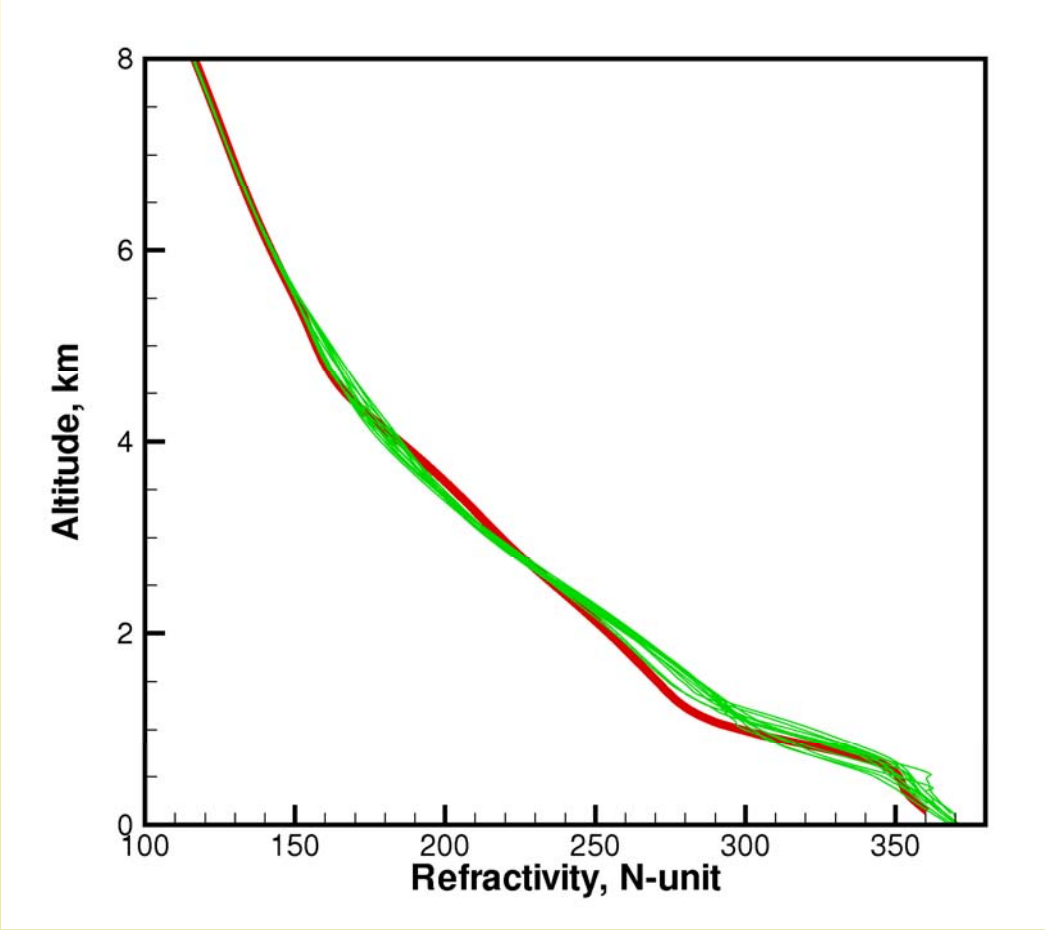
120° – 180°: non-unique

210° – 330°: unique



Retrieved refractivities

Retrieved refractivity profiles (green lines)
ECMWF vertical refractivity (red line)



Error:

$\delta\varepsilon \sim 0.005 - 0.01 \Rightarrow$

$\delta N/N \sim 1/3 \times \delta\varepsilon/\varepsilon \sim 1/3 \times 10\text{-}15\% \sim 5\%$

$\Rightarrow \delta N \approx 200\text{-}300 \times 5\% \approx 10\text{-}15$ N-units

Conclusions

- Inversion of radio occultation data
- Radio holographic BA errors (from CT spectrum)
- Unfolding of multipath:
    - spherical symmetry: CT algorithm
    - horizontal gradients: maps to larger BA errors
- Examples:
    - BA errors about 0.005 – 0.01 rad
    - N errors about 10 – 15 N-units