Filtering and Data Cutoff in FSI Retrievals

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Outline

- RO basics
- FSI-type retrievals
- Spherical asymmetry, deep occultations, and data cut-off
- Data pre-filtering
- Upper level filtering
- Conclusions

RO bending angle retrievals

RO is based on doppler measurements:

$$\omega(t) = n_L\,\mathbf{k}_L \cdot \mathbf{v}_L - n_G\,\mathbf{k}_G \cdot \mathbf{v}_G$$

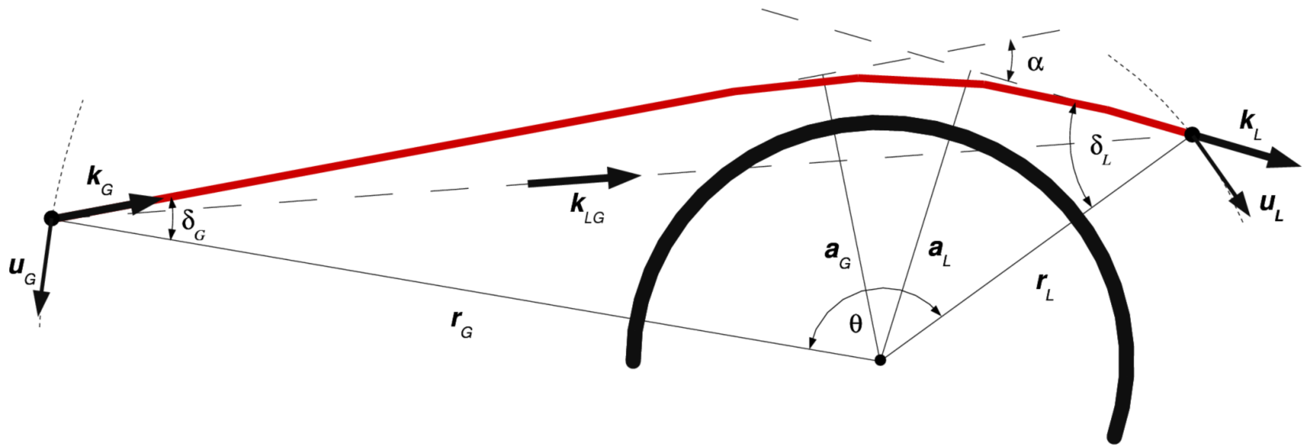
$$\omega(t) = k\,a\,\dot{\Theta} + k\frac{\dot{r}_L}{r_L}\sqrt{r_L^2 - a^2} + k\frac{\dot{r}_G}{r_G}\sqrt{r_G^2 - a^2}$$

$$\alpha = \Theta + \delta_G + \delta_L - \pi$$

(total doppler, Jensen et al.; can be integrated to total phase as well)

Based on definition of optical path length for individual rays by forming the time derivative

Fermat‘s principle: Spherical symmetric refractive index means impact parameter is constant along the ray („Bouger‘s law“)



Instantaneous frequency (aka GO retrieval)

Signal with a single frequency f_i : $$Z(f) = A\,\delta(f - f_i)$$

Inverse Fourier transform: $$z(t) = Ae^{j2\pi f_i t}$$

with phase $$\phi(t) = \arg z = 2\pi f_i t + \arg A$$

suggesting that $$f_i = \frac{1}{2\pi}\phi'(t)$$

is an meaningful estimate for the „instantaneous frequency" of the signal. Can be generalised to time varying phase and amplitude.

We call this the „Geometrical Optics" retrieval.

Group dealy (aka FSI retrieval)

Signal as puls at time τ_d:

$$z(t) = a\,\delta(t - \tau_d)$$

Fourier transform:

$$Z(f) = a\,e^{-j2\pi f \tau_d}$$

with phase

$$\Theta(f) = \arg Z(f) = -2\pi f \tau_d + \arg a$$

suggesting that

$$\tau_d = -\frac{1}{2\pi}\Theta'(f)$$

is an meaningful estimate for the „group delay“ or „arrival time“ of the pulse / signal.

Can be generalised to time varying phase and amplitude.

We call this the „Full Spectrum Inversion“ retrieval.

Multipath

Multi-component signal with multiple tones (e.g., due to „spatial" multipath):

$$Z(f) = \sum_k A_k \, \delta(f - f_{i_k})$$

Inv. Fourier transform:

$$\tilde{z}(t) = \sum_k A_k e^{j2\pi f_{i_k} t} = \tilde{A} e^{j2\pi \tilde{\phi}(t)}$$

- In order to obtain individual IFs, the full signal needs to split up into individual components.
- The derivative of the phase of the joint signal has no physical meaning; it just oscillates around.

- Similarly, the definition of group delay only makes physical sense if pulses with a given frequency only arrive at exactly one moment („temporal multipath")

So...

Are instantaneous frequency and group delay the same, provided there is no multipath of whatever kind?

- Yes! Can be proven applying the Method of Stationary Phase...

Why do we care about the FSI if it also has multipath issues as well?

- For circular orbits, monotonuous $\dot{\Theta}$ and spherical symmetry, doppler is just the impact parameter (multiplied with a constant and $\dot{\Theta}$); there is no temporal MP by construction:

$$\omega(t) = k\, a\, \dot{\Theta} + \cancel{k \frac{\dot{r}_L}{r_L} \sqrt{r_L^2 - a^2}} + \cancel{k \frac{\dot{r}_G}{r_G} \sqrt{r_G^2 - a^2}}$$

- In the FSI, realistic orbits are corrected by adding compensation terms to the phase measurements, and angle between satellites is used instead of time coordinate
- However, temporal multipath might be caused by spherical asymmetry.

(t, ω) ↔ (p, α) mapping

$$\omega(t) = k\,a\,\dot{\Theta} + k\frac{\dot{r}_L}{r_L}\sqrt{r_L^2 - a^2} + k\frac{\dot{r}_G}{r_G}\sqrt{r_G^2 - a^2}$$

$$\alpha = \Theta + \delta_G + \delta_L - \pi$$

Because

- orbits (positions and velocities) are determined by time,
- impact parameter is unique (spherical symmetry)

we have two equations with four unknowns, i.e. a mapping (or coordinate transform)

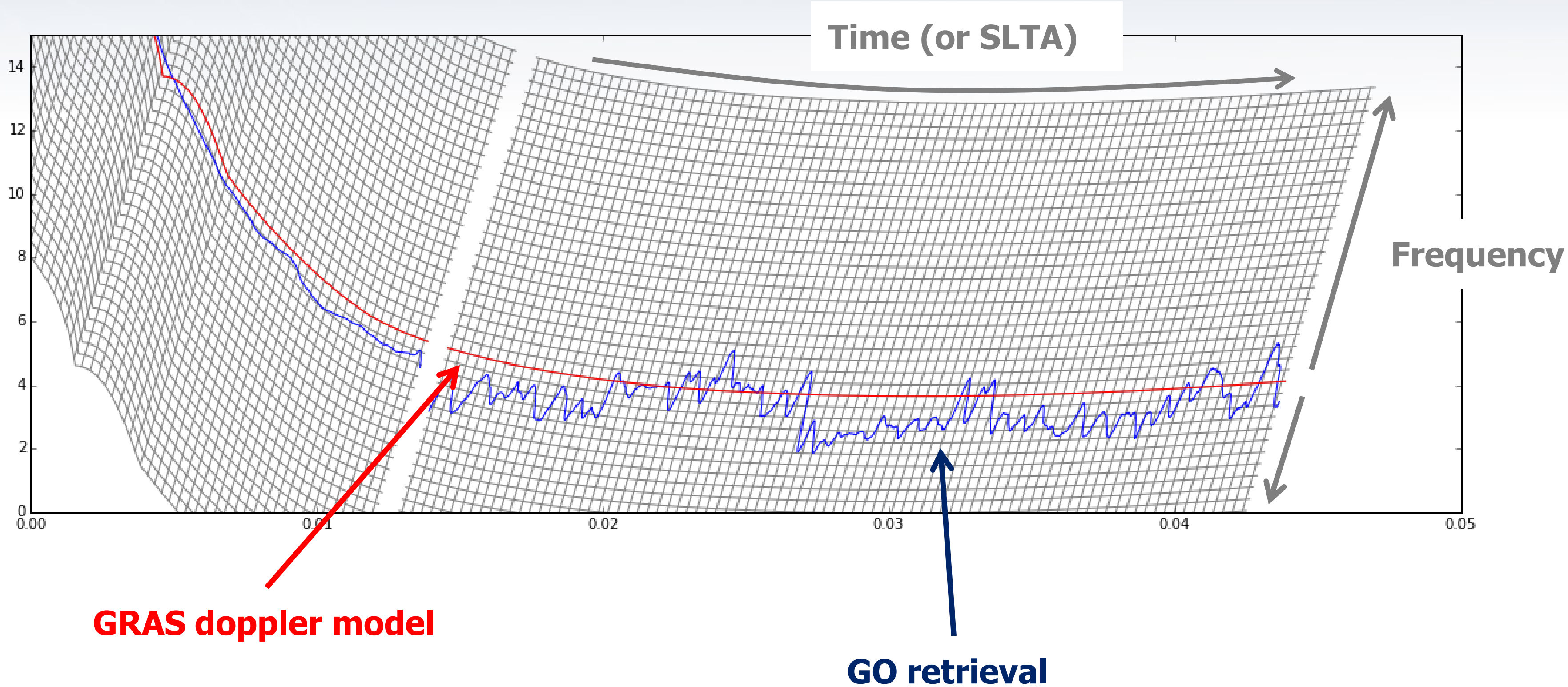
(t, ω) ↔ (p, α) and even (t, ϕ) ↔ (p, α)

where phase ϕ is just the integral over all ω (for a mono-component signal).

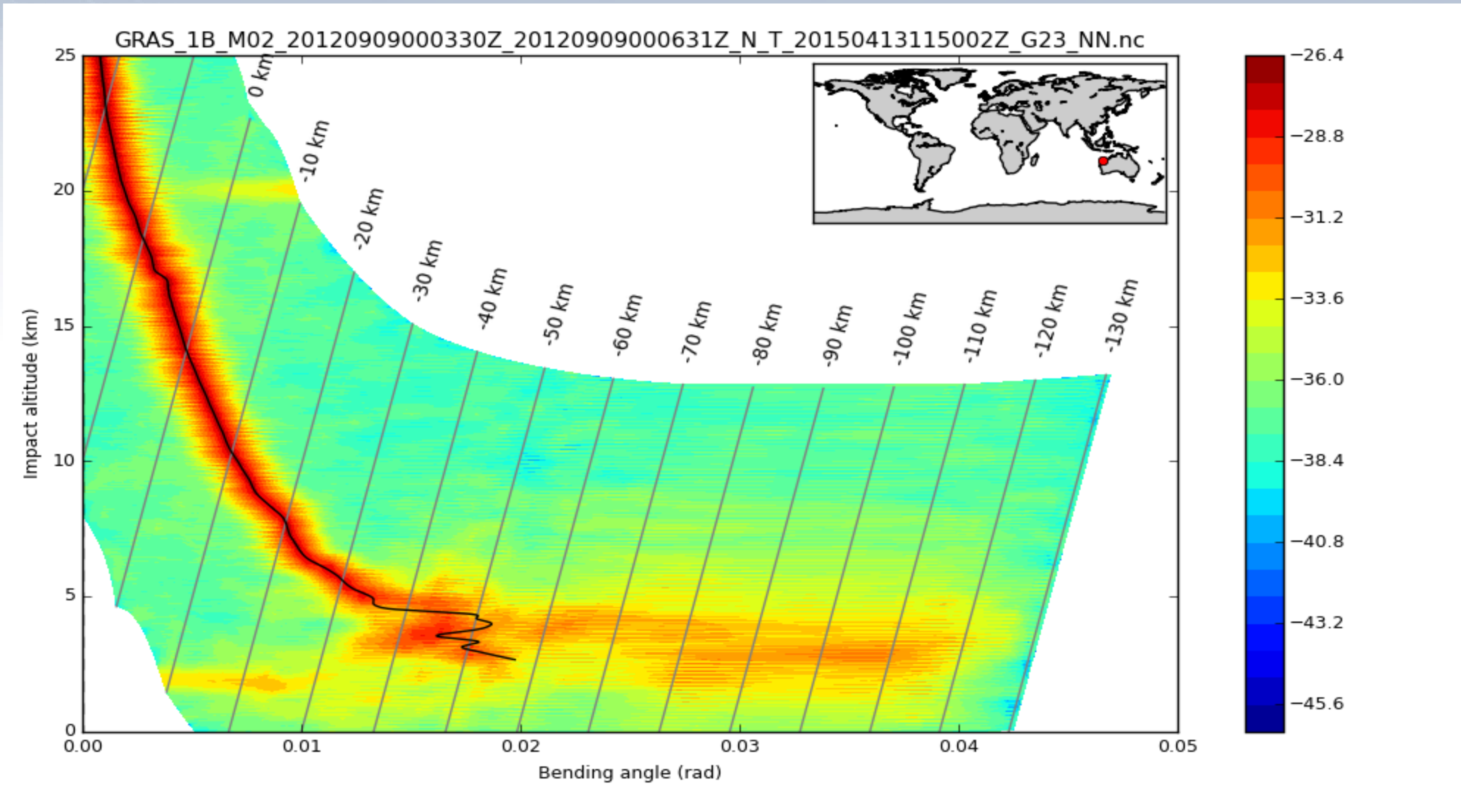
- Gorbunov et al. (2000's, several papers) made us aware that this mapping has certain elegant mathematical properties (it's a "canonical transform" as known from classical mechanics, geometrical optics, and quantum theory)

Spectral mapping (aka Radio Holography)

A simple application (apart from any RO retrieval) is to map time-frequency distributions (TFDs – like spectrograms) into impact parameter / bending angle space:



Spectral Mapping (cont'd – 2012/09/09 00:03:30)

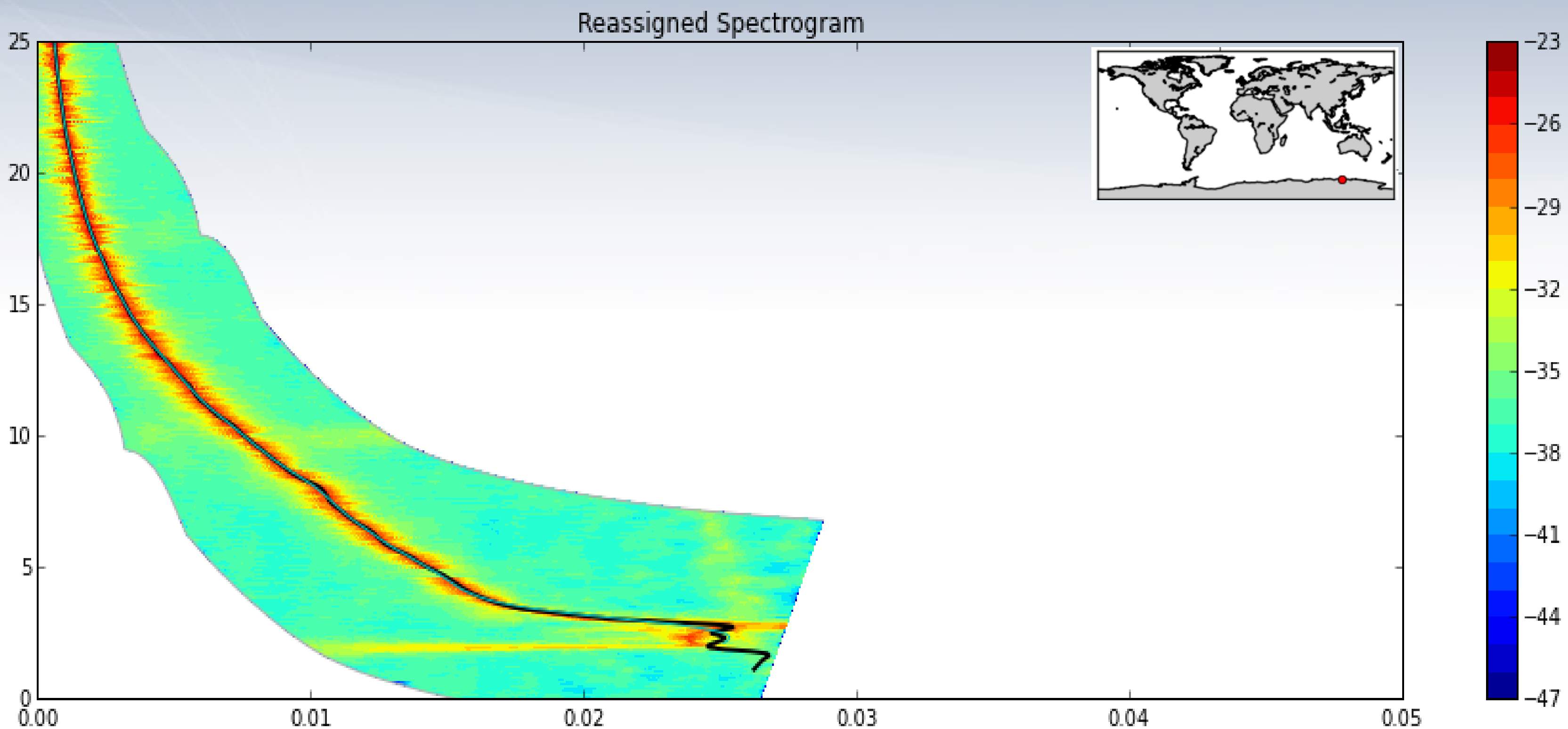


- A meaningful retrieval should closely follow the ridges in the spectrum denoting the "beam" of the occultation

Other types of retrievals

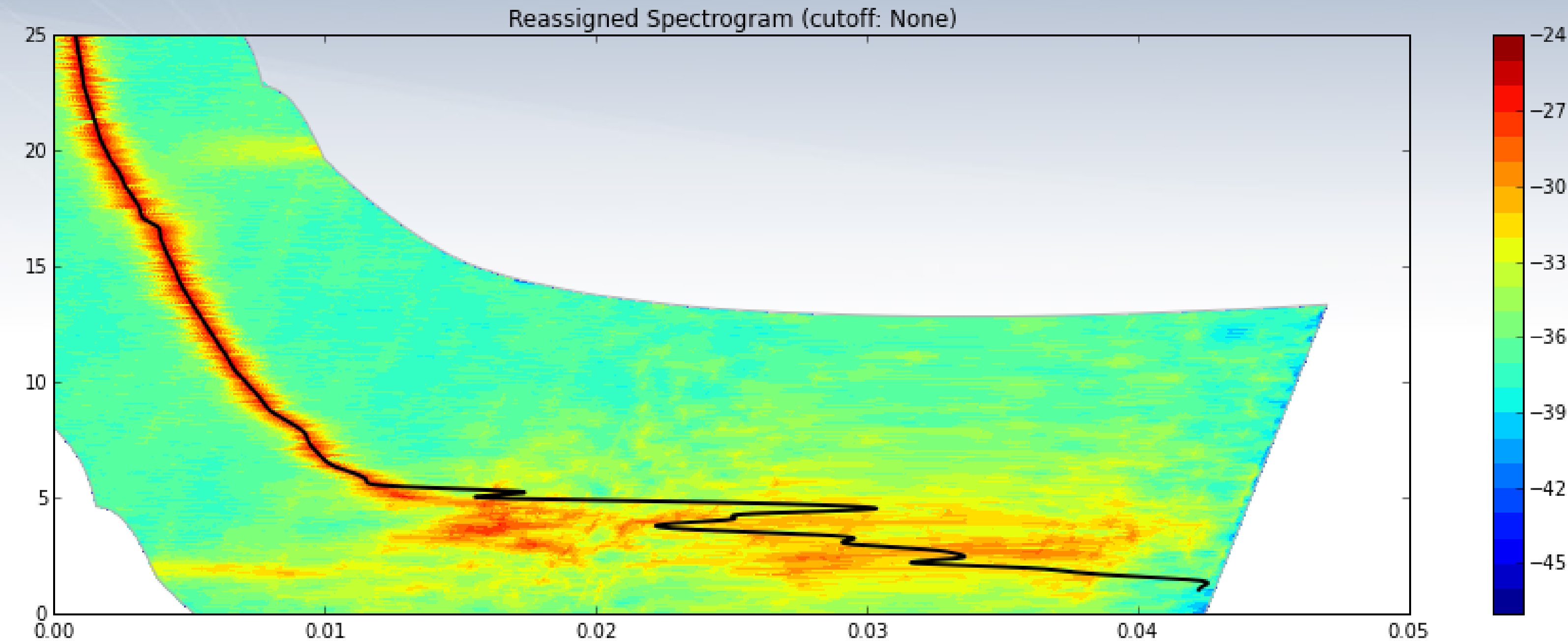
- Canonical Transform (Gorbunov): Explicitly transforms signal to (p, α) space (via an FIO) and calculates bending angle as derivative of transformed phase
- Phase matching (Jensen): Explicitly uses stationary phase method to numerically calculate transformed signal ("phase transform") and get bending angle as derivative of it's phase
  - These are "FSI-like" methods.
- Radio-holography: extract (p, α) from some kind of TFD
  - Out of fashion for actual retrievals (spectra are considered to be too broad), but very nice for understanding signal characteristics and doing diagnostics

Another one – 2012/09/09 00:02:25



- “Reassigned” time-frequency distribution provide better resolution compared to ordinary spectrograms (another topic)

But there was quality control / filtering / cutting off...



- Big spikes when using the entire measurement, unrelated to TFD ridges
- Looking at the spectra (especially the reassigned one), there are more than one tone at many impact parameters – so FSI-type methods won't work...
- Horizontal gradients?

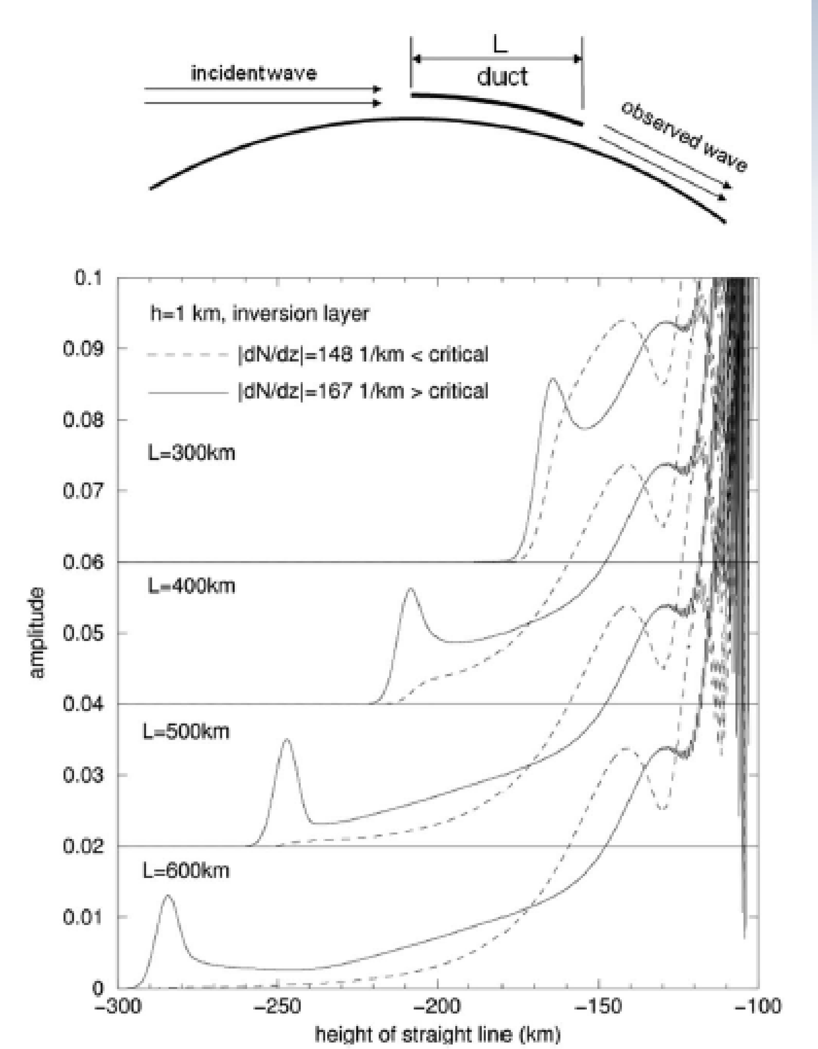
Deep Occultations

- Sokolovskiy et al. (2015): deep occultation signal come from regionally limited ducting layers – the "depth" of an occultation is linked to the horizontal extension of the ducting layer
- But that's not spherical symmetric... and will trigger temporal multipath behaviour of FSI-type methods...

- So let's cut them off...

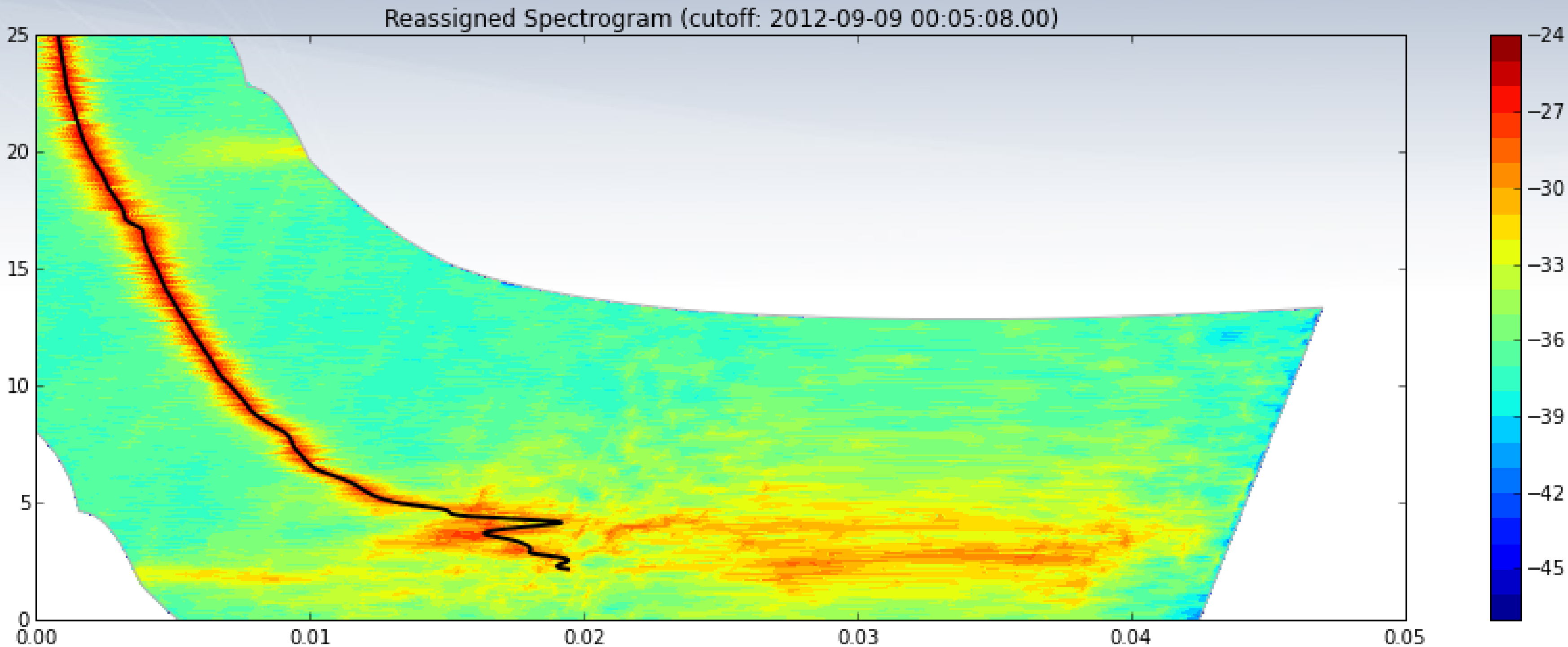
Notes:

- Sokolovskiy et al. (2010) also suggest to cut off data from deep occultations as "noise" contributes to biases in his retrieval system (and discuss the tradeoff between noise impacts and missing rays at alow SLTAs)
- In case of GRAS, such cases are well above the instrument noise (see one of the following slides)



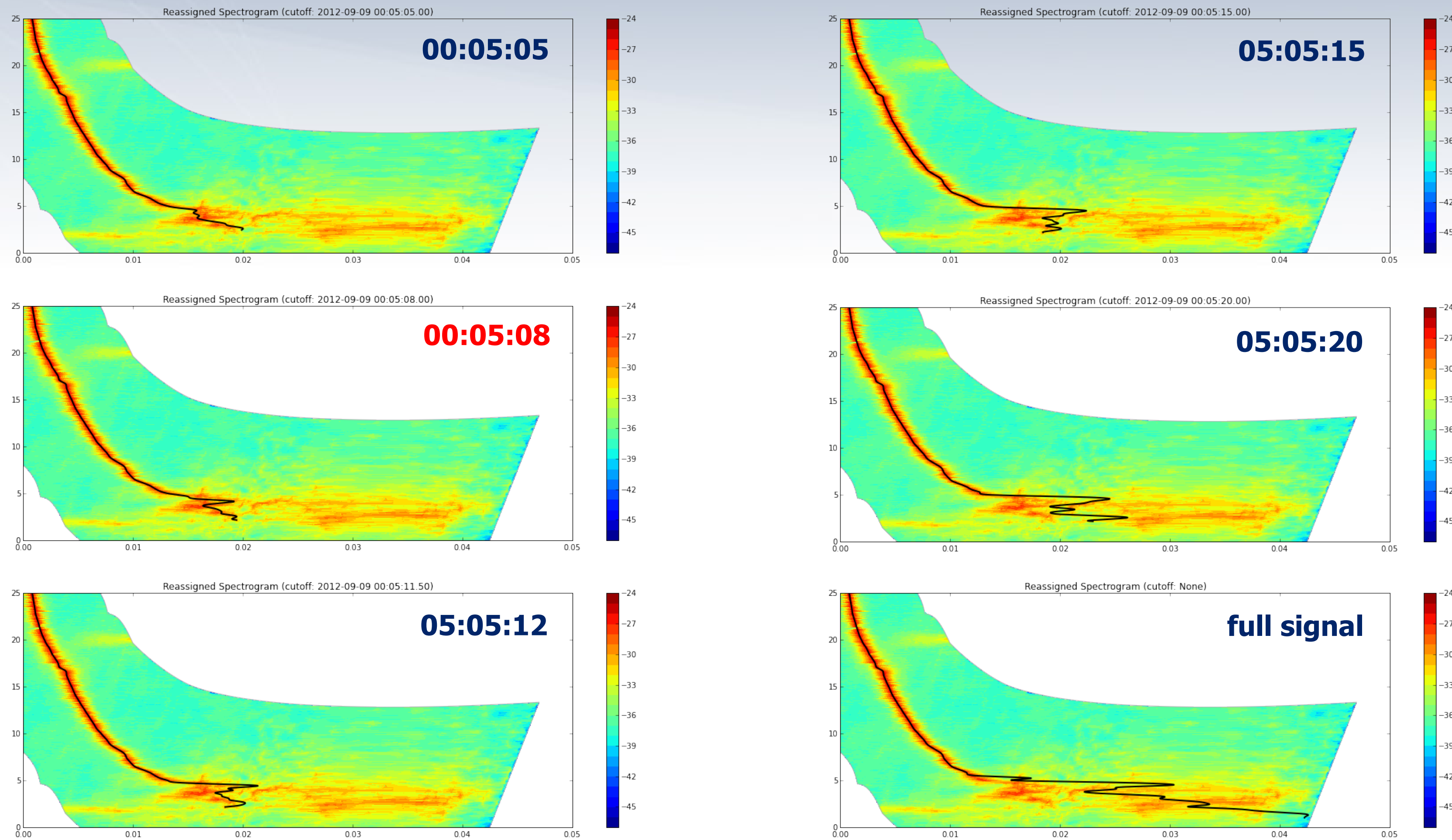
Sokolovskiy et al. (2015), Radio Science

...and that works...

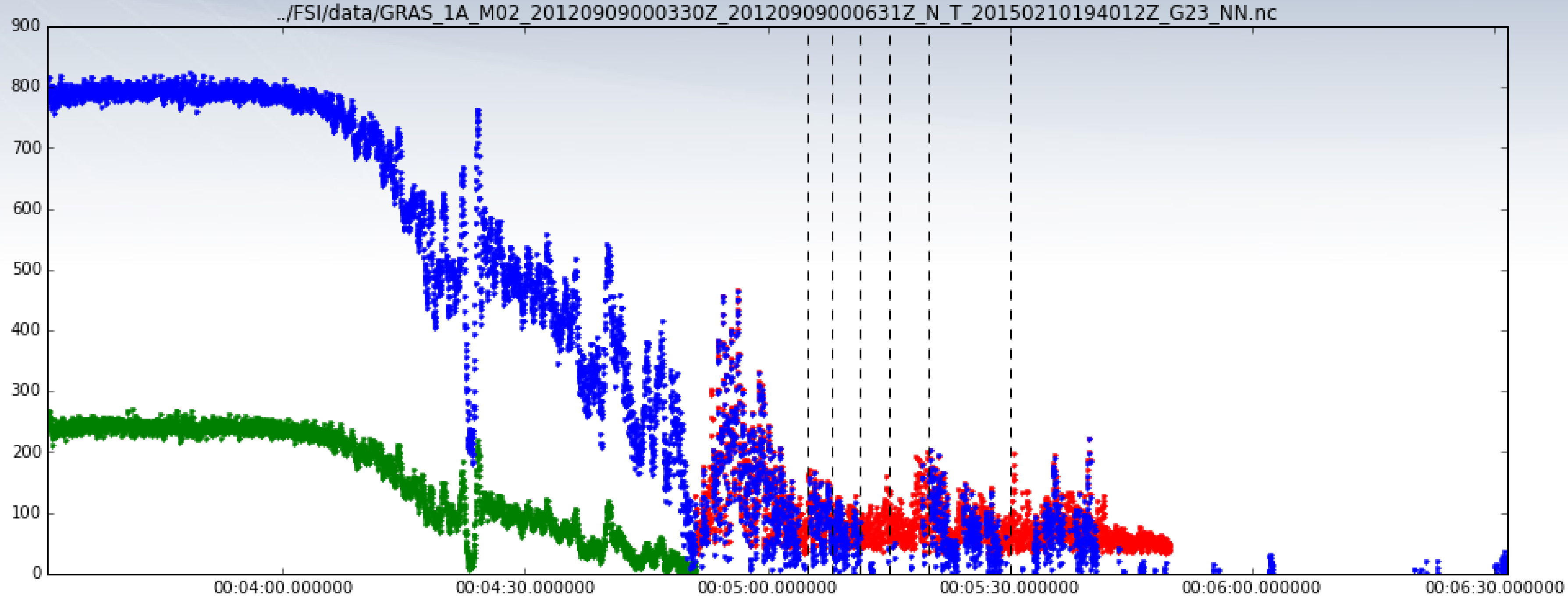


- ...but are results sensitive to the cut-off location / time?

…but is very sensitive to the cut-off point



SNRs

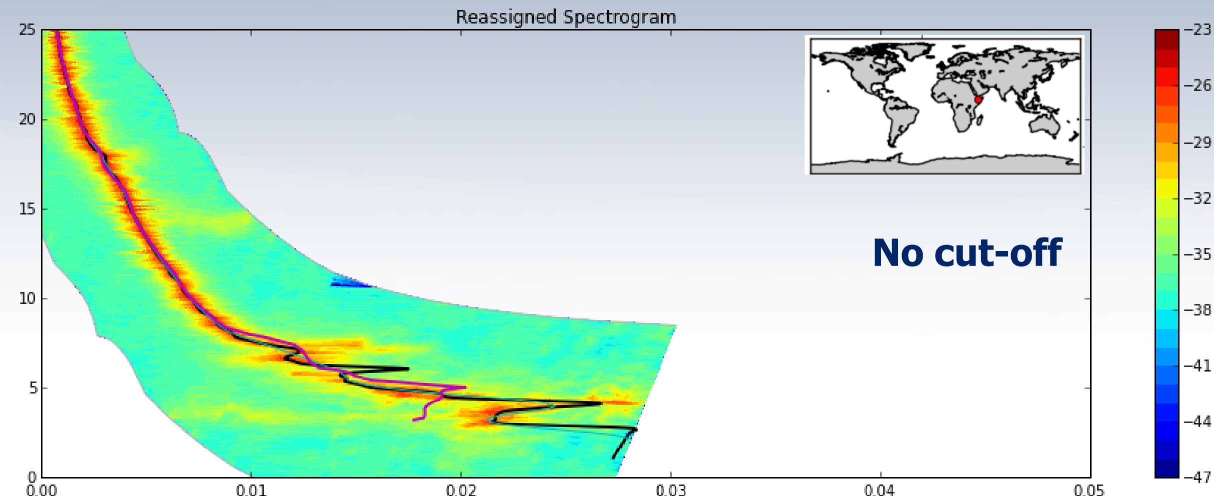


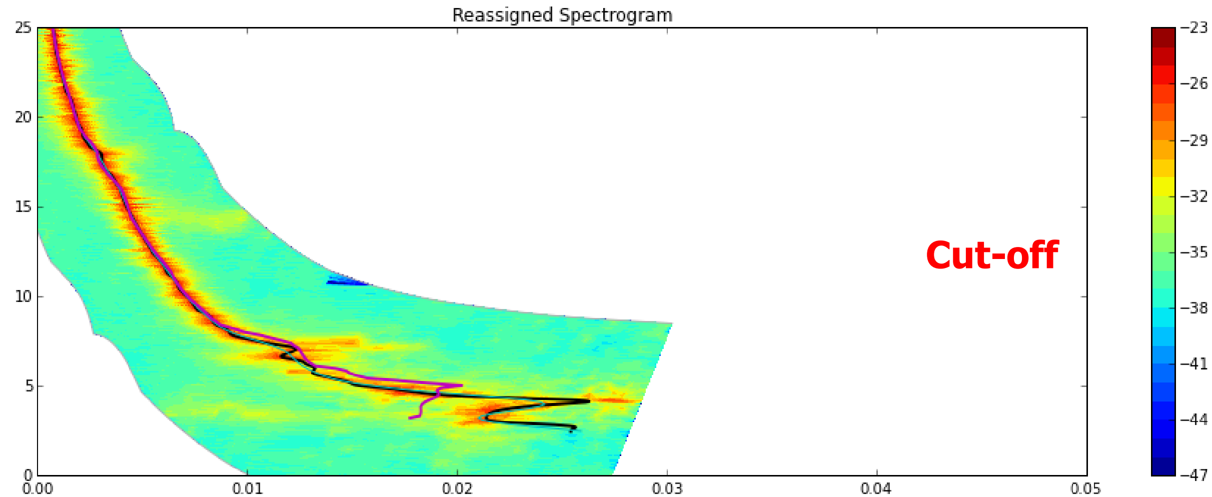
- Note: SNR of features contributing to the multipath are well above GRAS noise level
- And my apologies – Open Loop SNRs plotted with a vertical offset... :-((

Another example: 2008/07/01 17:09:09

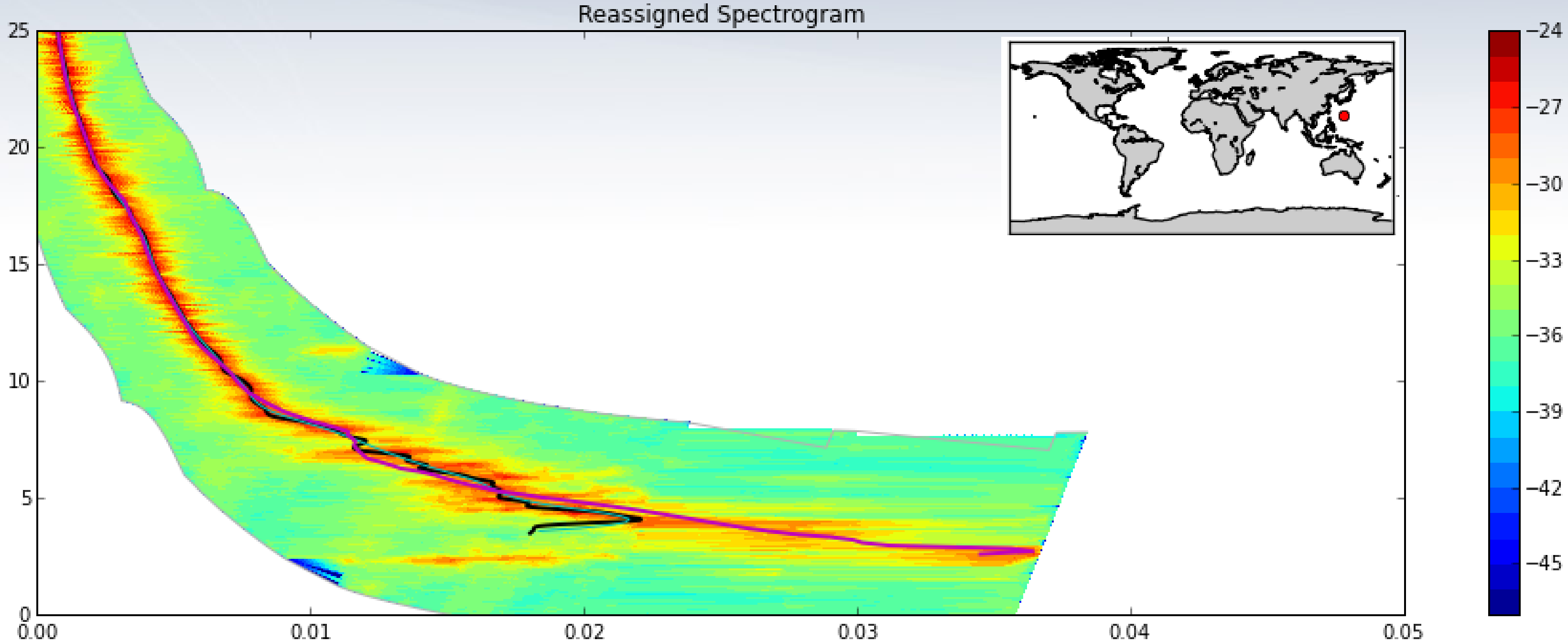
Implementation:

- Threshold-based cut-off for identifiable peaks after a fading period
- Threshold value SNR dependent, but limited
- Only below certain SLTAs
- ....



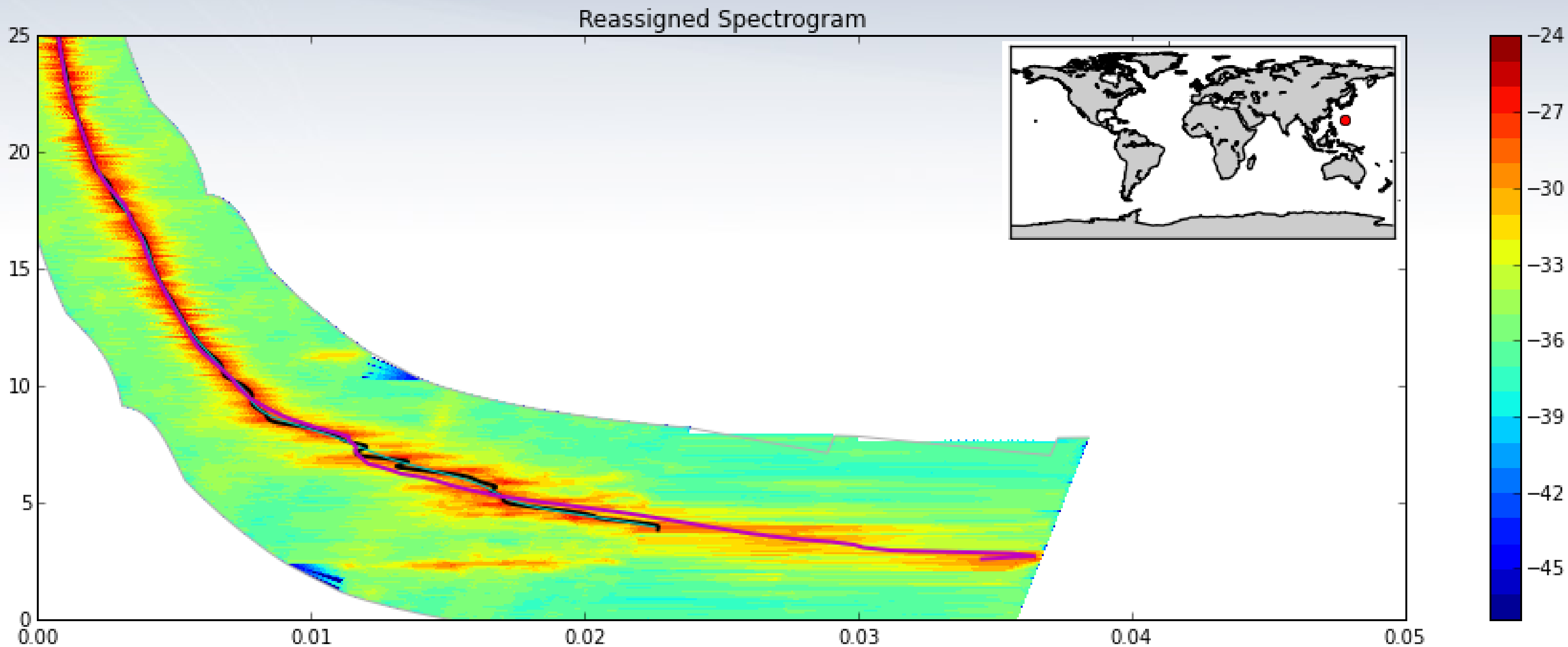


Pre-filtering (aka Radio-Holographic Filtering)



- Extract 1st moments from TFR (STFT or rSTFT) in time, map signal
- Apply bandpass filter (15 – 20 Hz), map back

Pre-filtering (aka Radio-Holographic Filtering, cont'd)



- Extract 1st moments from TFR (STFT or rSTFT) in time, map signal
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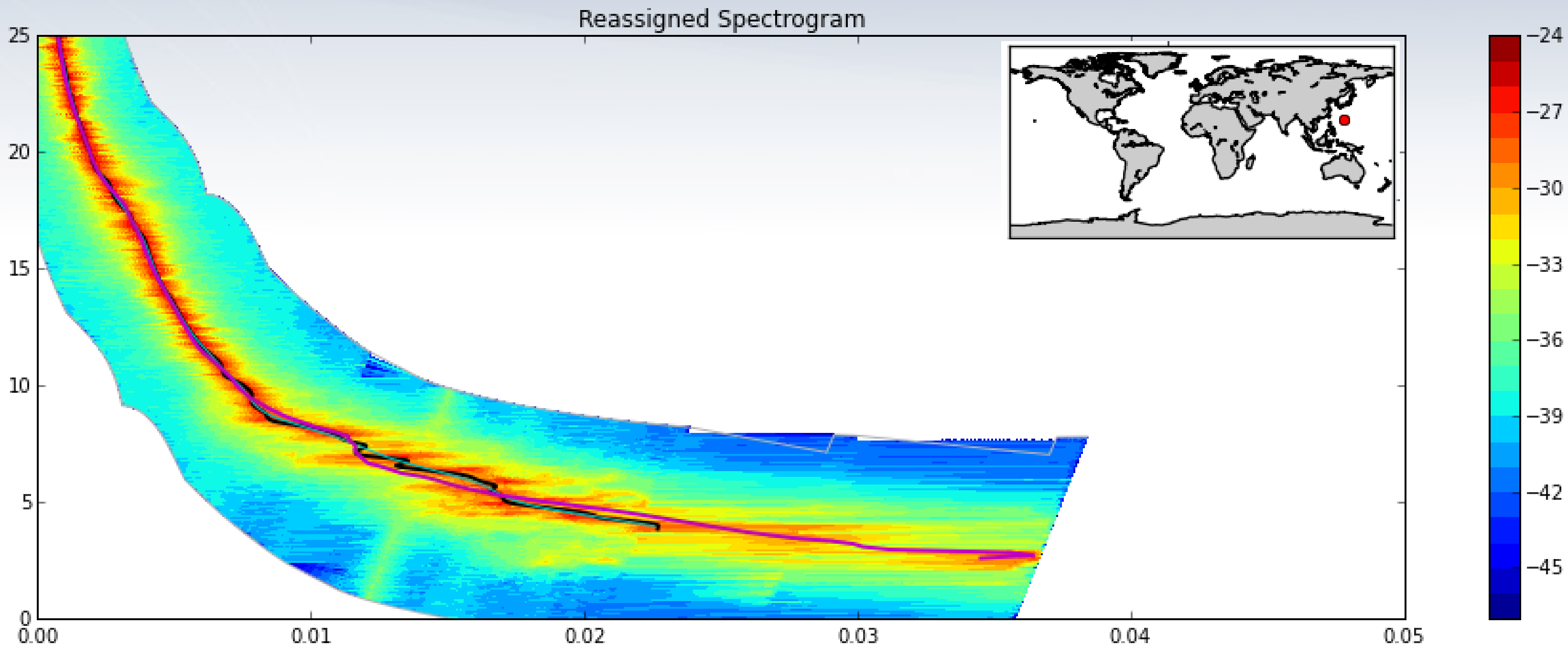
Pre-filtering (aka Radio-Holographic Filtering, cont'd)



- Extract 1st moments from TFR (STFT or rSTFT) in time, map signal
- Apply bandpass filter (15 – 20 Hz), map back

Higher up, we use an FSI as well...

Upper Level Smoothing in FSI-type Retrievals

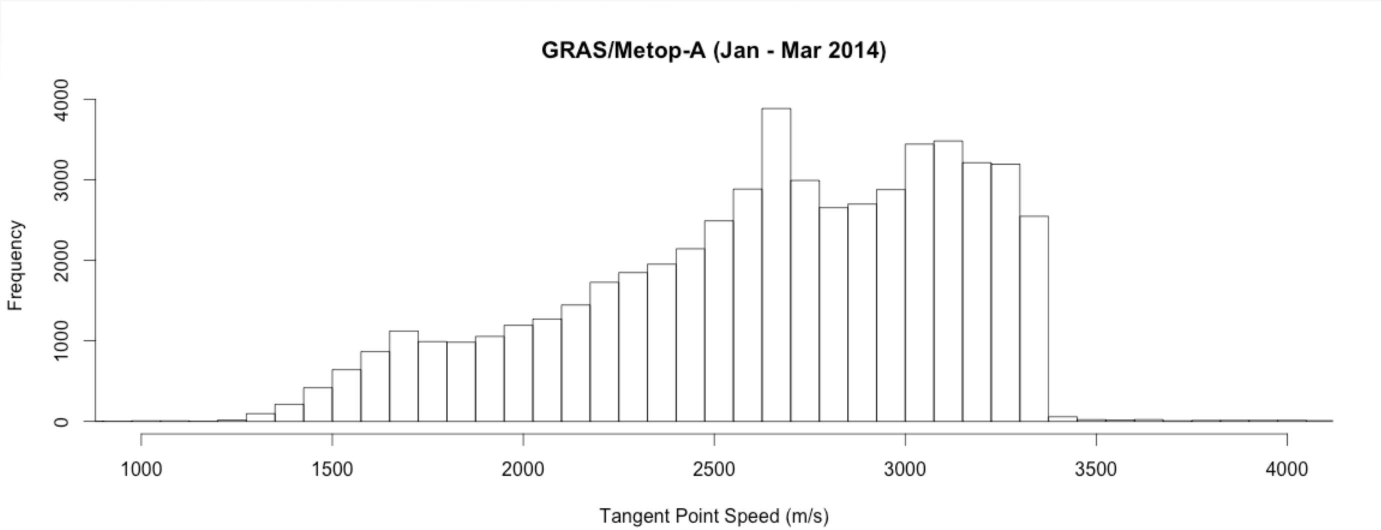
- In theory, GO and FSI-type retrievals should be equivalent as long as no multipath occurs... and equivalent filtering is applied.
- So why are people doing wave optics retrievals below, say, 20km, and geometrical optics above?

- And actually, while it's straightforward to manually adjust the smoothing for individual profiles (of excess phase in time for GO, and bending angle in impact space for FSI)...
- ...I never managed to show statistically that this can be done in practice.

- Well - not with the same filter width (in impact parameter space) for all profiles...

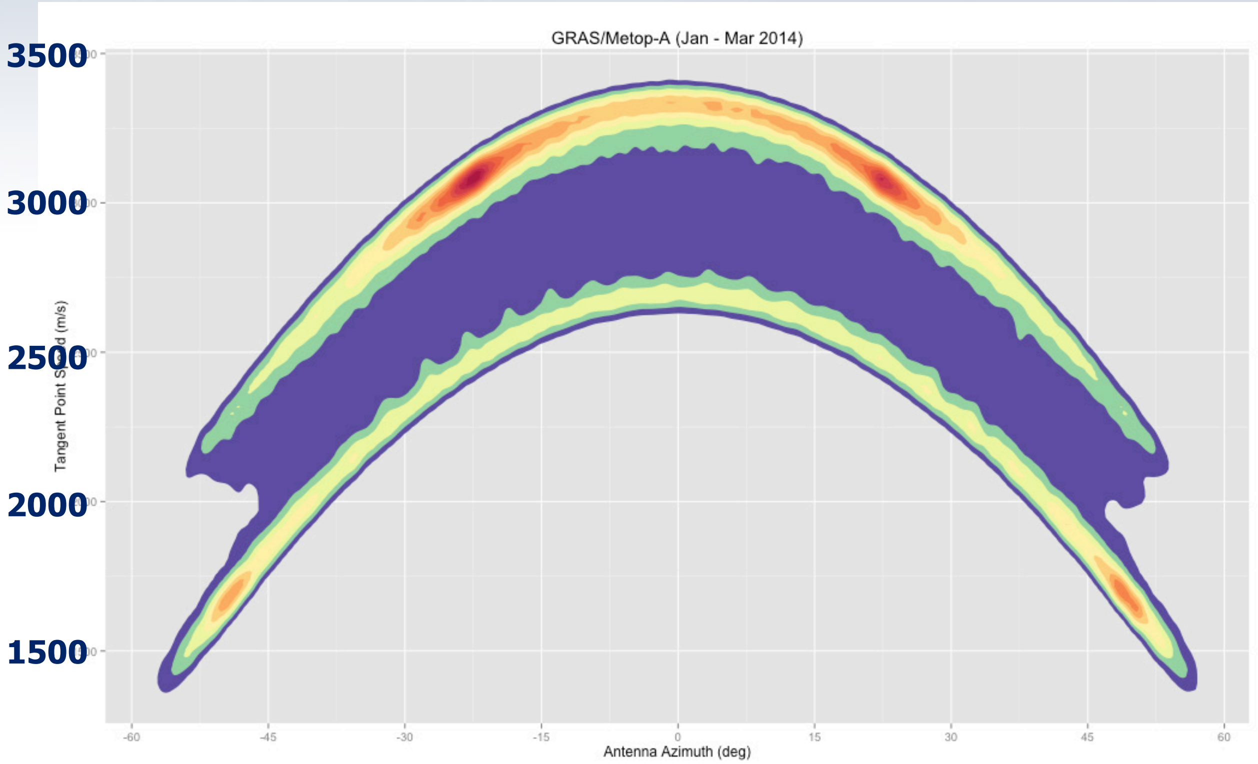
GO Smoothing

- 1.5 sec Savitzky-Golay (local polynomial regression) filter of excess phases



Mean (50 – 80km) vertical tangent point speed

Dependence on Antenna Azimuth

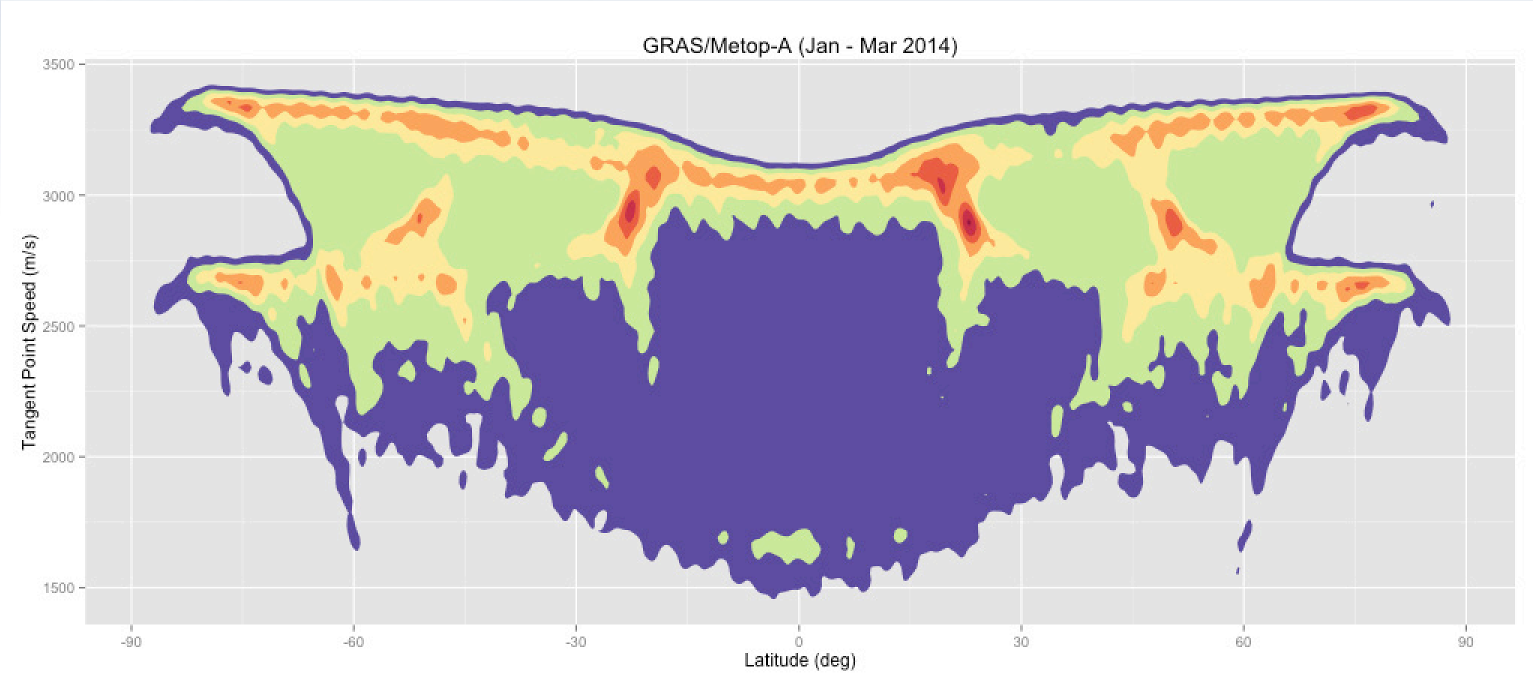


Depends on antenna azimuth:

- On the side of the antenna view, occultations take longer than for occultations occurring in the bore hole direction
- Bimodal distribution caused by counter vs. co-rotating GNSS satellites.

Latitudinal Distribution

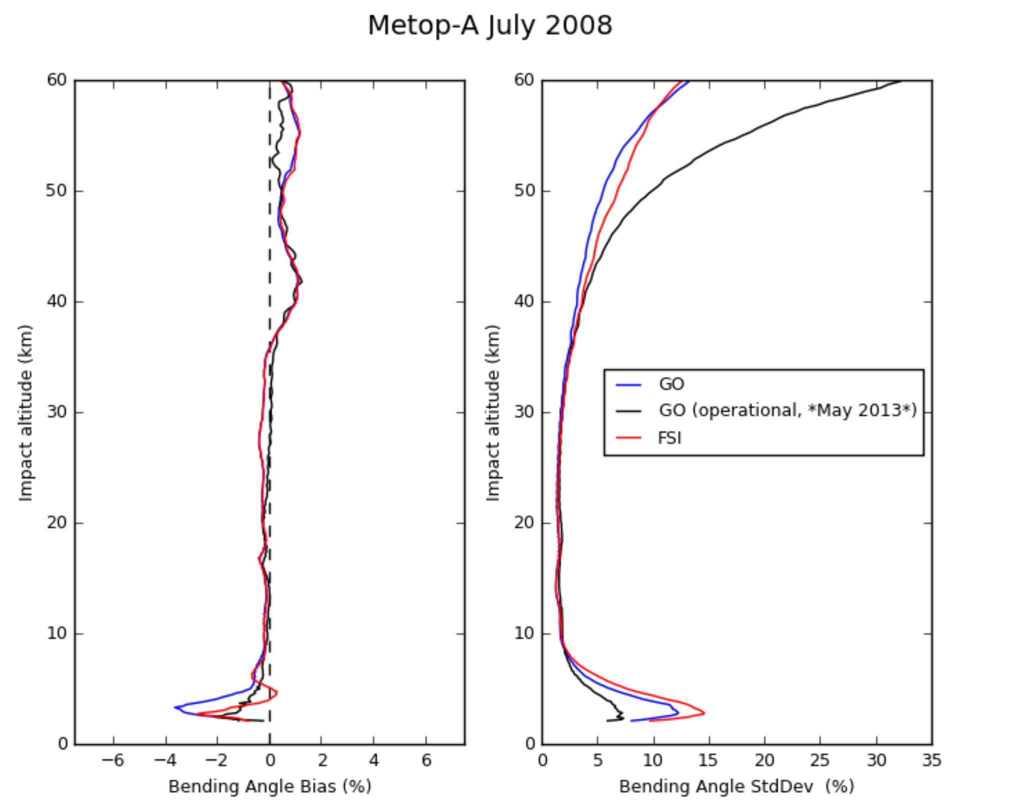
3500
3000
2500
2000
1500



Statistics against ECMWF

Implementation:

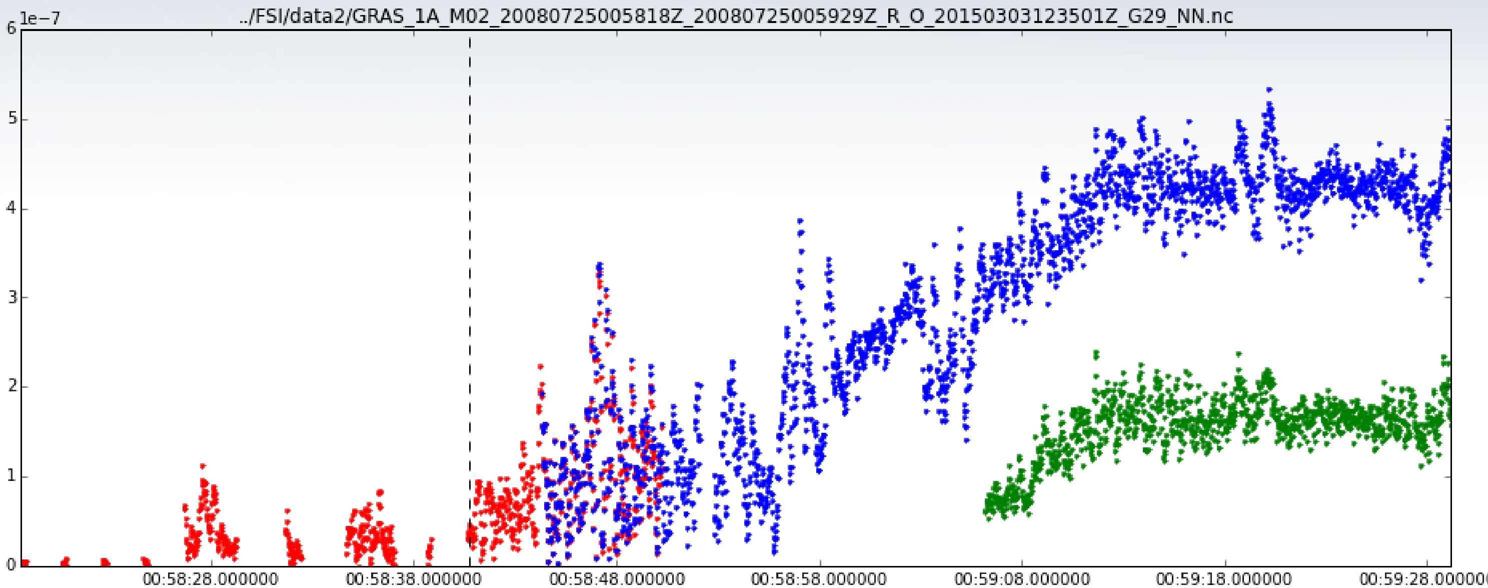
- local polynomial regression filtering of bending angles w/ variable bandwidth
- mesospheric bandwidth adjusted by vertical SLTA speed
- fixed tropospheric bandwidth
- shape of transition might benefit from improvement
- Note: When thinning, we do an additional step of bending angle smoothing
- vertical error correlations still requires some analysis



Conclusions

- For GRAS, FSI-type retrievals in the lower troposphere are complicated by frequent temporal multipath (same frequency / impact parameter occuring for multiple times)
    - Usually, such structures are attributed to strong horizontal gradients, which invalidate the assumptions inherent to FSI-type (and in fact, all current) RO retrievals.
    - If Sokolovskiy et al.'s (2015) interpretation of measurements at very low SLTAs is true, deep occultation data thus might only be of limited use for present RO data processing schemes.
    - To a degree, threshold-based cut off methods and radio-holographic filtering options can successfully reduce the impact of spherical asymmetry by removing parts of the signal spectrum caused by horizontal gradients. Th required tuning, however, raises ample opportunities for structural uncertainty.
    - For GRAS, the offending parts of the measurements are not pure noise.
- Filtering mesospheric FSI-type retrievals with dynamic bandwidths allows for upper altitude bending angle performance similar to the GO/IF retrievals (and vertical filter length in mesospheric and stratospheric RO retrievals are vriable with an orbit geometry dependent complicated structure)

Why does it end so early anyway?



IF (cont'd)

Signal with time varying phase and amplitude:

$$z(t) = A(t)e^{j\phi(t)}$$

Evaluate at times t_1, t_2; mean value theorem of elemental calculus:

$$\phi(t_2) - \phi(t_1) = (t_2 - t_1)\,\phi'(t)$$

Choose T as period of a single oscillation, $f_i = 1/T$, $t_2 = t_1 + T$, $\phi(t_2) = \phi(t_1) + 2\pi$

$$f_i = \frac{1}{2\pi}\phi'(t)$$

Here, t is an instant during a single cycle of oscillation with frequency f_i