LOfar COsmic-dawn Search (LOCOS)

Harish Vedantham [1]
Leon Koopmans [1]   Stefan Wijnholds [2]   Ger de Bruyn [2]
Benedetta Ciardi [3]

[1] Kapteyn Astronomical Institute, Univ of Groningen, Netherlands
[2] Netherlands Institute for Radio Astronomy (ASTRON), Netherlands
[3] Max Plank Institute for Astrophysics, Garching, Germany

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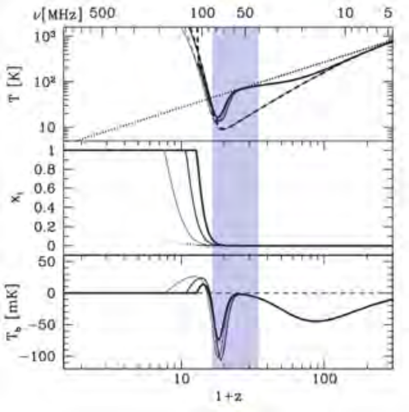
Motivation

LOCOS aims to measure the expected absorption feature from cosmic-dawn …



Pritchard & Loeb, PhRvD, 2008

… using the LOFAR Low Band Antennas (LBA).

http://blog.lofar-uk.org/

Initial Conditions: Hardware

- LBA operates from 10 MHz to 100 MHz ($140 > z > 13.2$).
  - Ionopsphere is a problem below ~ 40 MHz ($z \sim 35$).
  - FM bands are a problem above ~ 85 MHz ($z \sim 18$).
- No noise injection: separation of global signal and receiver noise is difficult.
- Current LBA dipoles are part of a station array (48 or 96 dipoles).
  - Additional constraints/priors from visibilities
  - High redundancy helps to diagnose/model systematics
- Dipole auto- cross-correlations can be recorded in parallel with standard LOFAR observations
  - Limited data resolution 200 kHz,10 sec: RFI occupancy is high (pilot data)
  - Will piggyback on AARTFAAC observations in future. (Science data)

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Initial Conditions: Experimental Design

- Foregrounds significantly higher than 100 MHz to 200 MHz range ($\frac{T_{70}}{T_{150}} \sim 6$)
- Need assessment of ionospheric effects: ionospheric effects $\sim \lambda^2$
- Need assessment of chromatic LBA beam effects: simple wire antenna over fractional bandwidth $\sim 100\%$

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Ionospheric effects

- Dynamic effects like scintillation may not be important in long integrations
- Static effects include refraction and absorption from a homogeneous ionosphere
- Simple model: homogeneous shell corresponding to F layer $\sim 200 - 400$ km
- $n_e = 5e11$ m^{-3} gives typical night time mid-latitude TEC of 10

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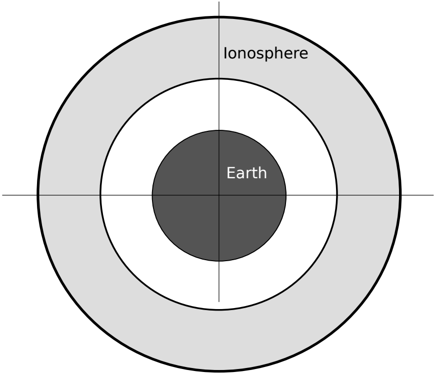

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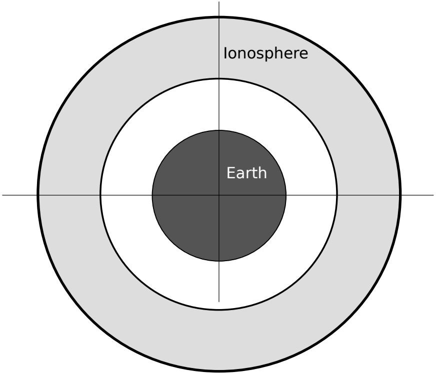

- Ionosphere is a rare medium: $\eta_{iono} = \eta_{iono}(\nu) < 1$
- Incoming rays suffer refraction
- There is a net ray deviation due to the Earth's curvature: $\delta\theta(\nu, \theta)$
- The radio horizon (freq dependent) is below the geometric horizon

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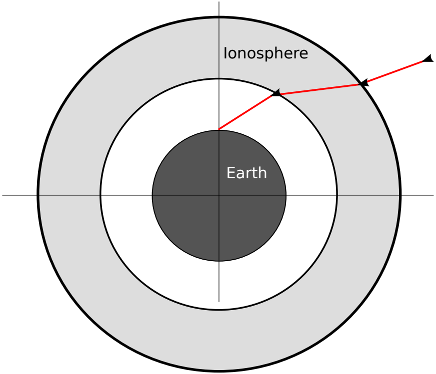

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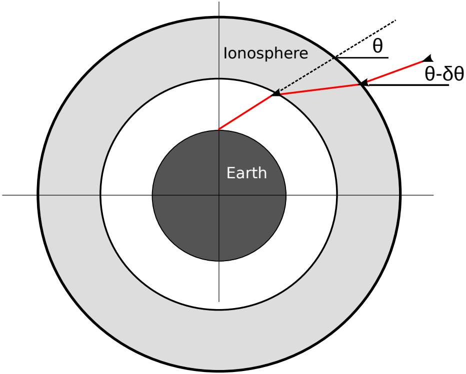

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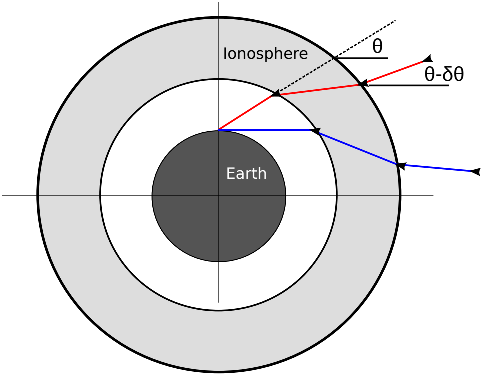

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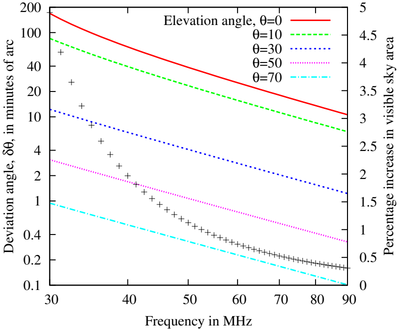

- The sky is lensed differently at different frequencies leading to chromatic mixing of spatial structure into spectral structure

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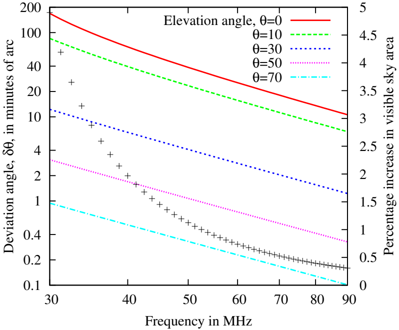

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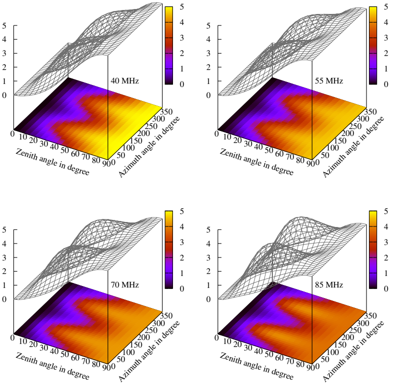
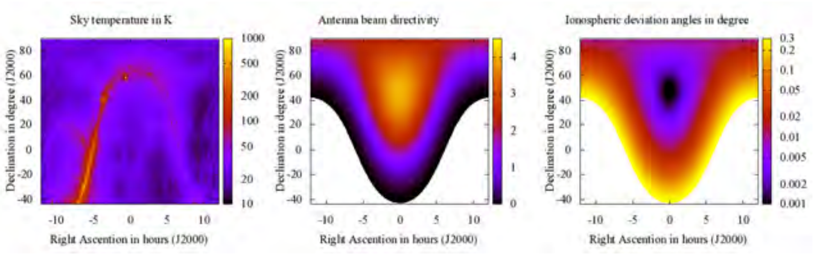
Chromatic beam



- Most of the chromatic features in the beam come from Fresnel reflection from the ground plane
- This mixes spatial structure in the foregrounds into spectral structure

Quantifying chromatic effects using simulations



- Skymodel
  (i) Haslam
  408 MHz map
  ($\alpha = -2.54$)

  (ii) PCA skymodel
  from de Costa et
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- Antenna beam
  (i)Non-chromatic
  $\sin^2\theta$ beam

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- Ionospheric
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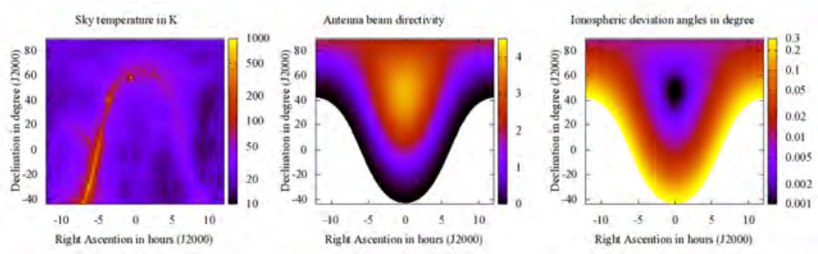

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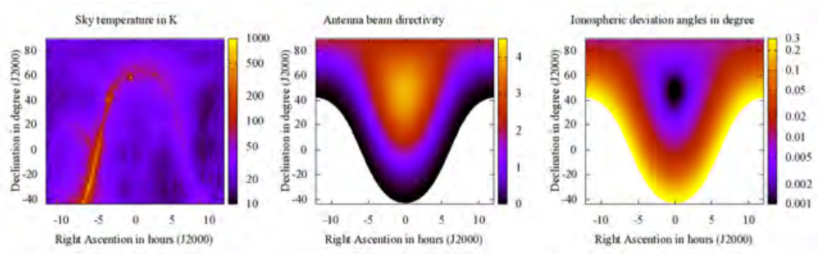

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A simple metric for evaluation

- How bad are the chromatic effects depends on how well we can separate the foregrounds from the 21 cm signal in their presence

- Model 1: $T_{sky} = \widetilde{T_f} + T_{21} \longrightarrow \chi_1^2$ (Blue model)
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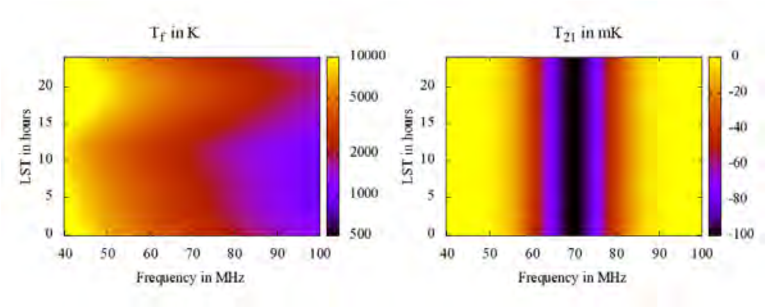

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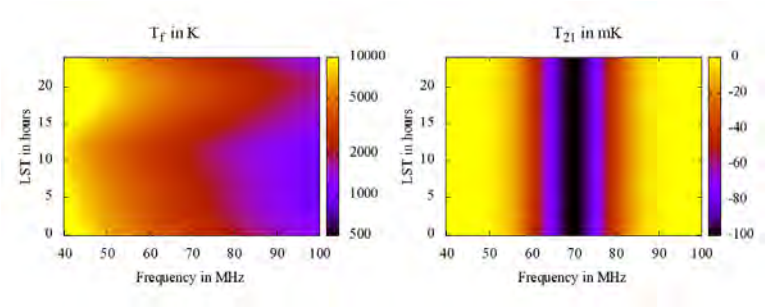

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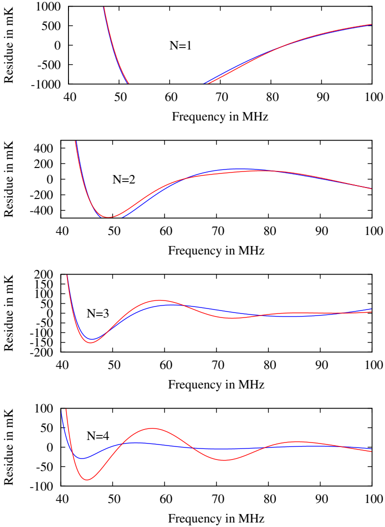
$$\widetilde{\log T_f} = a_0 + a_1 \log \nu + a_2 (\log \nu)^2 + \ldots + a_N (\log \nu)^N$$



Sky: Scaled Haslam map
Beam: Ideal ($\sin^2 \theta$)
Ionosphere: Yes

For 24 hours of integration (N=3)
$\chi_1^2 \sim 1.4$
$\chi_2^2 \sim 1.55$

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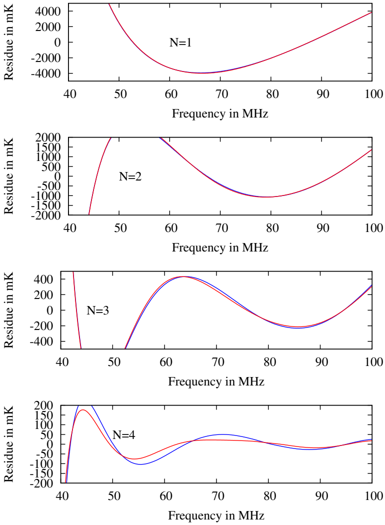

Sky: Scaled Haslam map
Beam: LOFAR LBA
Ionosphere: No

For 24 hours of integration (N=3)
$\chi_1^2 \sim 59.5$
$\chi_2^2 \sim 63.5$

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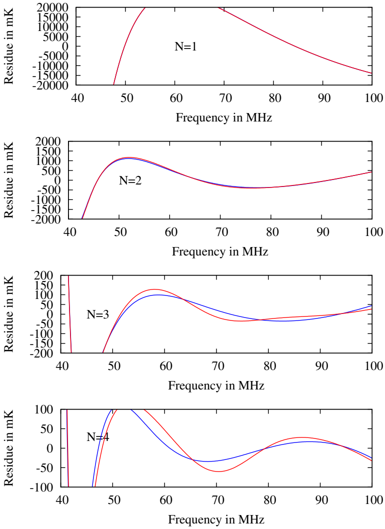

Sky: de Costa et al
Beam: non-chromatic $\sin^2\theta$
Ionospheric: Yes

For 24 hours of integration (N=3)
$\chi_1^2 \sim 5.5$
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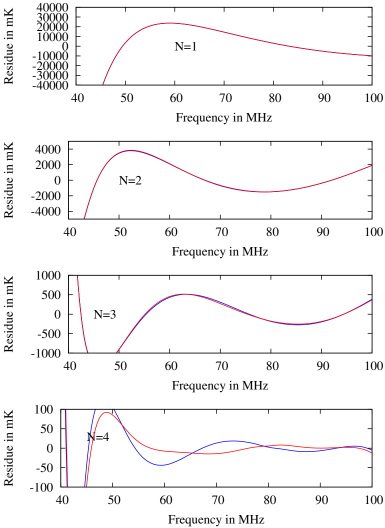

Sky: de Costa at al.
Beam: LOFAR LBA
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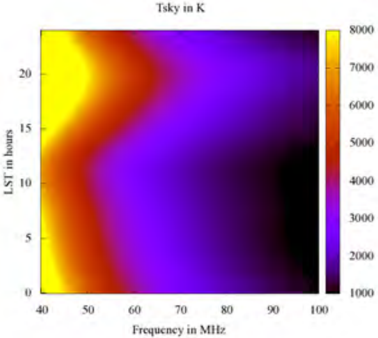
For 24 hours of intergation (N=3)
$\chi_1^2 = 76.0$
$\chi_1^2 = 81.0$

Is the spectra that complicated?



- SVD of the dynamic spectra— $T_{sky} = U \Sigma V^H$— gives us an orthonormal basis for spectral (V) and time (U) variability.
  (also see Liu & Tegmark, 2012)
- The spectral basis *approximately* resemble polynomials.
- The first 4 basis functions describe the mean spectrum to the required level.
- An optimal foreground fit requires no more than 4 parameters. Polynomials are not the most efficient basis.

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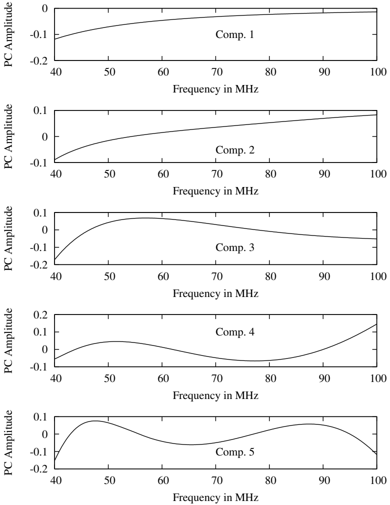

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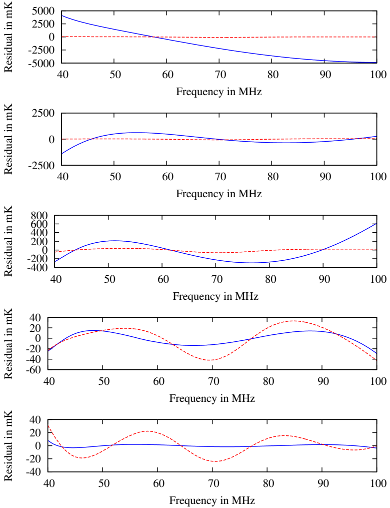

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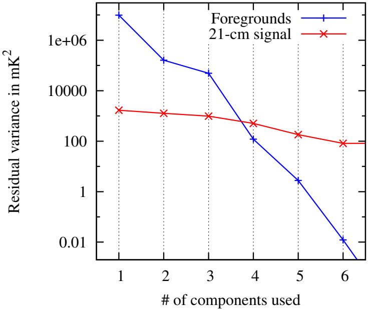

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A more efficient way to model the foregrounds

- Going to higher order polynomials ($N > 3$) is inefficient.
- We have not used the full spectral information present in current foreground models (de Costa et al.).
- We have not used the time domain information in the dynamic spectra (spatial correlation of sky brightness)
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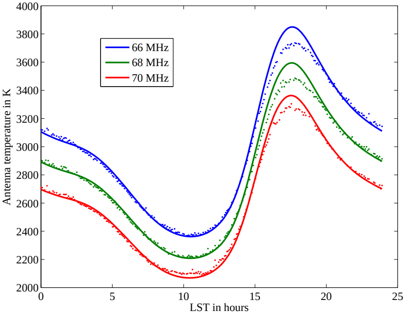
Forward modeling— first look



- $T_{obs}(\nu, t) = G(\nu)[T_{sim}(\nu, t) + T(\nu)] \longrightarrow$ Estimate $G(\nu)$ and $T(\nu)$
  See Rogers at al. 2004
- A simple model fits the data to $\sim 1\%$
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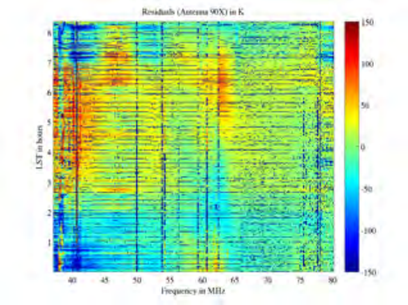

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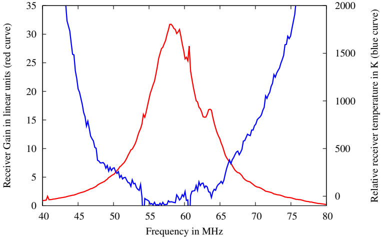

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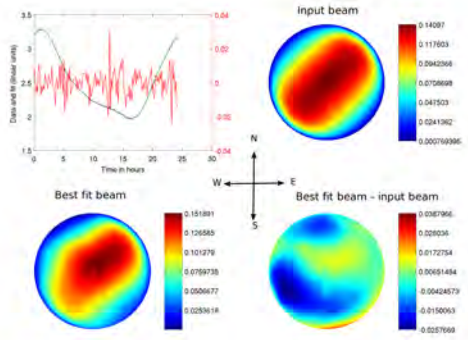

- Perturb the fiducial beam to fit away the 1% residuals.
- Differential beams are similar across freq and pol.
- Strong suggestion of wrong CasA flux in the skymodels by $\sim 10\%$

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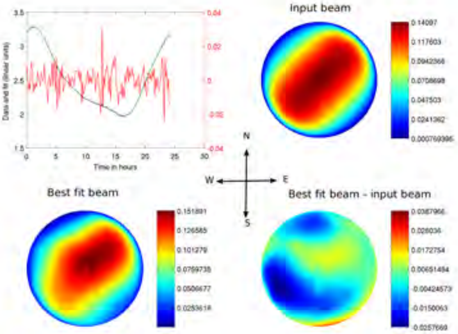

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Conclusions

- Ever-present ionospheric refraction gives chromatic mixing ($\sim$ few%)
- LBA beams give additional chromatic mixing.
- All chromatic effects may be fit with just 4 or 5 parameters
- Polynomials are inefficient basis as they discard well known priors (sky and beam)
- First-go at forward modeling looks promising for LOCOS
- Future science data will provide:
  (i) better time,freq resolution
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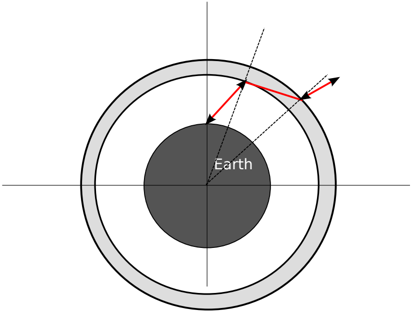

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