A Minimum Ionospheric Model (MIM) for LOFAR

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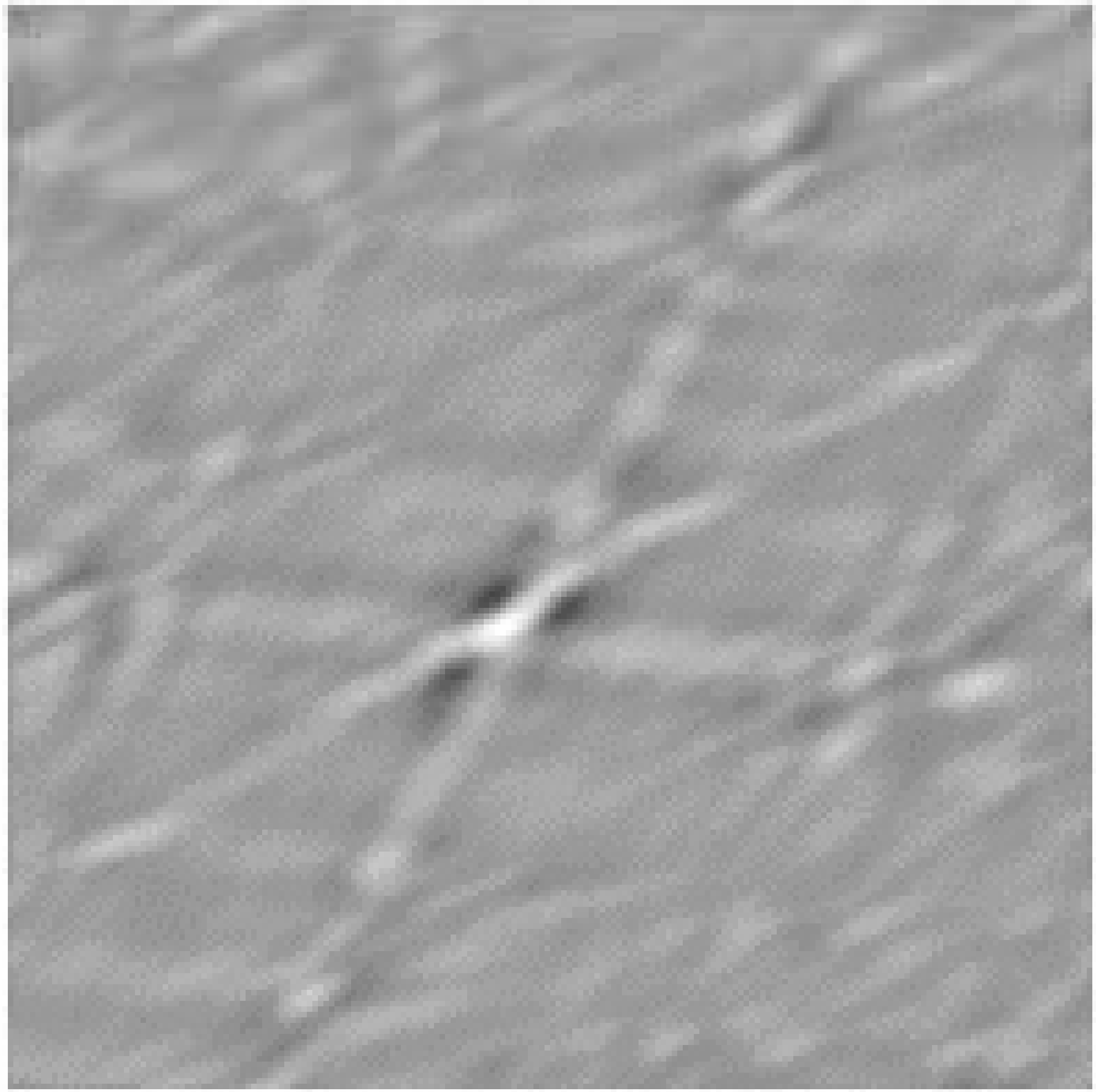
The LOFAR challenge

- Pathological Ionosphere (1 rad / 10 sec)
  - Affects source subtraction and imaging
- (Very) crowded fields
  - Source confusion
  - PSF sidelobe confusion: increases noise
- Unstable station beam shapes
  - Affects source subtraction and imaging
- High station side-lobes
  - Bright sources (incl galactic plane and Sun)

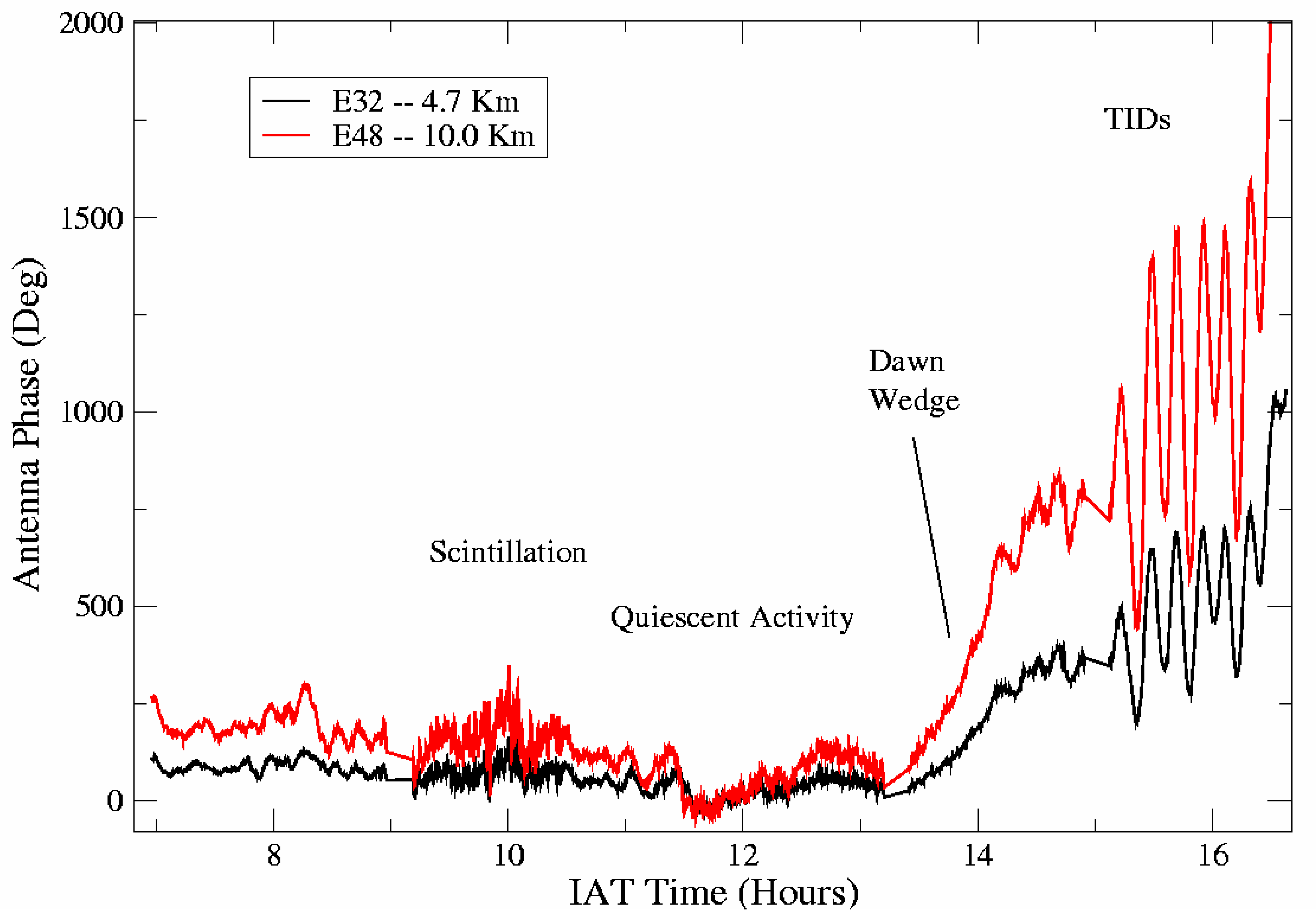
Virgo A, VLA 74 MHz

~1 degr



Courtesy Rick Perley (NRAO), Gary Bust (ARL, U.TX)

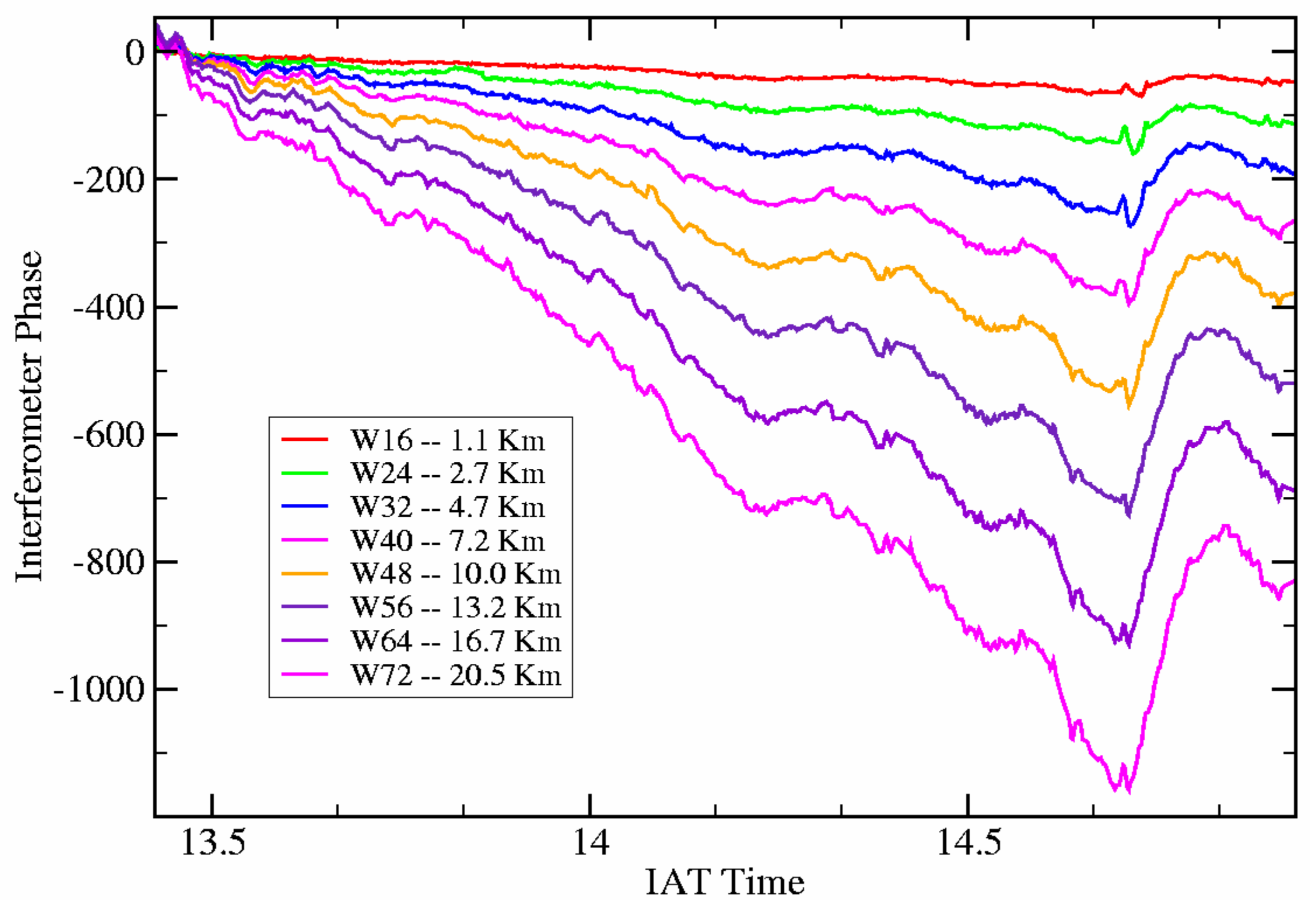
Virgo A: ionospheric phase



Virgo A: Dawn Wedge Phase

All antennas on West Arm during 'Dawn Wedge' period.

This shows a thickening wedge over the array which started about 1 hour before dawn, and was terminated by the onset of a large wave event.



Comparable to, but easier than, adaptive optics

- Mostly large-scale motion
  - ‘Seeing-cell’ larger than field-of-view
  - Source images do not ‘break up’ so much
- More reference sources available
  - 10-50 bright sources per field
  - SNR>3 in 10 sec
- But: we can learn from each other

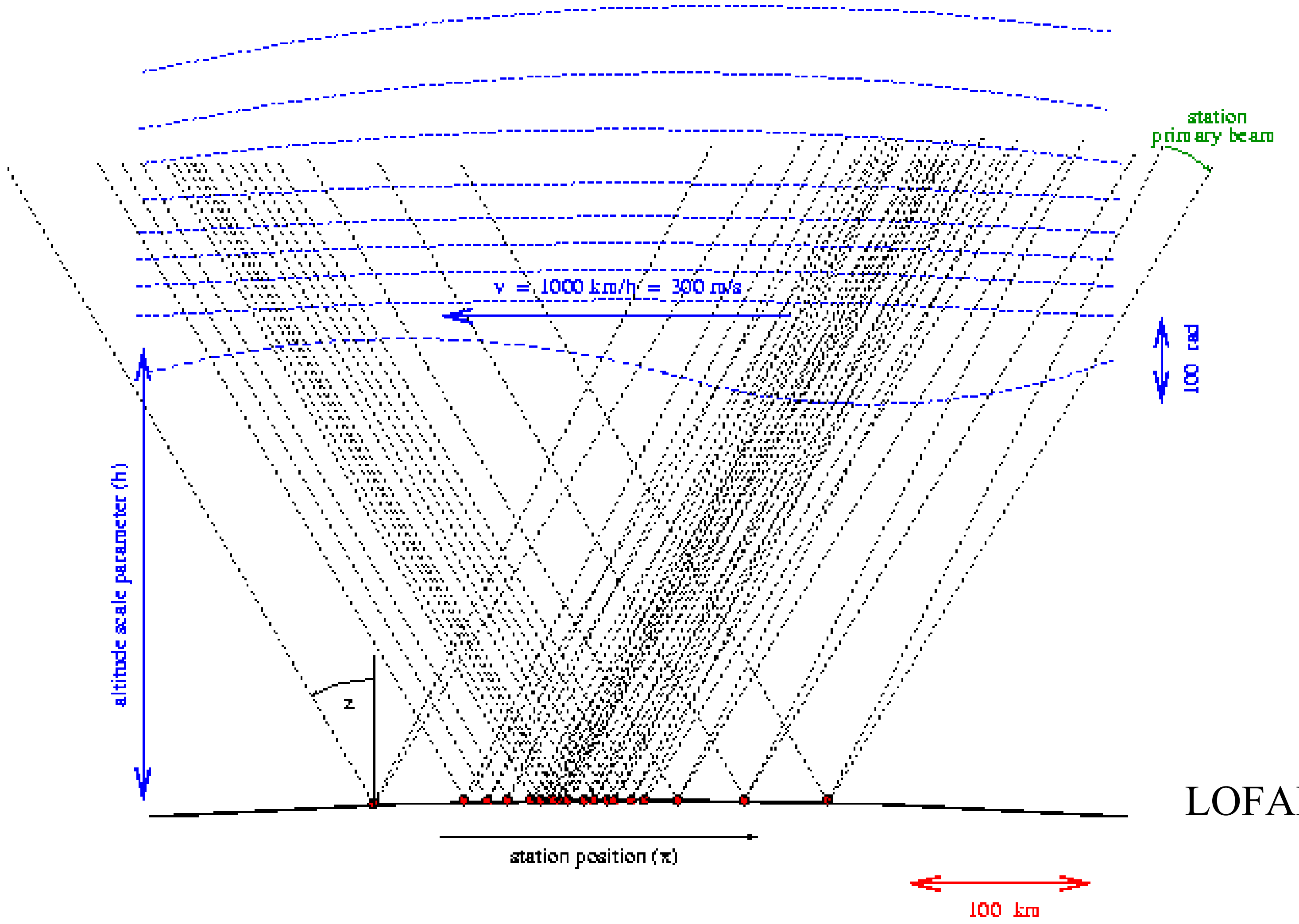
Evolutionary path to MIM

- 2001: Independent 2D phase-screen for each station beam (~10-20 parameters each): Barely enough bright calibrators.
- 2003: *Peeling* brings the realisation that fainter sources may be used too, provided their phase excursions are limited by tracking
- WSRT LFFE: solving for phase gradients only
- Global MIM drastically reduces the nr of parameters, and thus the nr of calibrators

Minimum Ionospheric Model (MIM)

- Minimum nr of parameters (few bright sources available, sometimes none)
- Only deal with observables (not interested in internal structure of ionosphere)
- Assume large-scale (>100 km) structure and go progressively smaller, until ….

Ionospheric blanket with many piercing points



LOFAR

Step 1: zenith model

Excess path in zenith direction (z=0):

$$L_0(f) = -40.3 \times (100/f)^2 \times TEC \quad m$$

Typical: TEC=5 $\longrightarrow$ $L_0(100MHz) = -200$ m

As a function of station position (x):

$$L_1(x) = L_0\,(1 + p_1 x + p_2 x^2 + p_3 x^3 + \ldots)$$

$p_k = p_k(t)$

Step 2: zenith angle

$$L_2(x,z) = L_1(x) \; (x - h \tan(z)) \; S(z)$$

$$S(z) = 1/\cos(\arcsin(R\sin(z)/(R+h)))$$

Earth radius R and ionospheric 'altitude' h

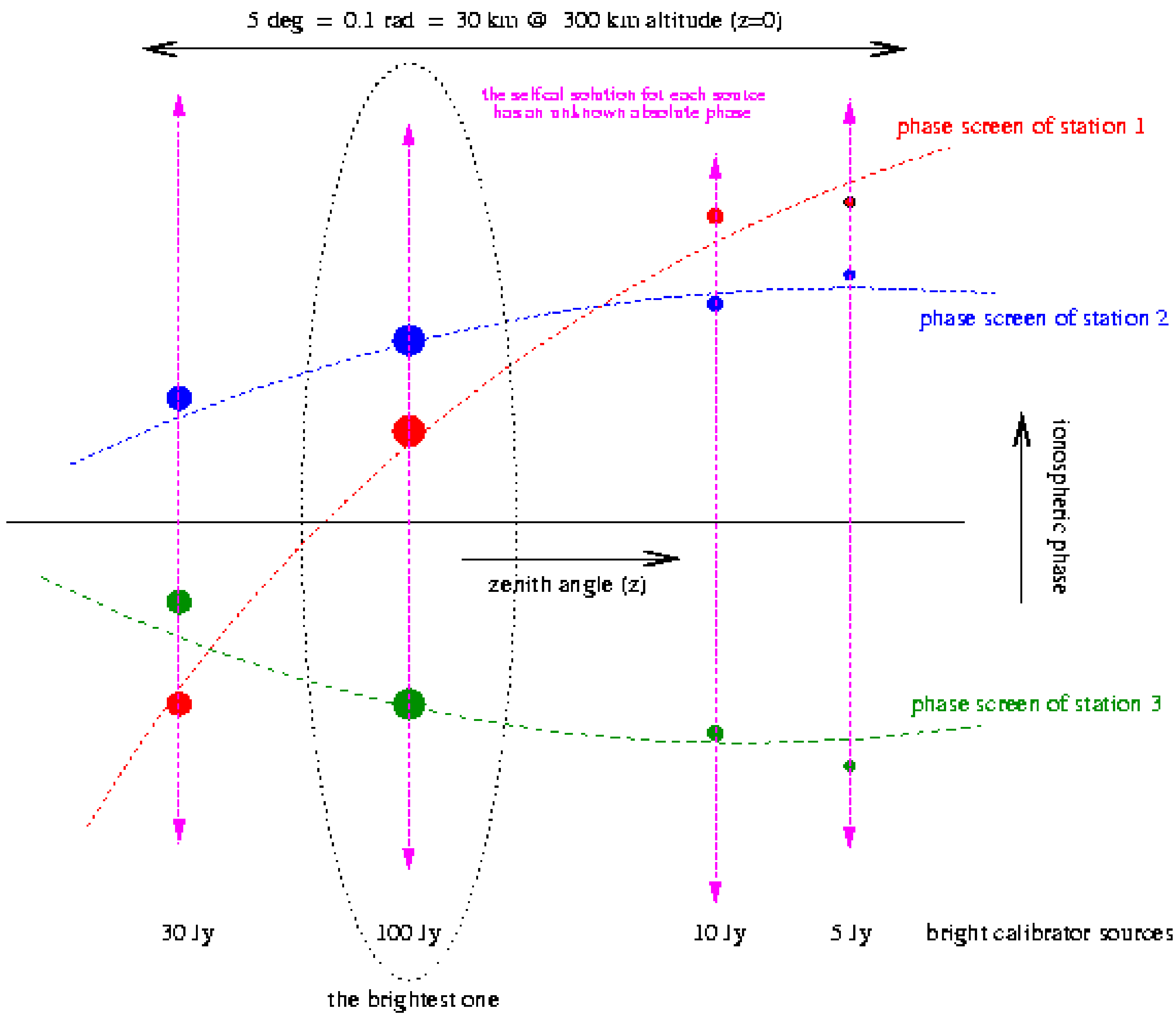
NB: The altitude parameter h (~300 km) is just a coupling constant that introduces z-dependency. An incorrect value will be absorbed in the estimated values of the coefficients p_k.

Step 3: 2D sky frame

$$L_1(x, z) \longrightarrow L_1(x, y, z_{North}, z_{East})$$
$$\longrightarrow L_1(x, y, RA, DEC)$$

So, given the MIM parameters ($p_k(t)$, h) we can calculate the *absolute* ionospheric phase from an arbitrary station (x,y), in the direction (RA, DEC) of an arbitrary point in the sky.

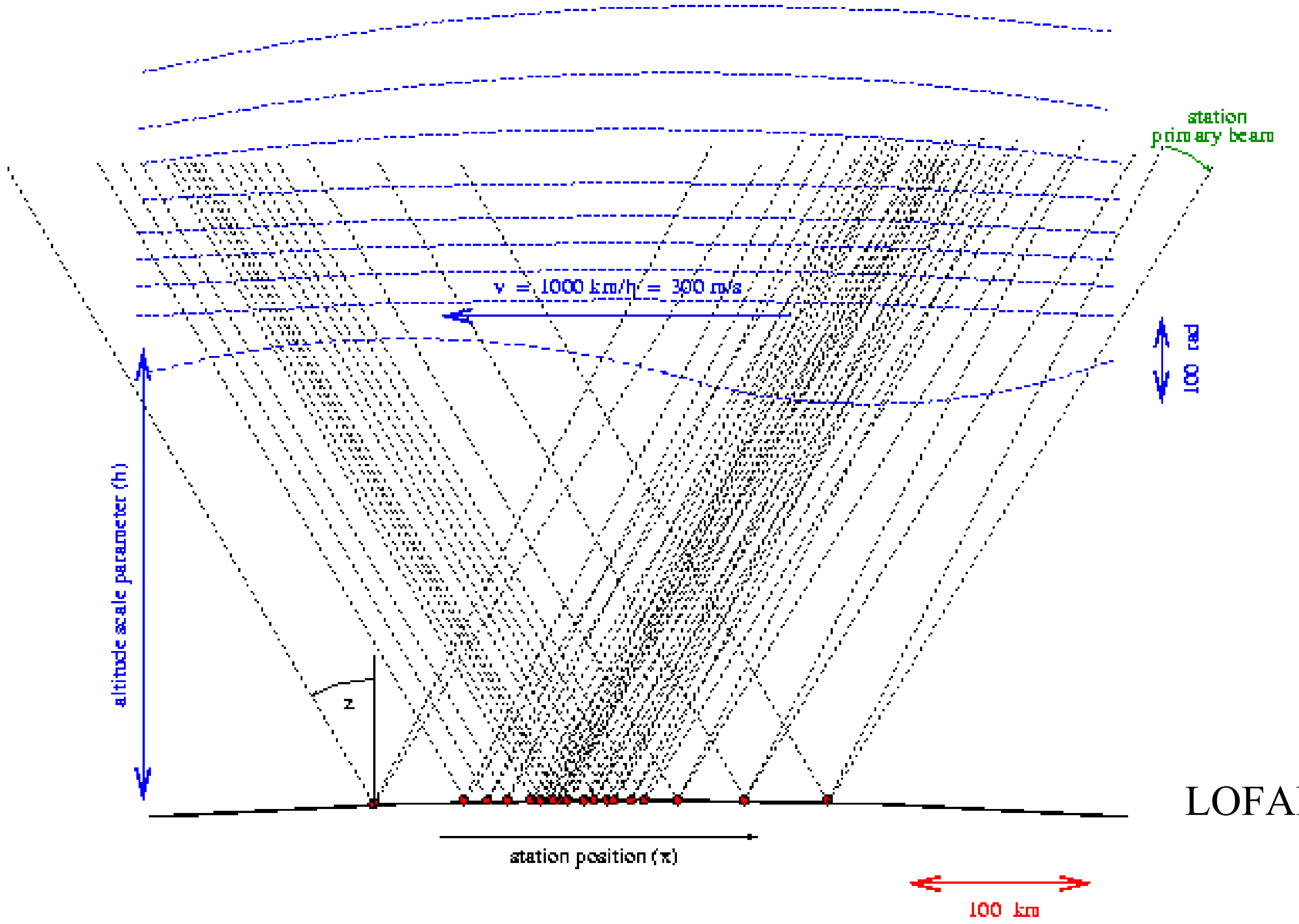
Note the tiny nr of parameters: typically < 20


5 deg = 0.1 rad = 30 km @ 300 km altitude (z=0)
the selfcal solution for each source
has an unknown absolute phase
phase screen of station 1
phase screen of station 2
phase screen of station 3
zenith angle (z)
ionospheric phase
30 Jy
100 Jy
10 Jy
5 Jy
bright calibrator sources
the brightest one

Procedure

- Do phase selfcal on the brightest source in the main lobe of the station beam
- Estimate 10-20 MIM parameters (h, p_k) from $N_{station}$ phases. Remove 2π ambiguities by minimising the internal inconsistency.
- Use the remaining inconsistency to determine whether to add or remove MIM parameters.

Ionospheric blanket with many piercing points



LOFAR

A plethora of possibilities…

- Include other calibrators in the field (main lobe)
- Include calibrators in different LOFAR beams to get greater sky coverage
- Include calibrators in the side-lobes
- Use MIM to track the ionosphere during the observation (within a radian, or better)

Main lobe and side-lobes

- How to separate phases due to the voltage beam and the ionospheric?
- Main lobe: differential (except for beam shape differences): negligible?
- Far side-lobes: Calibrator may be in different sidelobes: π jumps
- Zeroes…

Use of moving ‘frozen’ pattern?

- Does not seem very useful…

Gain effects (scintillation)

- Focussing effect (10 km blobs). Rare.
- Distinguish from sidelobe gain
- Straightforward MIM extension…

Faraday rotation

$\mathrm{TEC} = \int N_e \, dl \;\; m^{-2}$

$\mathrm{RM} = \int N_e \, B.dl \;\; rad/m^{-2}$

- More complicated than phase:
  - Angle with Earth magnetic field
  - Integral along (curved) path
- Do we need 3D ionosphere model?
- Or can we use large-scale MIM approach?
- We need some polarised ‘anchor’ points…

Conclusions

- MIM looks like a useful concept
- The ionosphere is a problem, but it might also be an opportunity…
- Let's try it !