Evaluation of Ionospheric Correction Methods for the European VLBI Network

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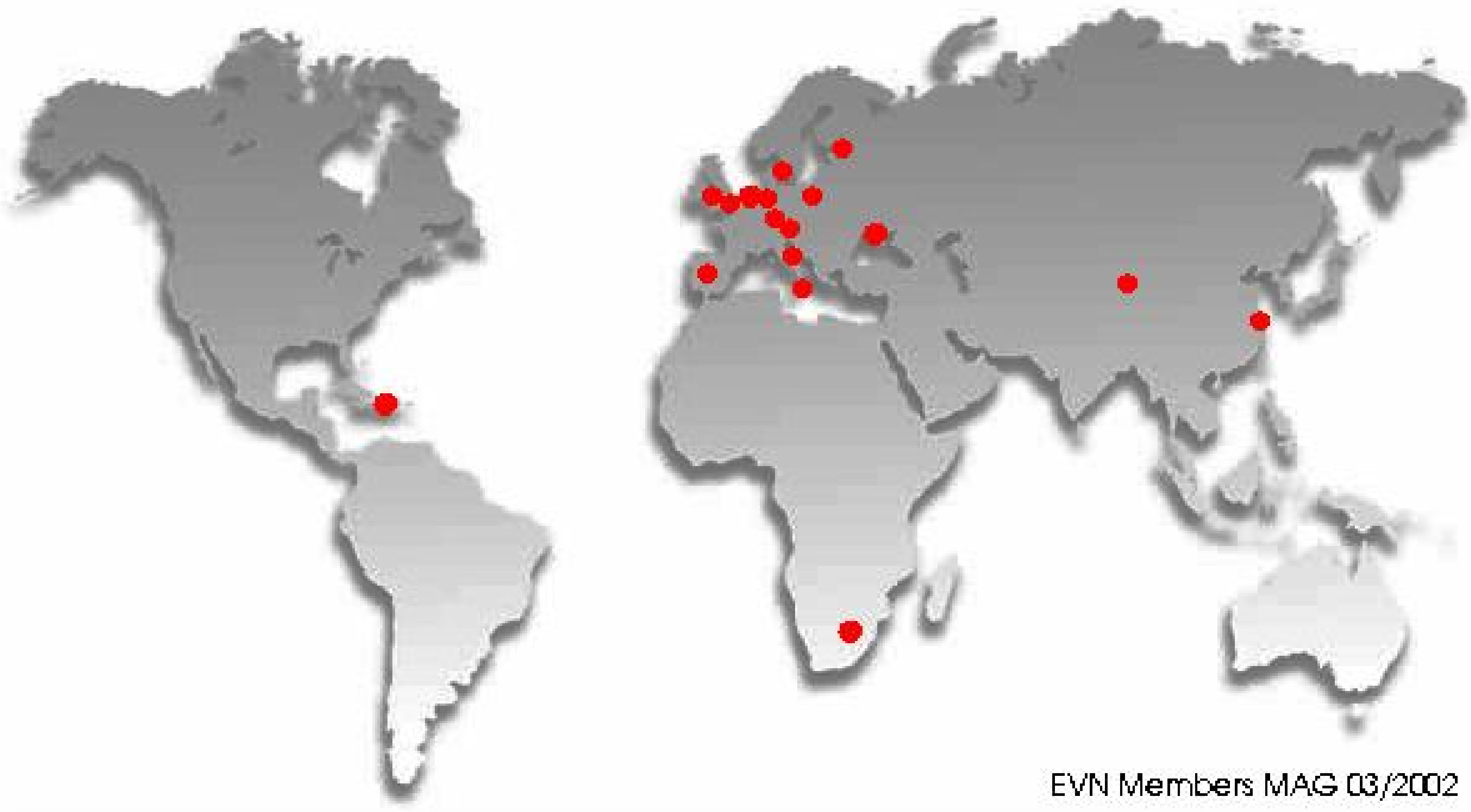
Abstract

As part of the Advanced Long Baseline User Software (ALBUS) project funded by the EU through the RadioNet consortium, we are evaluating and implementing several algorithms to apply different ionospheric correction methods to very long baseline (VLBI) data. We are focusing on methods to predict the total electron content (TEC) along the observed slant paths for each VLBI antenna. The TEC values will, in turn, be used to predict the path delays for individual frequency channels. These predictive methods will include estimates based on dual-frequency GPS measurements of the ionospheric delay from GPS receiver stations co-located with VLBI antennas as well as nearby GPS station measurements (from networks such as EUREF). We will also exercise empirical and theoretical ionospheric models such as the International Reference Ionosphere (IRI) model and the Parameterized Ionospheric Model (PIM). Two-dimensional global ionospheric electron content models, such as the global vertical TEC files produced by CODE, ESOC, JPL, and so on (the IONEX files currently used for ionospheric corrections in the AIPS task TECOR) and three-dimensional models such as Fusion Numerics' numerical ionospheric forecasting system will also be included for analysis. Furthermore, local GPS station measurements will be combined with the global models to attempt to resolve small-scale structure in the ionosphere.

The EVN

The European VLBI Network (EVN) is an interferometric array of radio telescopes spread throughout Europe and beyond (see Figure below), which conducts unique, high resolution, radio astronomical observations of cosmic radio sources. It is the most sensitive VLBI array in the world, thanks to the collection of extremely large telescopes that contribute to the network.



EVN Ionospheric Calibration

The greatest number of EVN observations are made at L-band frequencies, where the ionospheric delay is important. Correcting for this delay is crucial in order to increase the coherence time to enable self-calibration of modestly weak sources, or to even detect the faintest sources. Achieving phase errors less than 15° requires slant total electron content (TEC) measurements accurate to better than 0.05 TECU (1 total electron content unit, or TECU is 10^{16} electrons per square meter). Phase referencing techniques (calibration using a strong source located a few degrees away) reduce the requirement to only a relative accuracy of 0.05 TECU.

But TECOR Already Exists ....

- TECOR uses IONEX format files
- standard IONEX files sampled at 2 hour intervals
- grid spacing 5° by 2.5° (lon x lat)
- effectively 2-D model ignoring height information

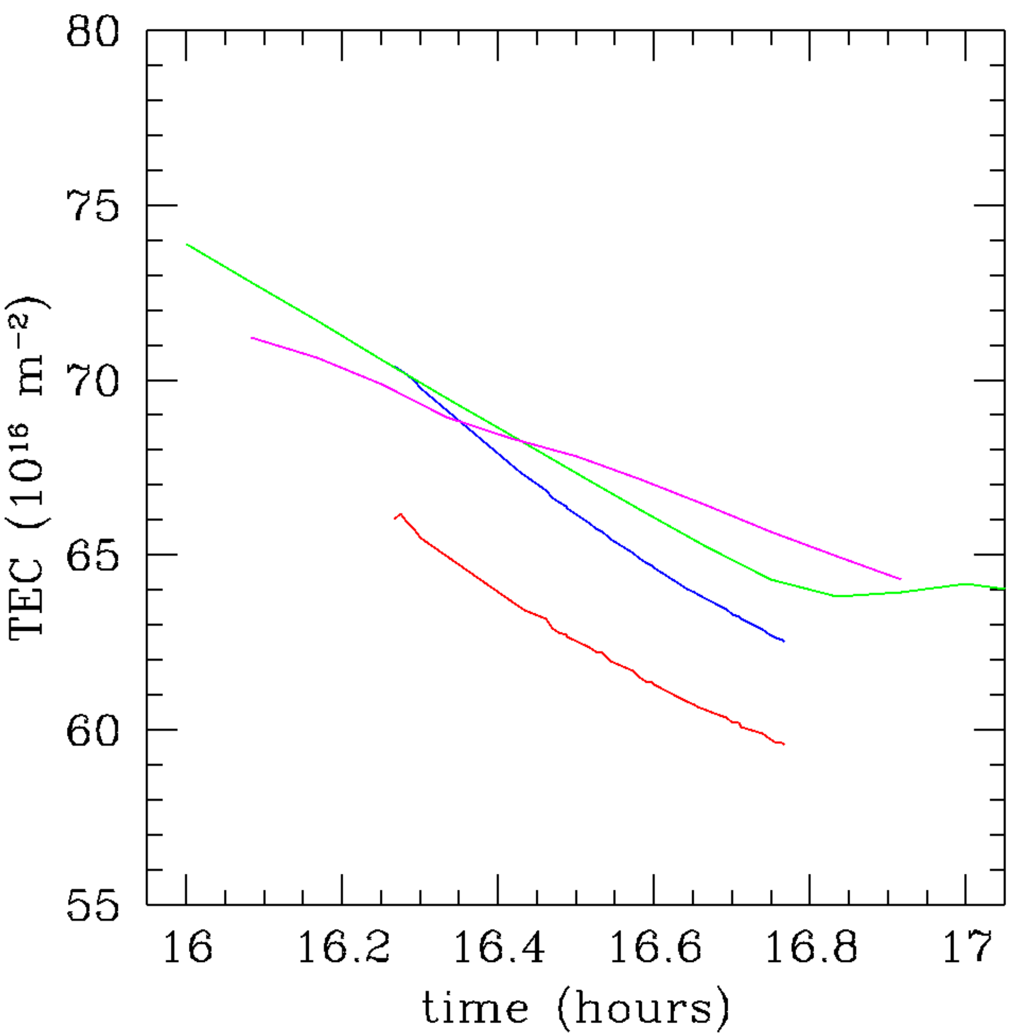
- Ionospheric modeling rapidly developing for industry and military applications
- GPS receivers co-located with 8 EVN antennas
  - this information must be useful at some level
- Need to evaluate performance for EVN stations
  - TECOR tested for VLBA, not EVN

Data and Models Being Investigated

- Empirical models
  - International Reference Ionosphere (IRI)
- Theoretical and semi-empirical models
  - Parameterized Ionospheric Model (PIM)
- Global data models
  - 2-D —global vertical TEC (IONEX)
  - 3-D —FusionNumerics
- GPS station and ionosonde measurements
  - GPS stations co-located with 8 EVN antennas
  - Global network of GPS stations providing RINEX data
  - Coverage over Europe good, but need more over Africa, Asia, Atlantic
- Combinations of the above

EVN N05L2 Test Data

8 hours of EVN test time during 2005 June were used to make observations to test ionospheric calibration for phase referencing with the EVN. Efforts to date have concentrated on software development to automatically gather incorporate new datasets into AIPS for user processing. Different ionospheric datasets predict differences of up to 5 TECU, often with substantially different slopes.



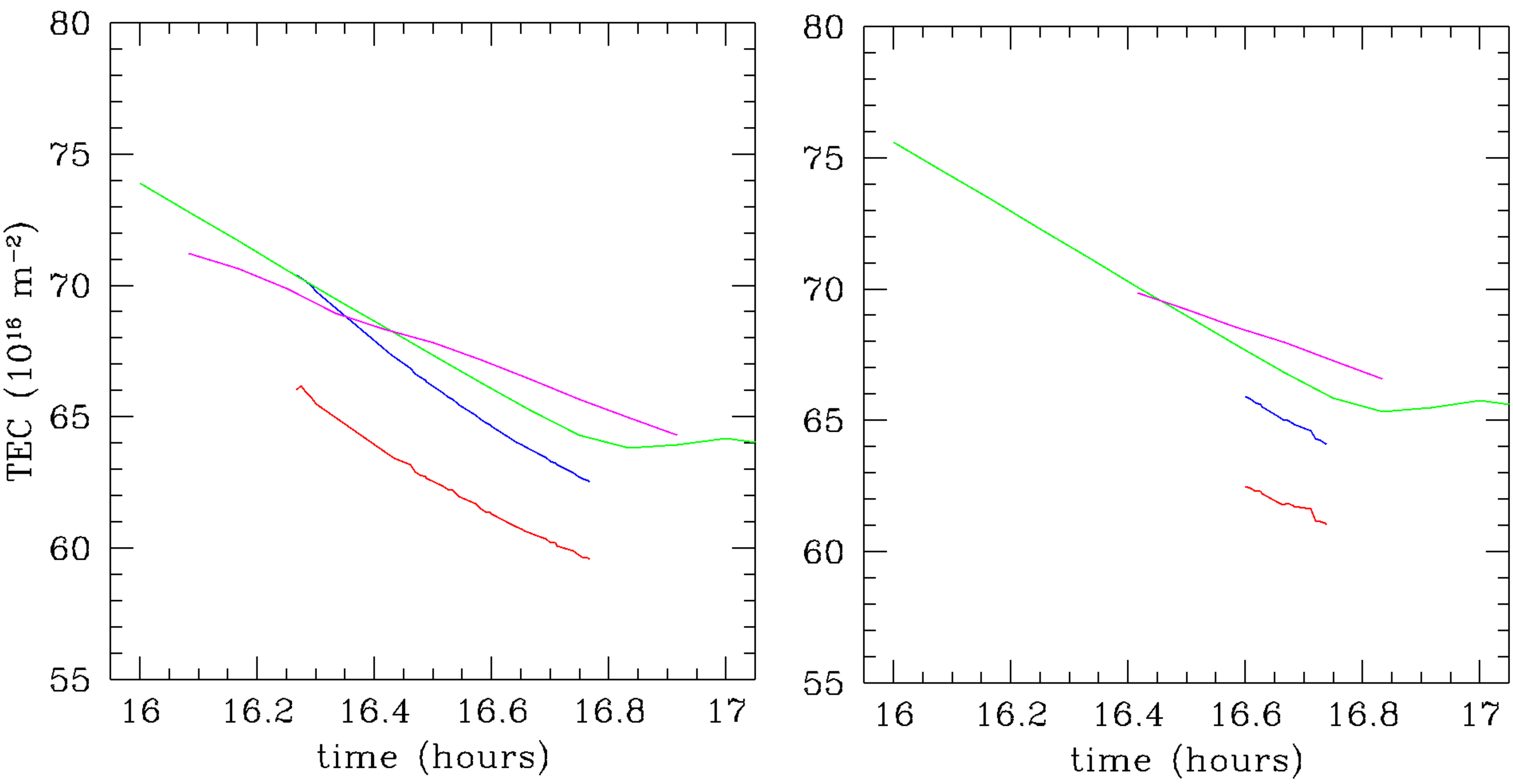
Source: J1159-2148

IONEX (CODE)
IONEX (JPL)
PIM
FusionNumerics

EVN N05L2 Test Data: 2

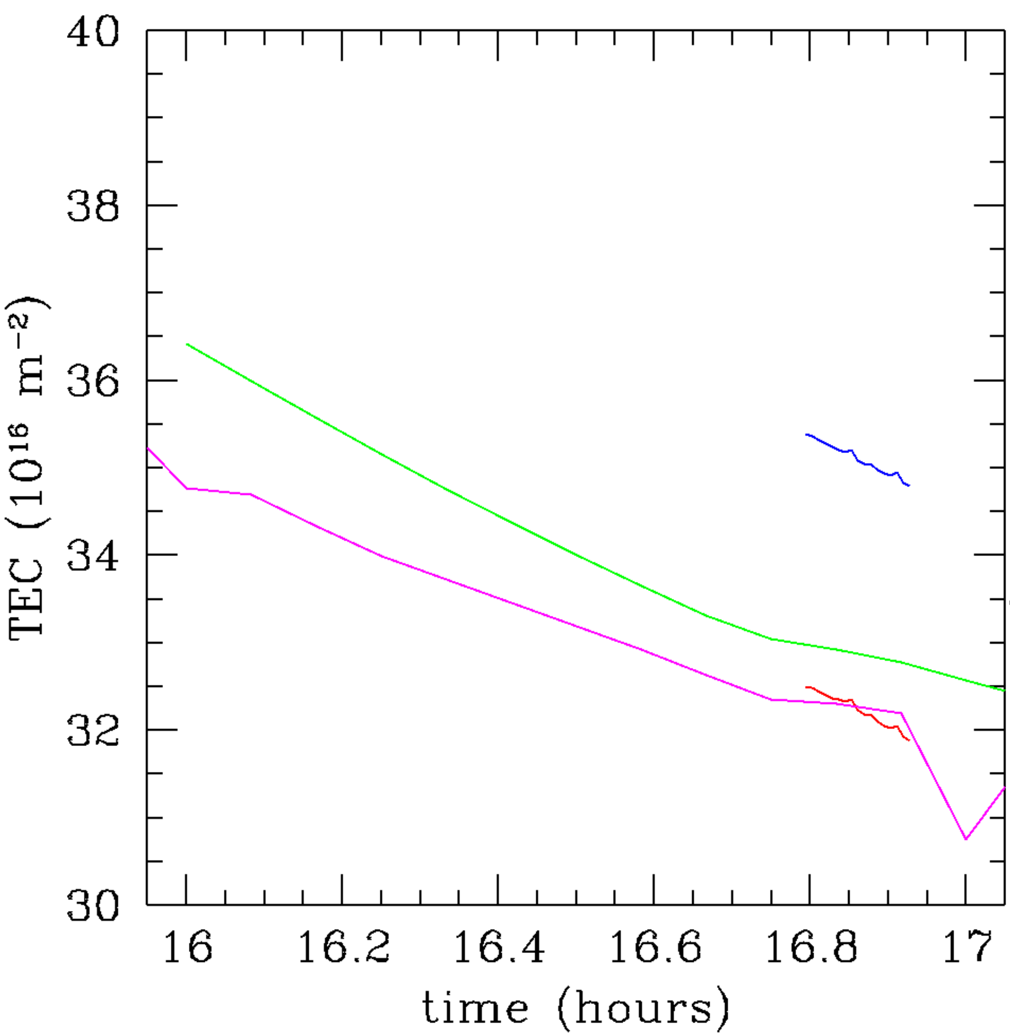
Phase referencing from a calibrator source (left) to a target source (right). Relative differences between sources are much smaller than differences between models. But the IONEX predictions (TECOR) often have jagged bumps > 0.5 TECU.

Source: J1159-2148 J1159-2228



EVN N05L2 Test Data: 3

Because of their coarse grid spacings, the IONEX models have noisy slant TEC predictions. The 3D FusionNumerics predictions are normally better, but also occasionally have extreme jumps. Theoretical (PIM) and empirical (IRI) models are more smooth, and are probably better at removing the long-term relative differences in the ionosphere for phase referencing.

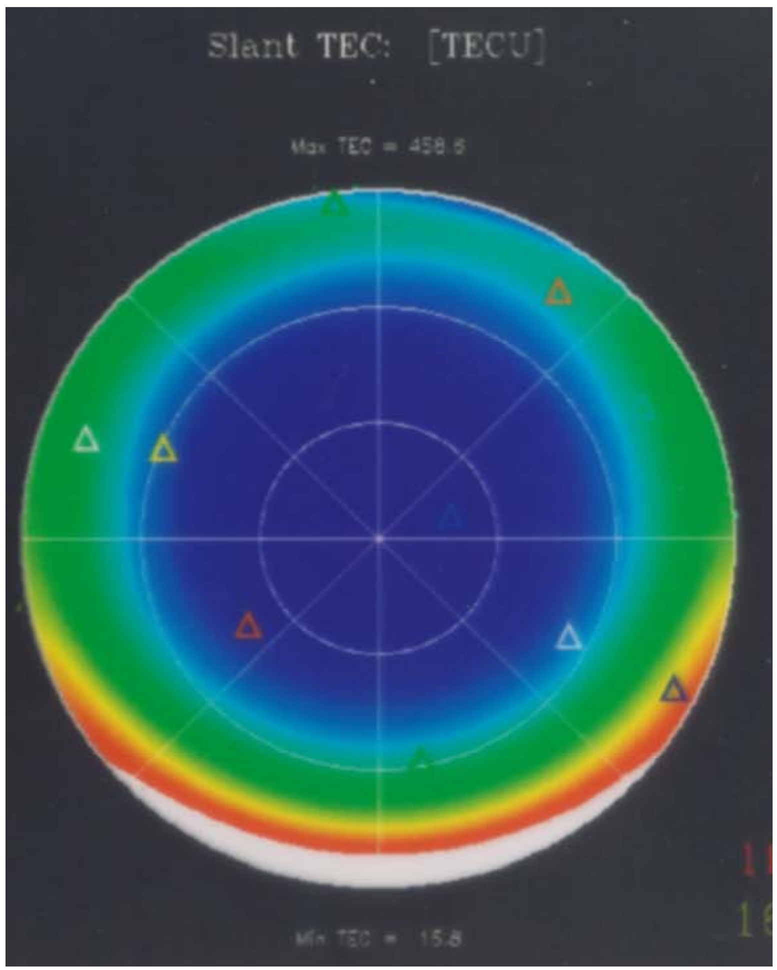


But, none of these models are able to account for short-timescale effects such as TIDs. Direct measurements, such as those from GPS receivers, are almost certainly required in some form.

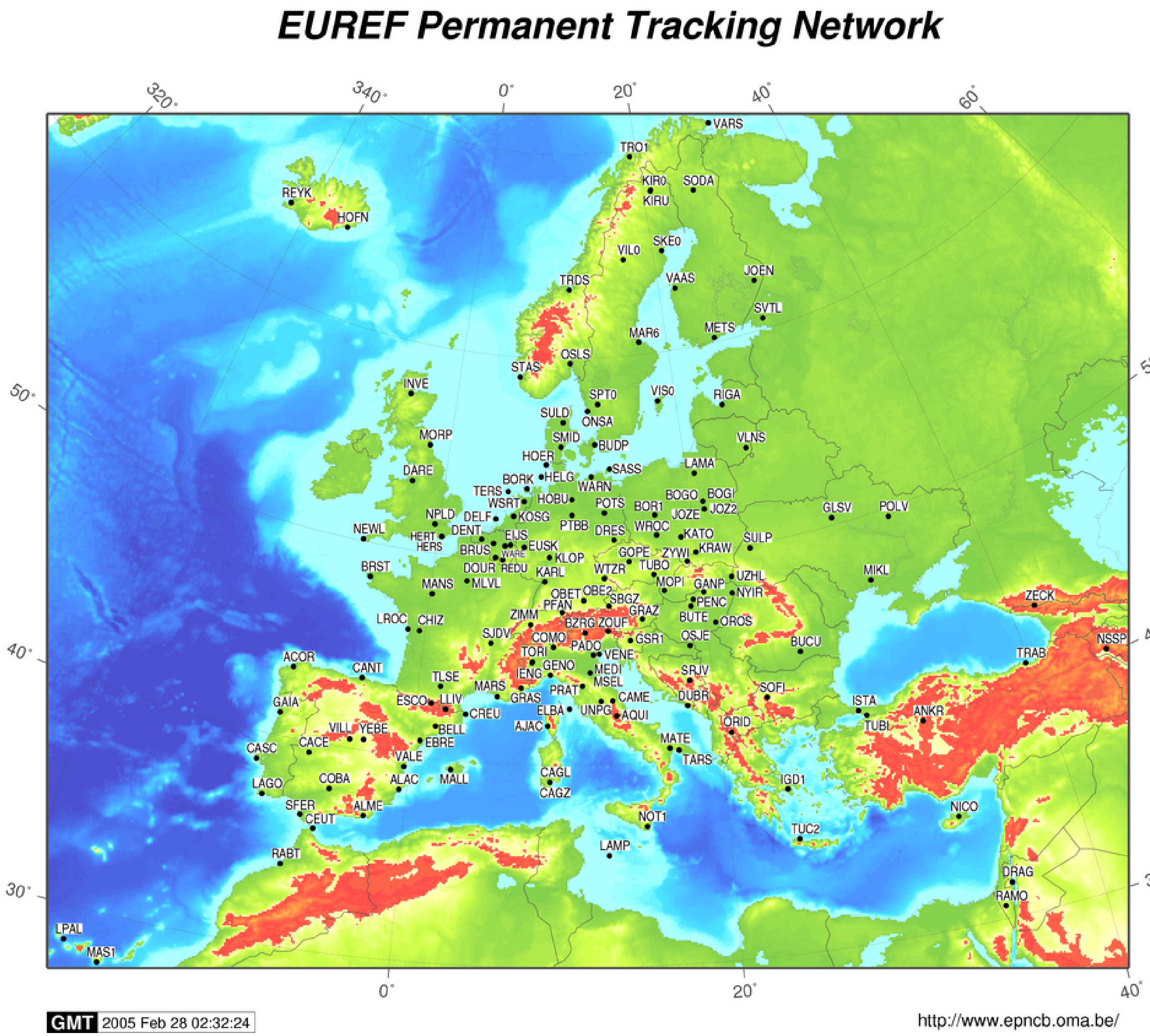
Source: 3C273B

Single GPS Receiver Inadequate

GPS satellites are normally too widely spaced on the sky to adequately sample the ionosphere using a single receiver. In the figure below, triangles show one instantaneous view of GPS satellites above the Westerbork station (in the Netherlands). Zenith is at the center, and the horizon at the edge of the circle.



European GPS Stations



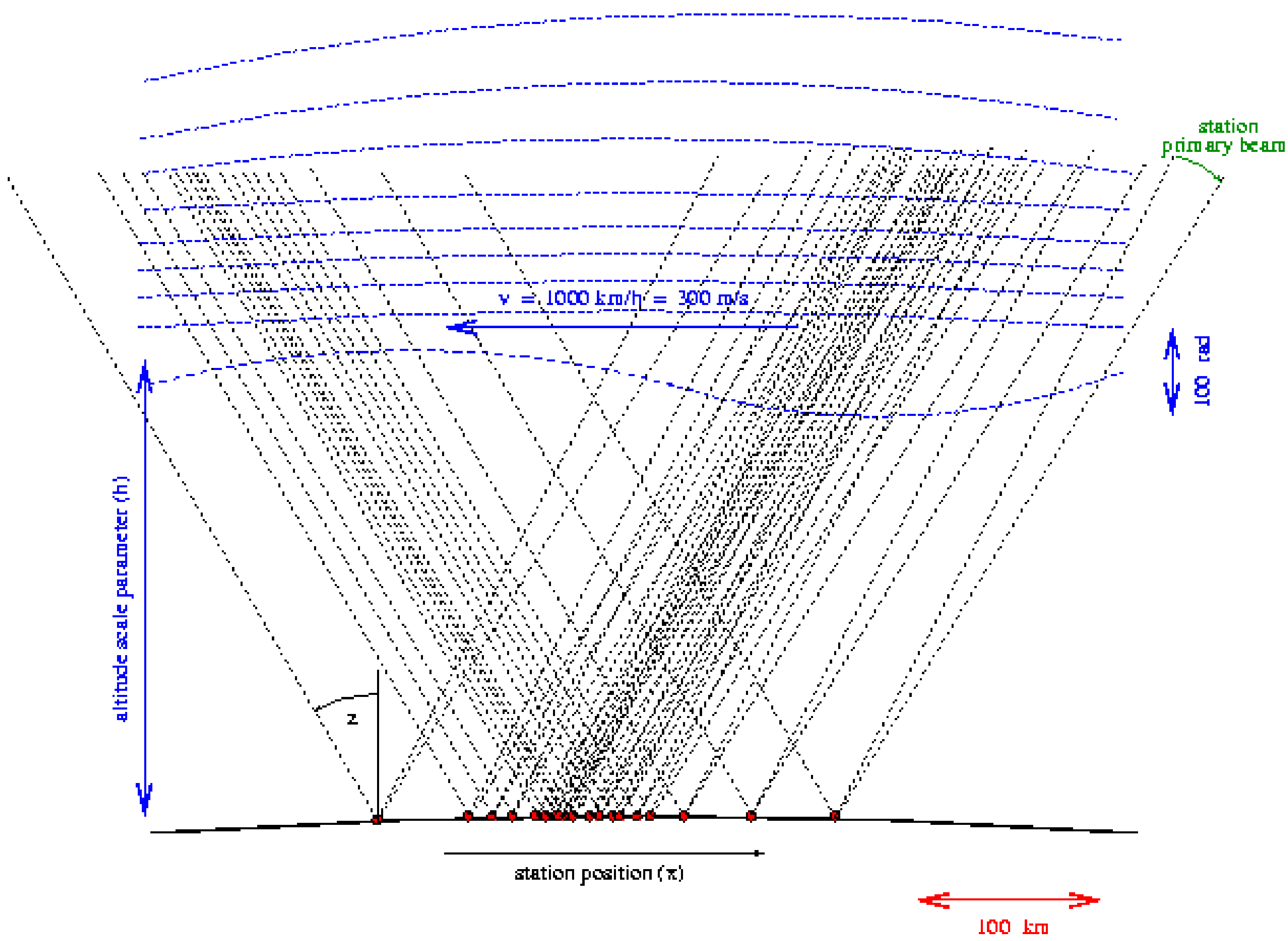
8 EVN stations have co-located GPS receivers

Data from many other GPS receivers publicly available

Can combine nearby GPS measurements to improve model

Ionosphere with Many Pierce Points

This diagram (from a LOFAR calibration talk by J. Noordam) shows the concept of measuring the ionosphere using observations of a few sources (or GPS satellites) using many ground stations.



MIM: Minimum Ionospheric Model

The MIM model was suggested by J. Noordam for calibrating LOFAR. It aims to model the ionosphere using a minimum number of parameters using a completely empirical modeling approach.

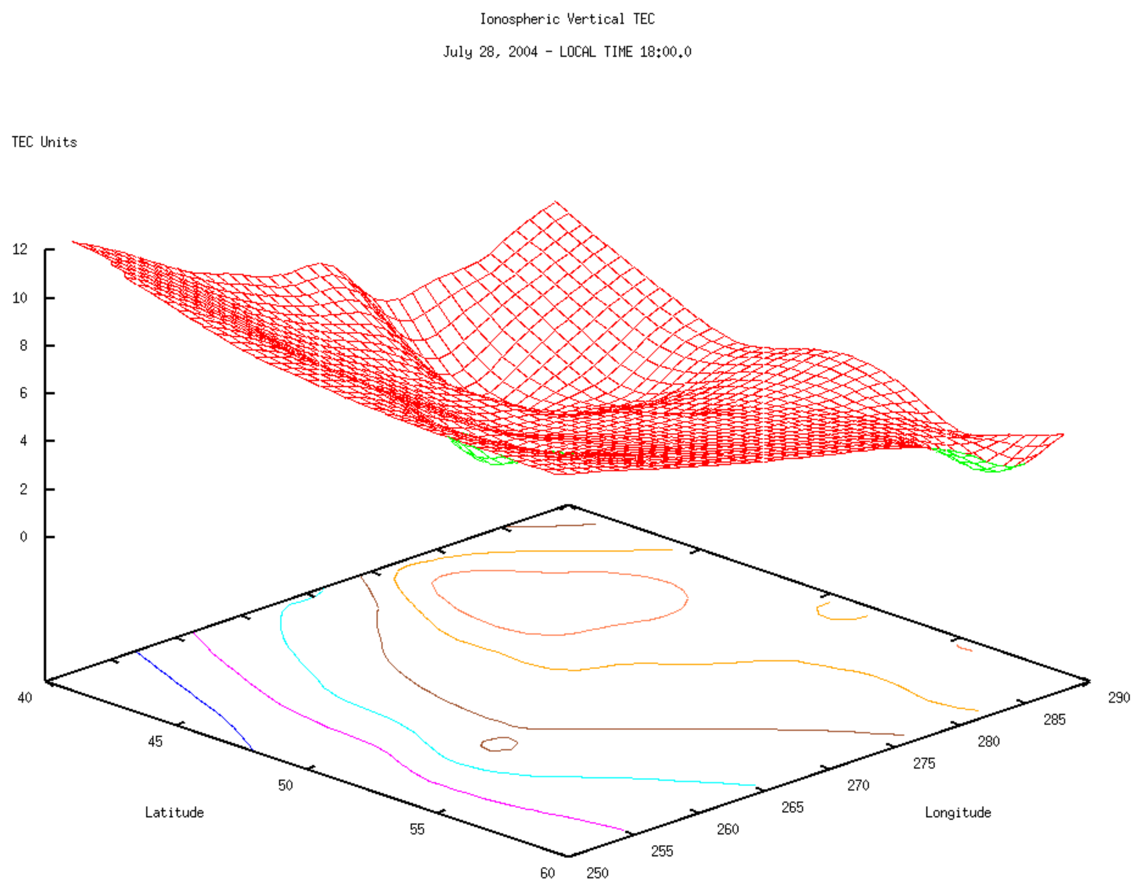
The model suggests using a thin approximation to the ionosphere, but can be expanded to accommodate a thick ionosphere. The ionosphere is modeled as an arbitrary function (e.g. polynomial) of latitude and longitude of the ionosphere (or other suitable coordinates).

Data points can come from (bright) sources in the sky (calibrators) or other information such as GPS measurements.

The fit is made with as few parameters as necessary to provide an accurate model over a patch of the sky.

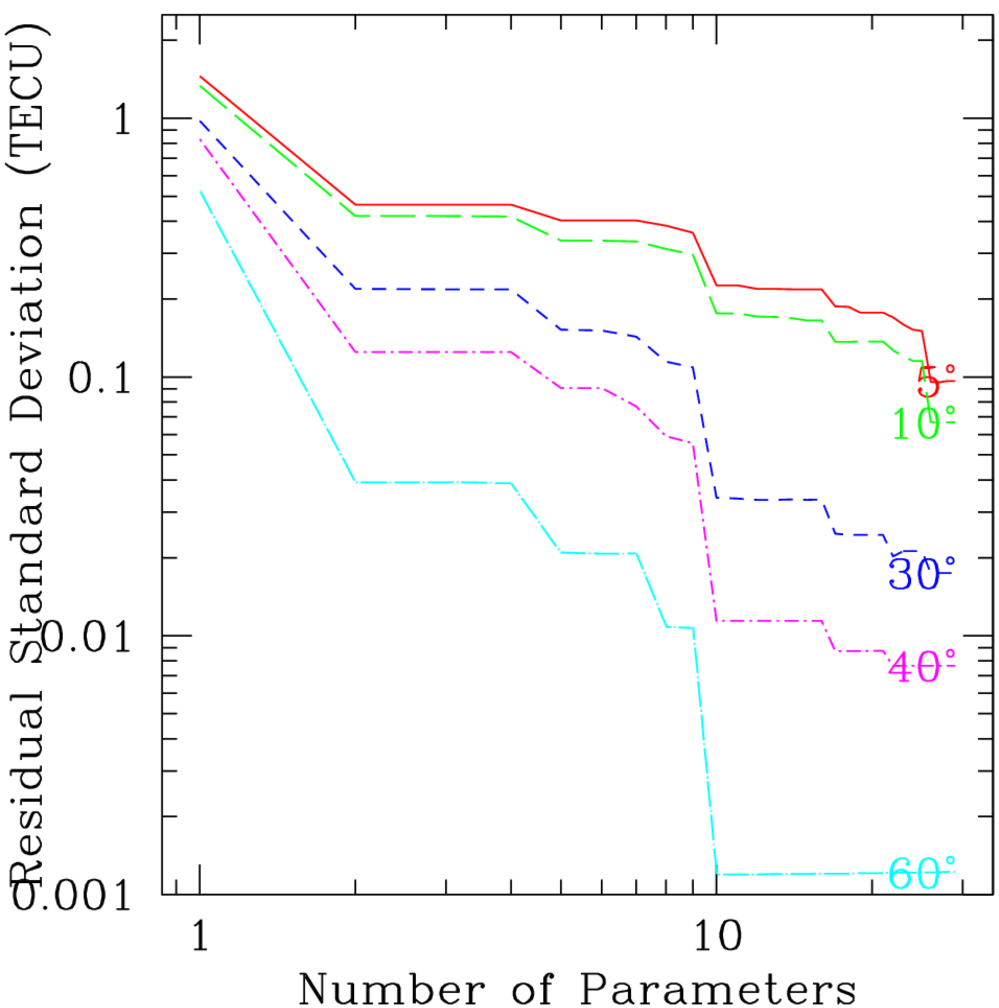
MIM Similar to Existing Procedures

The description of MIM is similar to models already being produced by the ionospheric community. An example from the GPSTk package (http://gpstk.sourceforge.net/index.html, see Tolman et al. 2004) is shown here. A polynomial fit is made to the vertical TEC value of the ionosphere above North America.



Testing the Limits of MIM: Accuracy

MIM can only be useful to astronomers if it can accurately model the ionosphere. Here is a plot showing the RMS residuals from a fit to synthetic ionospheric data above the European region. The synthetic data were generated from integrations along the line of sight to about 1000 sources



randomly distributed on the sky through a 3D ionosphere. As the number of parameters is increased, the residual level decreases. The different curves indicate elevation limits below which data-points are ignored.

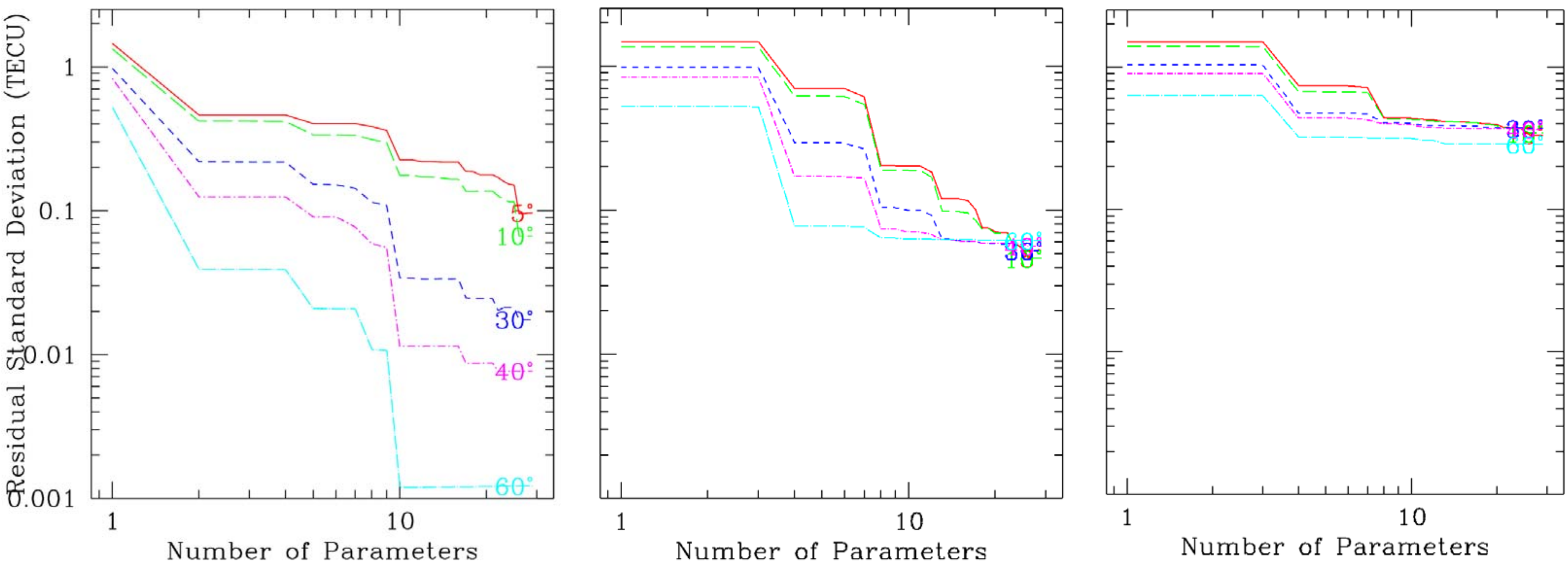
L-band measurements require an accuracy of at least 0.05 TECU, while LOFAR will probably require an accuracy of at least 0.001 TECU.

Testing MIM: Station Location

MIM assumes a 2D ionosphere. This appears to work well for data from stations taken close to one another. However, as the distance between ground stations is increased, the RMS levels of the MIM fits increase.

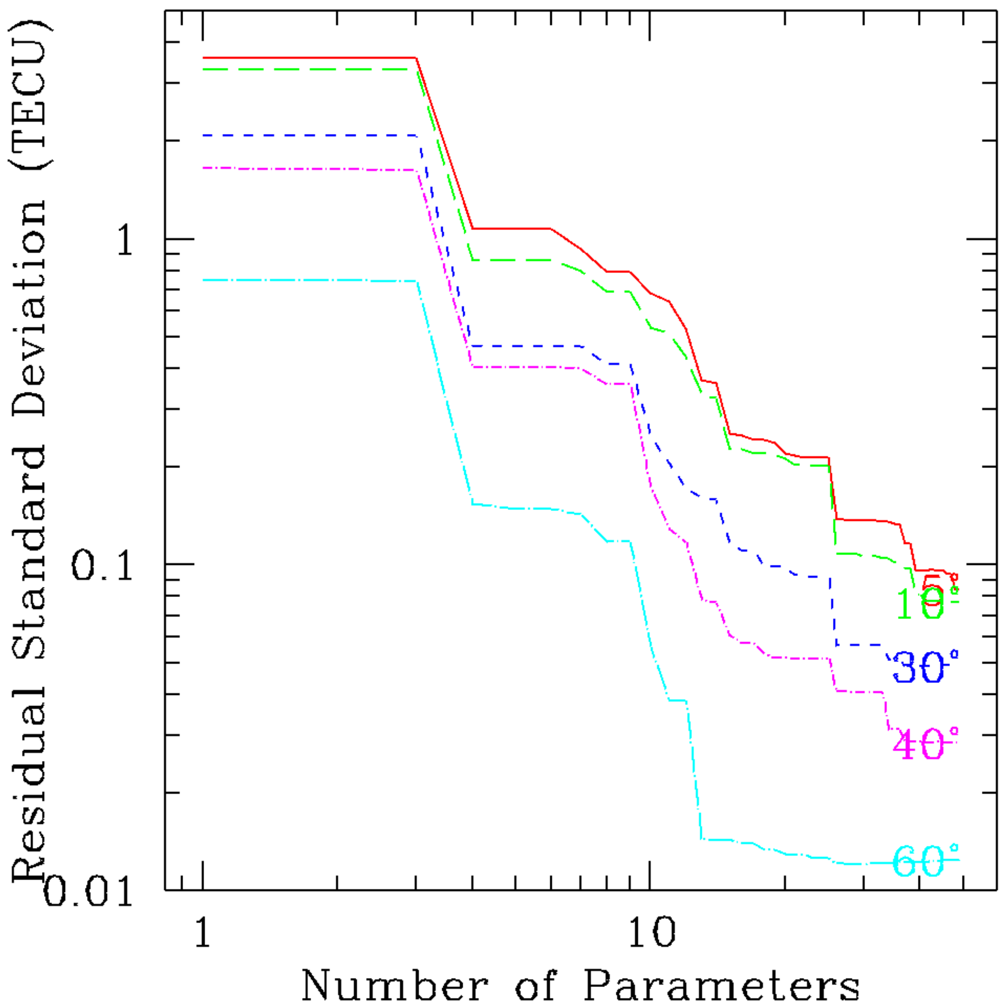
Maximum Station Distance:

1 km | 50 km | 1000 km



Testing MIM with PIM

The MIM tests presented above were performed using a realistic, but simple, 3D model integration. We have also tested MIM using the Parameterized Ionospheric Model (PIM). The figure below shows the results for stations located within 1 km of a central telescope. The results are similar for models including measurements at low elevations. But the residual RMS level for high-elevation observations is degraded. We believe that this is probably a result of the limited precision in the PIM software implementation of the numerical integration, rather than a failure of the MIM model with a more complicated synthetic model.



Conclusions

- GPS-based ionosphere models with course grid resolutions (IONEX, FusionNumerics) still produce jitter in slant TEC predictions at levels much higher than acceptable for L-band calibration of the EVN, but are better than nothing.
- Formula-based models such as PIM and IRI are smooth enough for L-band calibration, but are not accurate enough for LOFAR.
- All of these models are unable to track short-term variations such as TIDs.
- MIM may be a promising method to calibrate the ionosphere for LOFAR, with about 10 parameters necessary to describe the ionosphere.
- There are too few GPS stations located within 50 km of individual EVN stations to be able to use MIM. (There are too few GPS satellites available above the horizon.)

Future Work

- A full analysis of the EVN test observations from 2005 June will be made starting next month.
- For phase referencing, relative differences are the most important, and the coherence after phase referencing will be measured.
- Improvements to the MIM model are possible. It should be possible to improve the performance at low elevations and moderate distances between ground stations.