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Simulation of the Effects of the Low Latitude Ionosphere on the Performance of a Satellite-Based Augmentation System

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Outline

- Introduction – Objectives
- Description of the RBMC/IBGE data
- Description of the Simulation
- Results and Discussion
- Conclusion

Introduction

- Ionospheric effects exhibit extreme variability in space and time, significantly degrading the performance of a Space-Based Augmentation System (SBAS).
- This is particularly true at equatorial anomaly latitudes, where intense gradients in the vertical TEC (total electron content), plasma bubbles and scintillation can be observed, depending on the existing geophysical conditions.
- Brazil is one of the countries in the world that may be affected by both crests of the equatorial anomaly. Therefore, designing a SBAS to serve its large area will be a challenging task and planners would benefit from the availability of simulation tools.

Objectives

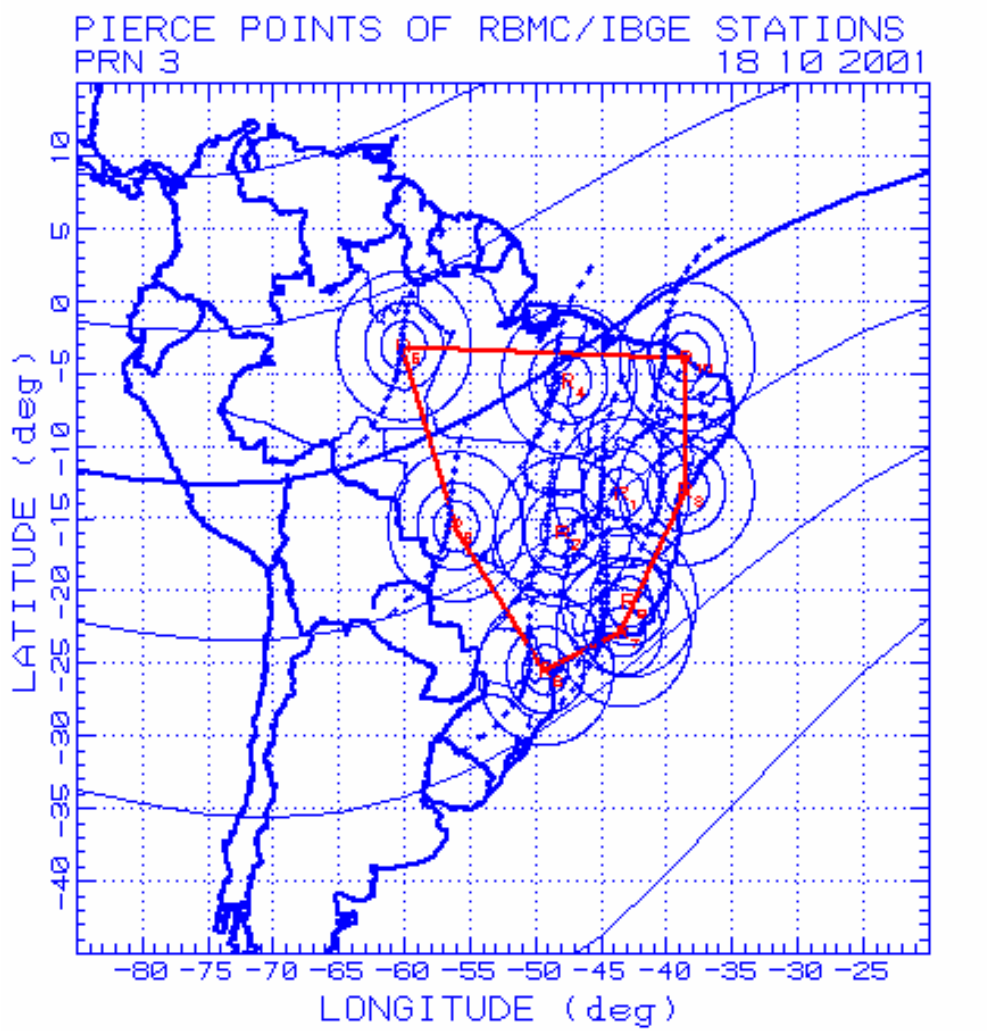
- To describe a simulation model of the effects of the equatorial anomaly and of plasma bubbles on the performance of a SBAS in the Brazilian sector and present corresponding results. This model couples:
  - sTEC data, measured by the Rede Brasileira de Monitoramento Contínuo (RBMC) of the Instituto Brasileiro de Geografia e Estatística (IBGE);
  - the Parameterized Ionospheric Model (PIM 1.7) [Daniell et al., **Radio Science**, **30**(5), 1499-1500, 1995], driven by realistic input values;
  - orbital dynamics model for the actual Global Positioning System (GPS) constellation of satellites based on SP3 data;
  - a model of SBAS based on the procedures in the WAAS Minimum Operational Performance Standard (MOPS) Document [RTCA/DO-229], with modifications.

Description of the simulation (orbital dynamics)

- Positions of 28 satellites in actual GPS constellation in ECEF coordinates (x, y, z) provided by linear interpolation of individual components based on SP3 data (http://www.ngs.noaa.gov/GPS/GPS.html);
- Positions assumed to be exact.

Description of the simulation (low-latitude ionospheric model)

- Using RBMC data, the model provides, at each simulation step:
  - sTEC along paths from PRNs to ground-based reference stations and users inside the convex envelope;
  - vTEC at vertices of rectangular 5º x 5º latitude/longitude grid (IGPs) inside the convex envelope.

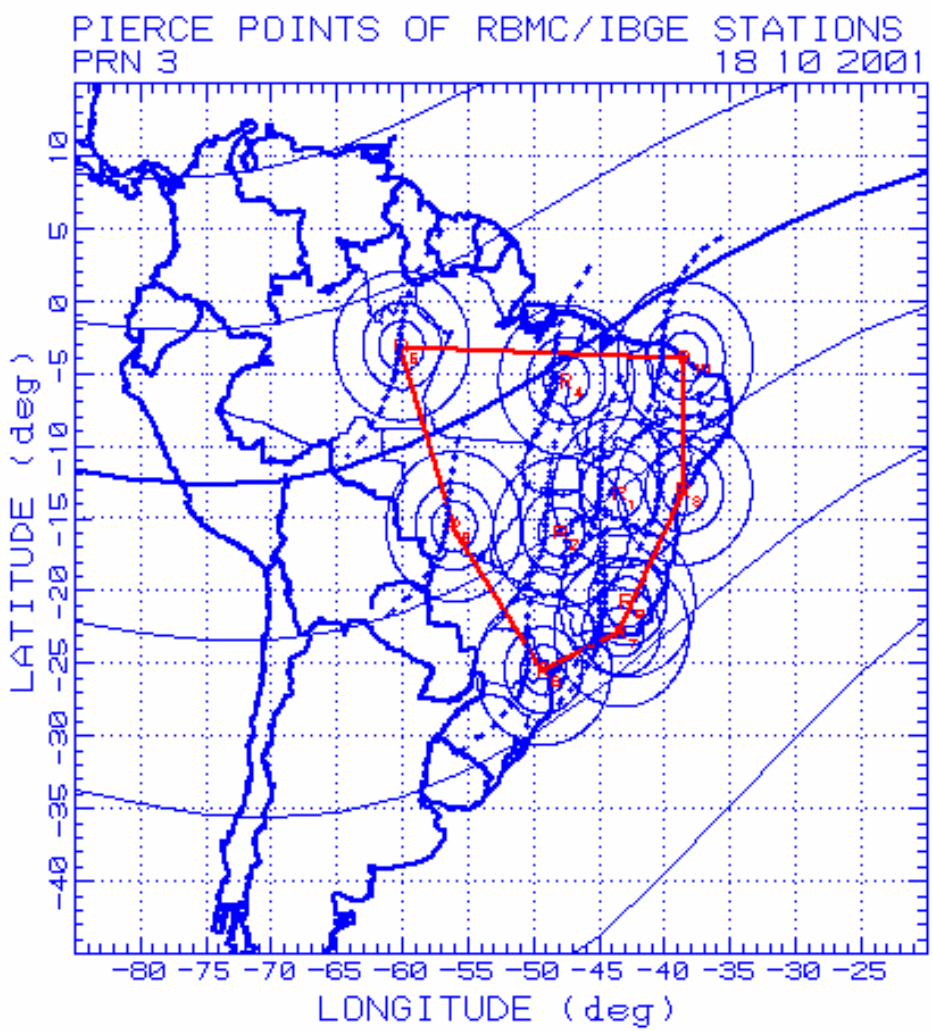


Description of the simulation (low-latitude ionospheric model)

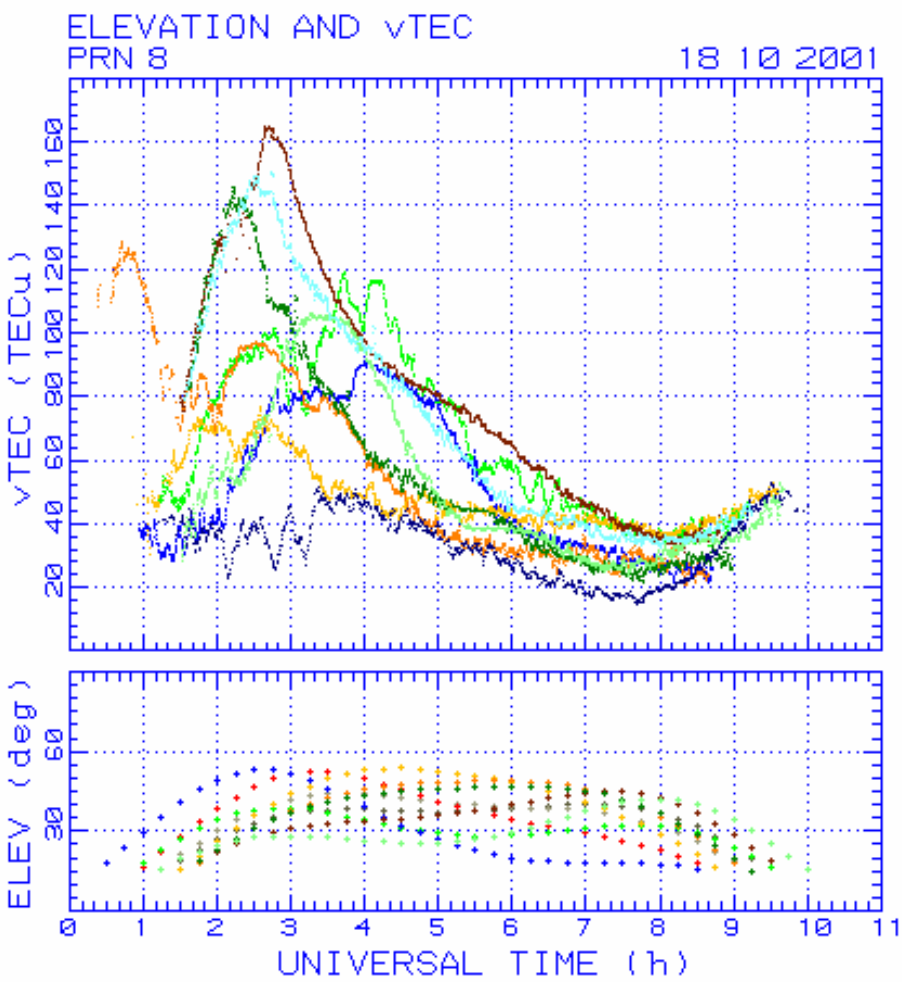
- Interpolation:

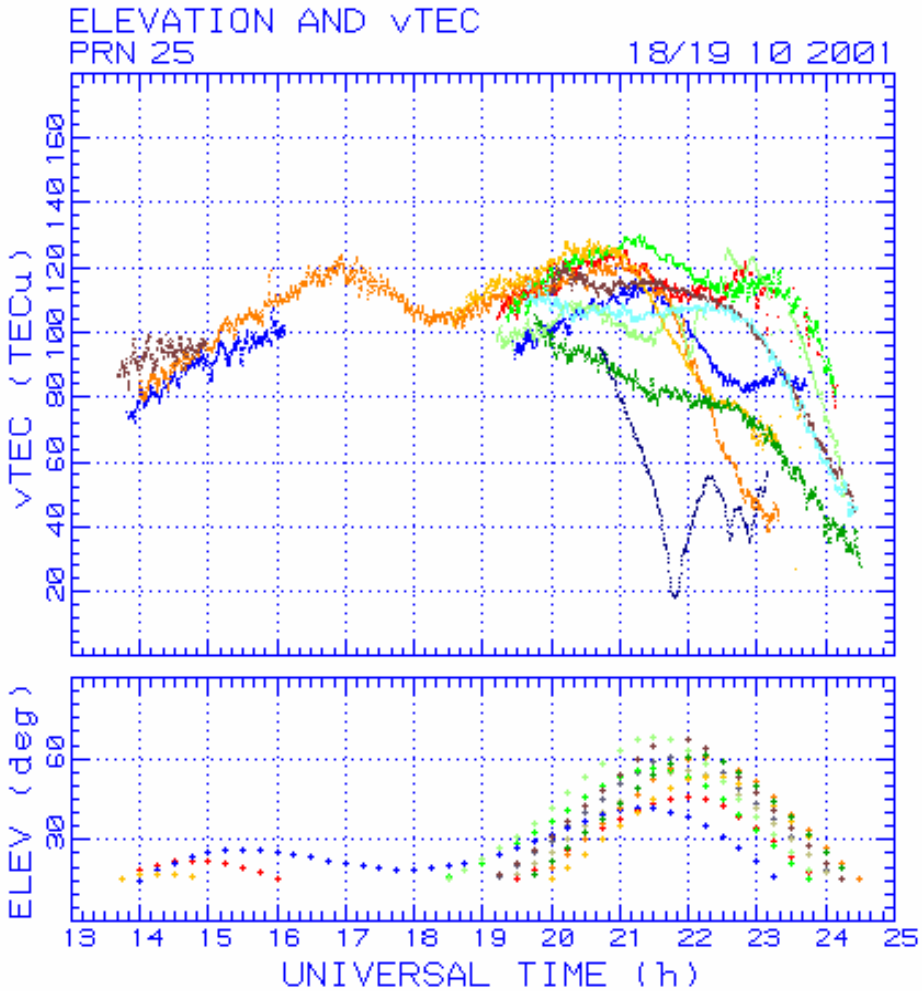
$$sTEC = \frac{\sum_{i=1}^{N_{RBMC}} (sTEC_i / d_i)}{\sum_{i=1}^{N_{RBMC}} (1/d_i)}$$

where d_i is the distance from RBMC station i to reference station, user, or IGP.

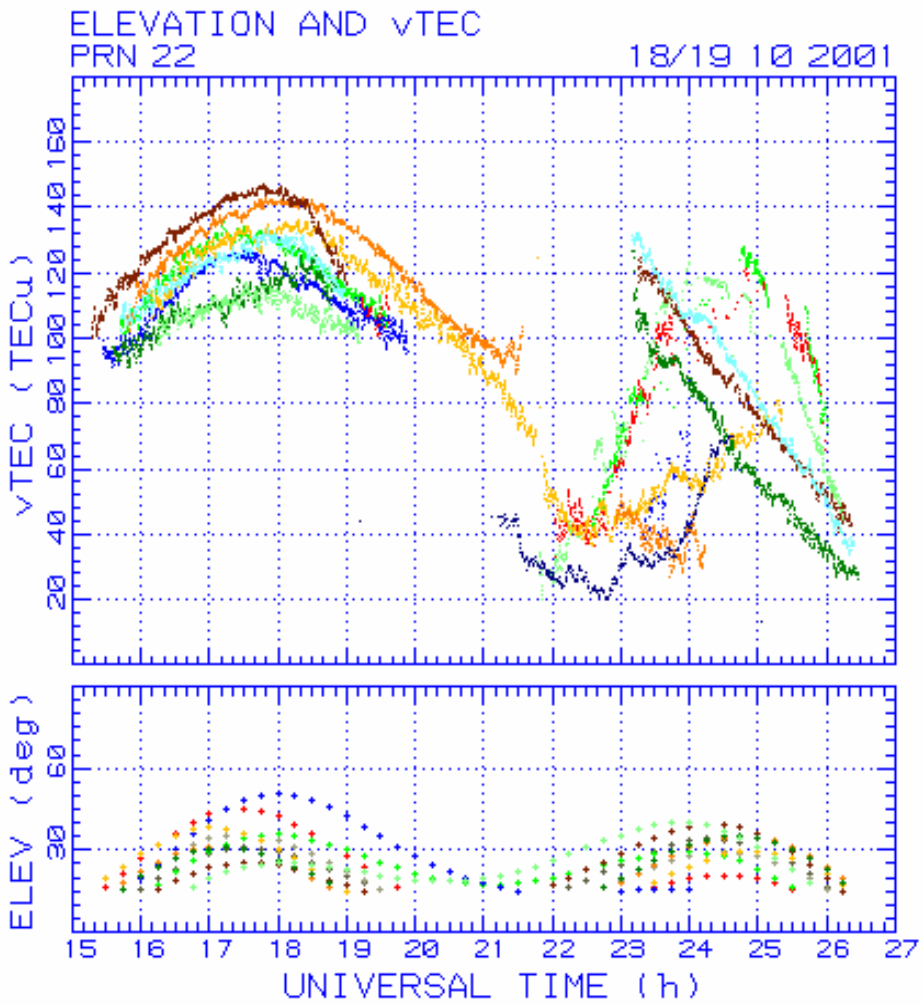


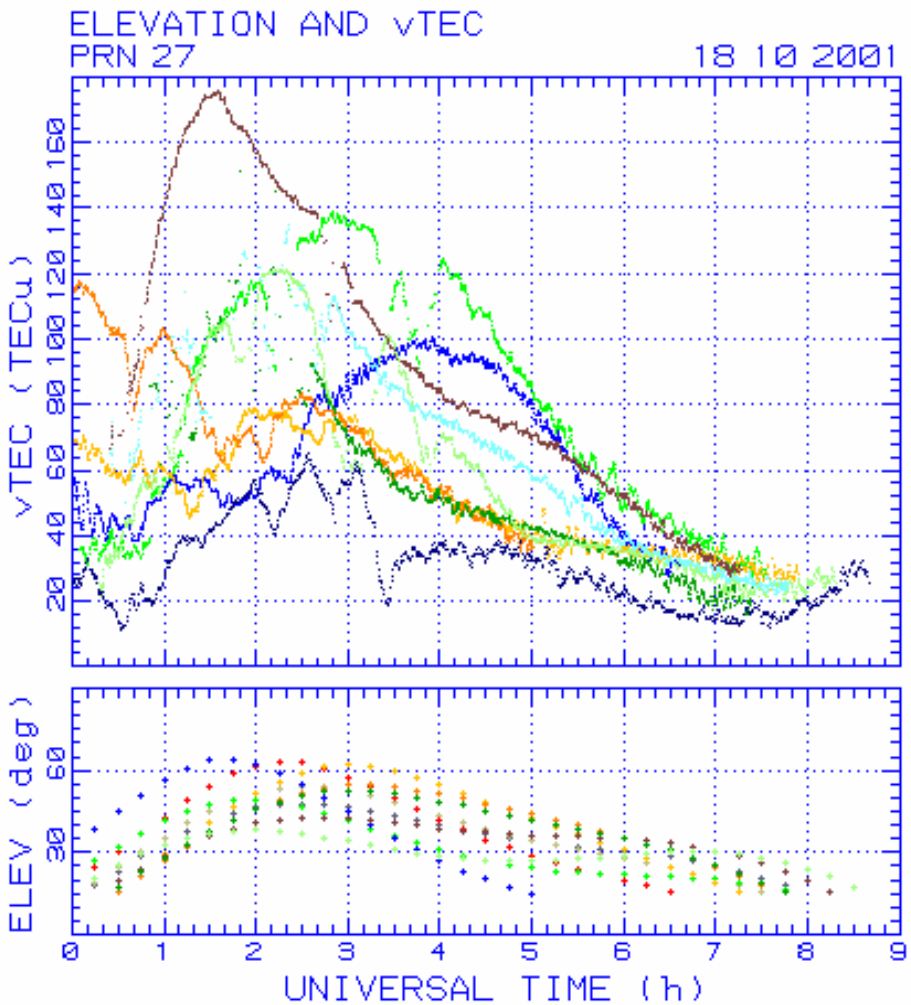
Description of the simulation (low-latitude ionospheric model)





Description of the simulation (low-latitude ionospheric model)

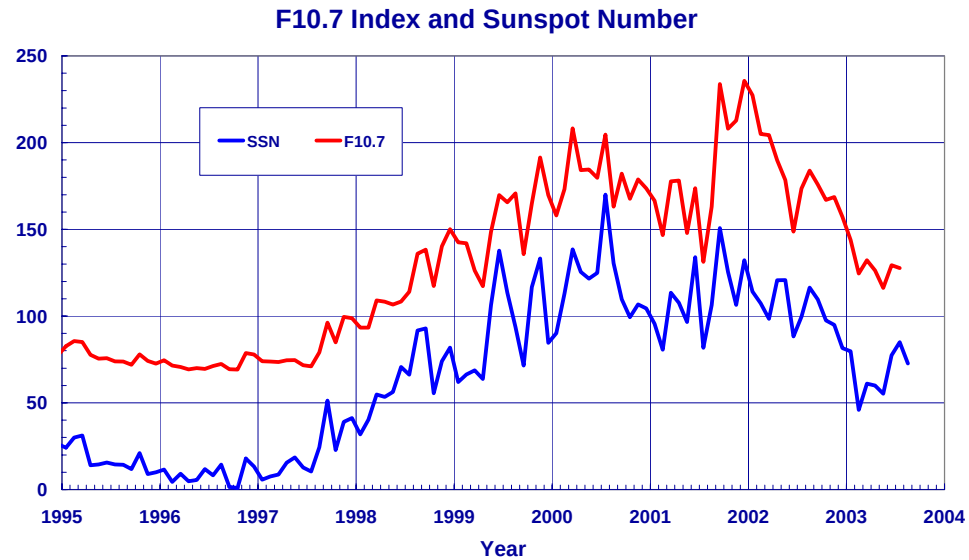


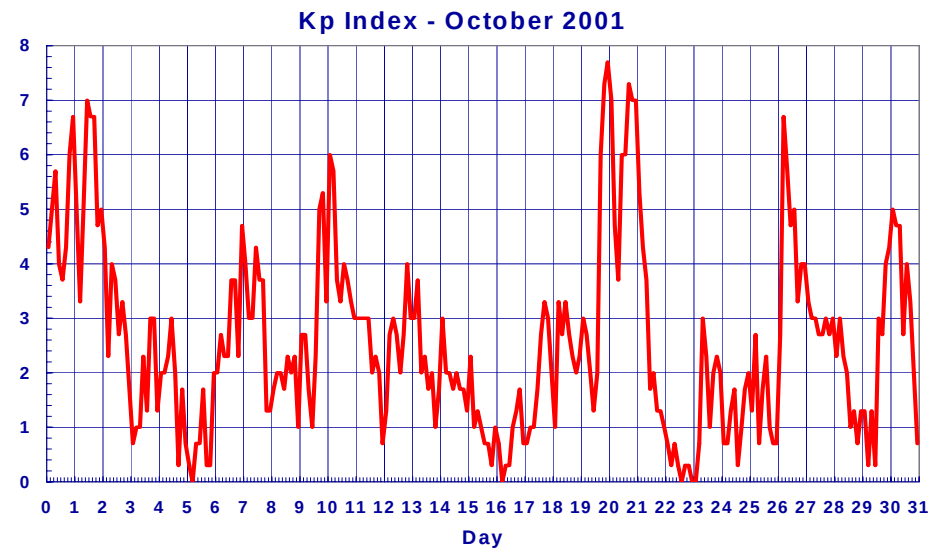


Description of the simulation (low-latitude ionospheric model)

- As a backup for RBMC, PIM 1.7 provides, at each step:
  - sTEC along specified azimuth and elevation from ground-based reference stations and users
  - vTEC at rectangular 5º x 5º latitude/longitude grid

considering solar and magnetic activity indices F10.7 (27-day running mean) and Kp (3-hour values).

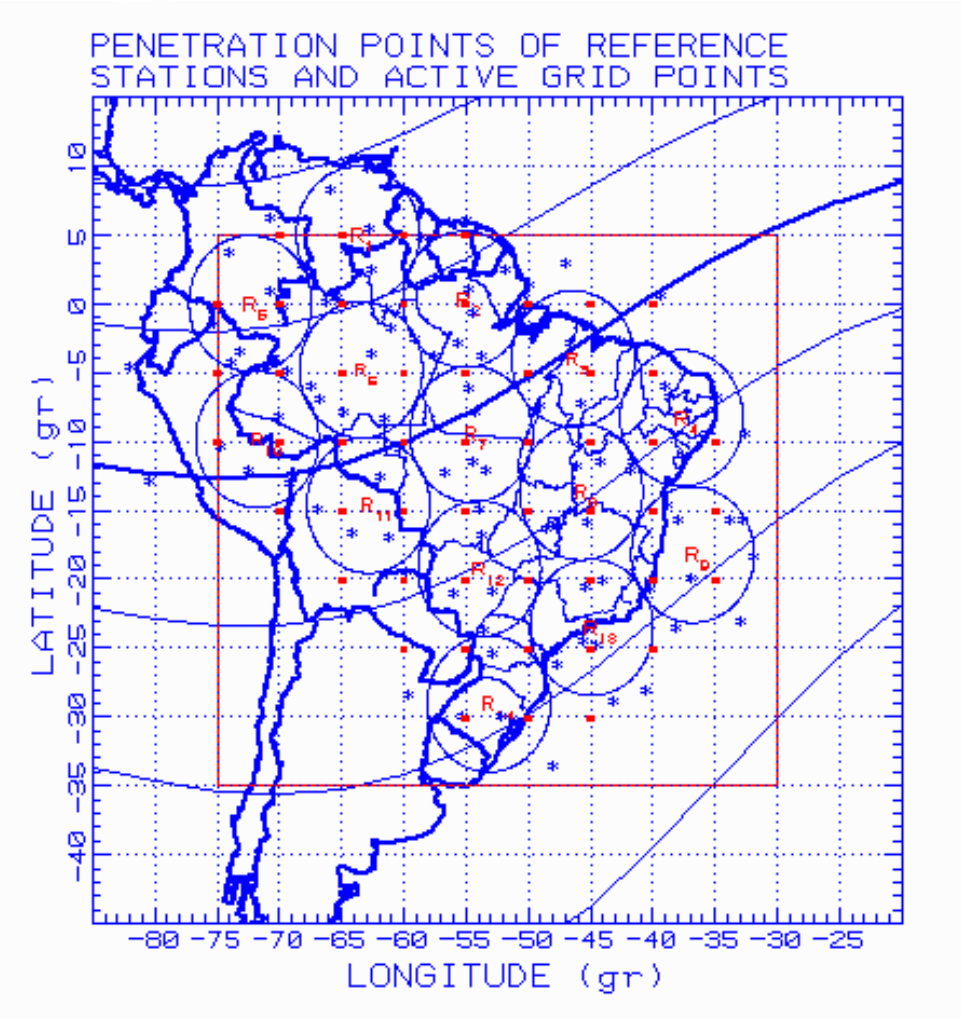


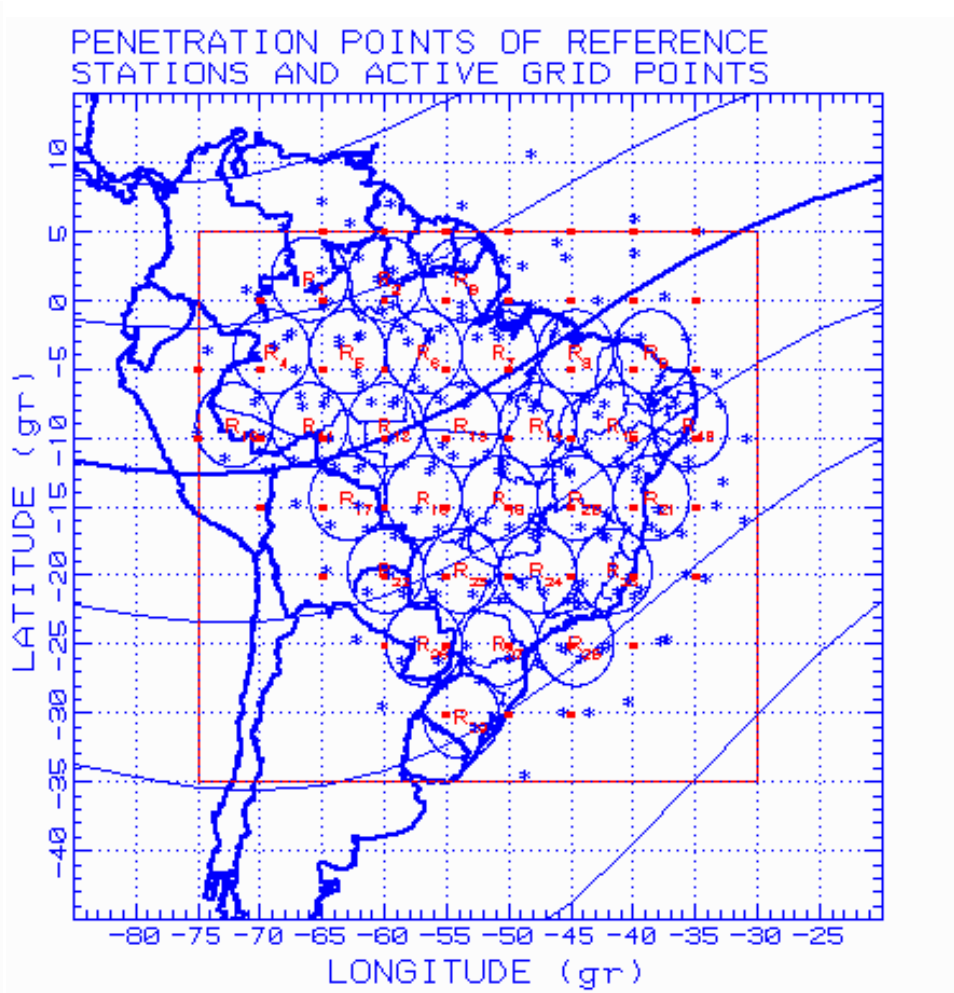


Description of the simulation (low-latitude ionospheric model)

- RBMC considers the effects of the equatorial anomaly and of plasma bubbles on TEC;
- PIM 1.7 considers the effects of the equatorial anomaly on TEC;
- TEC values provided by RBMC or PIM 1.7 assumed to be exact;
- Inside the convex envelope of the RBMC stations, RBMC data and PIM used in 1/3 and 2/3 of the cases, respectively.

Description of the simulation (SBAS)

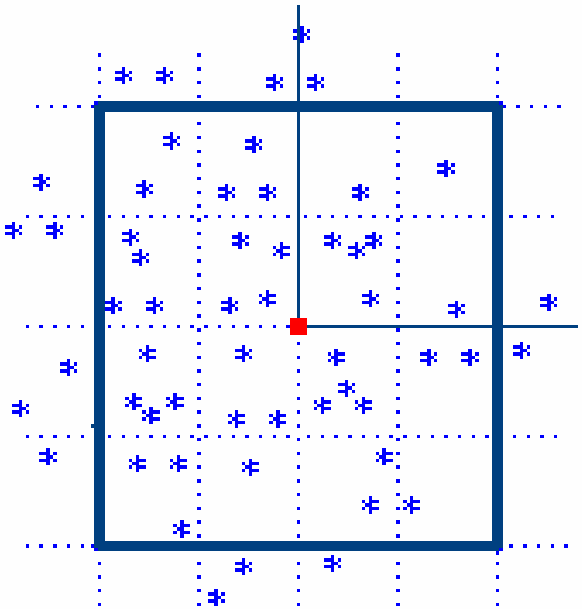




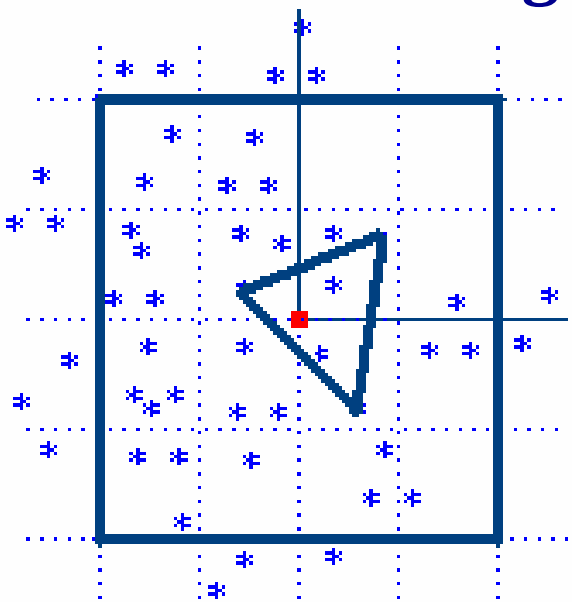
Description of the simulation (SBAS)

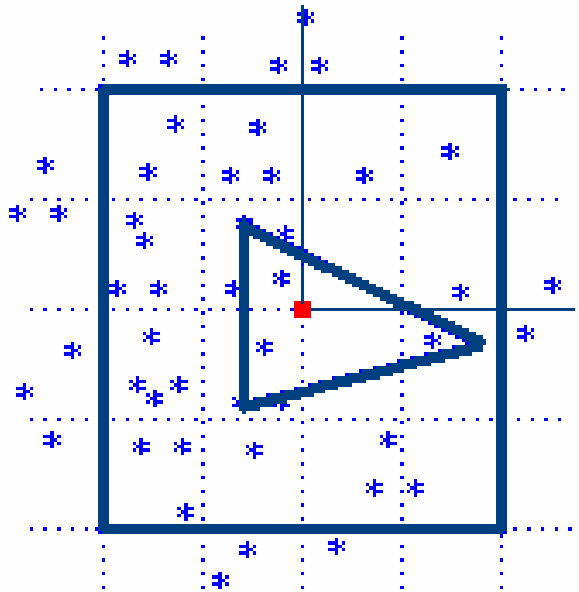
- sTEC at each reference station IPP mapped into vTEC;
- Set of vTEC values at these IPPs used to estimate vTEC values at IGPs according to two interpolation schemes.

Planar Fit



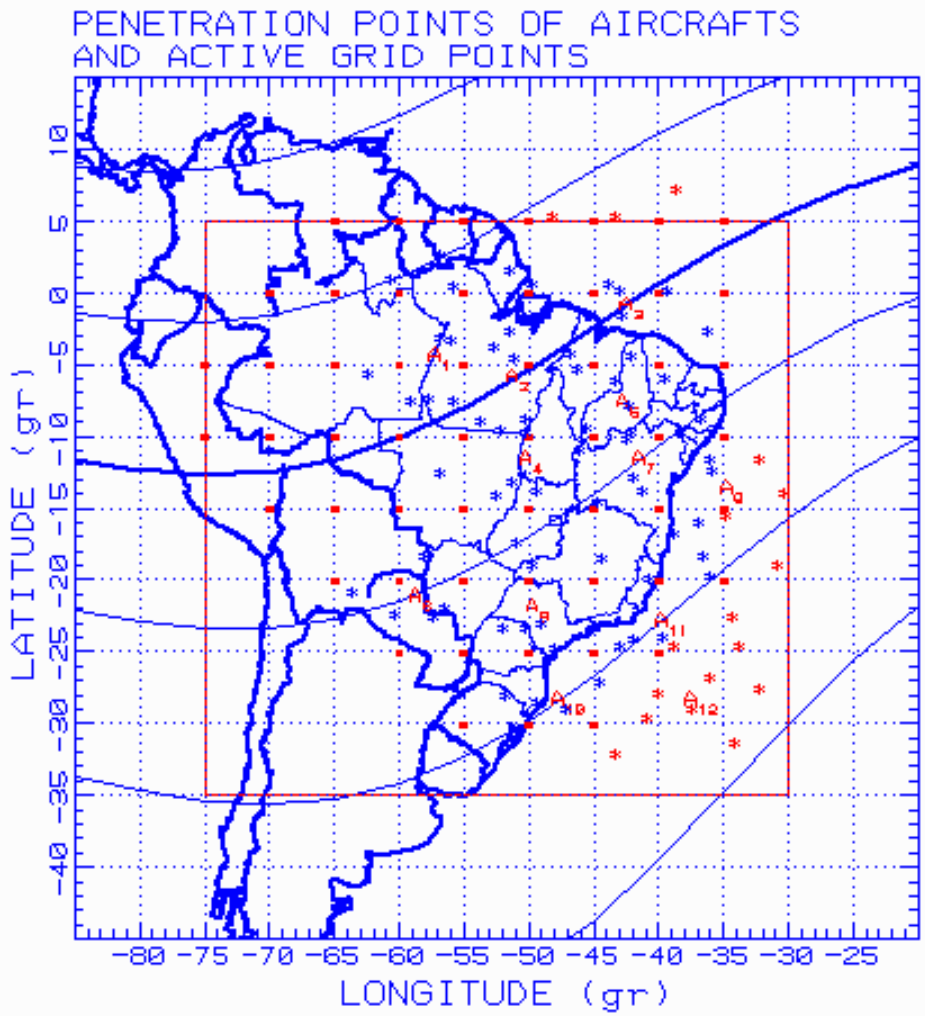
Triangular Fit





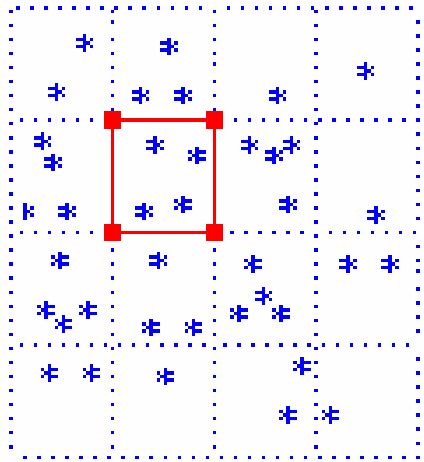
Description of the simulation (SBAS)

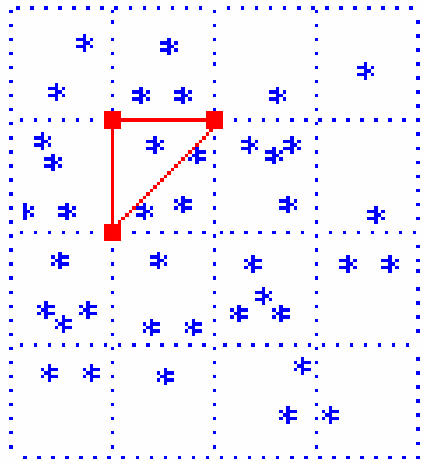
- vTEC values at IGPs also directly obtained by ionospheric model (RBMC/PIM);
- Statistics of error ($vTEC_{dir}$-$vTEC_{int}$) for each IGP and each interpolation scheme.

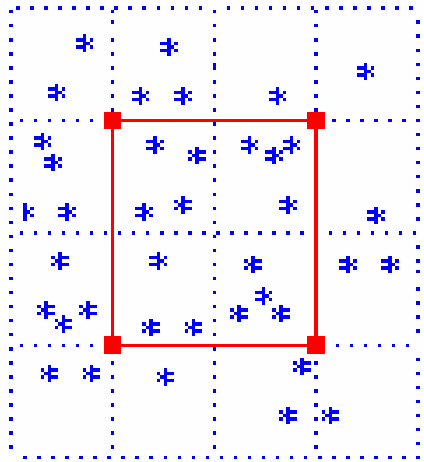


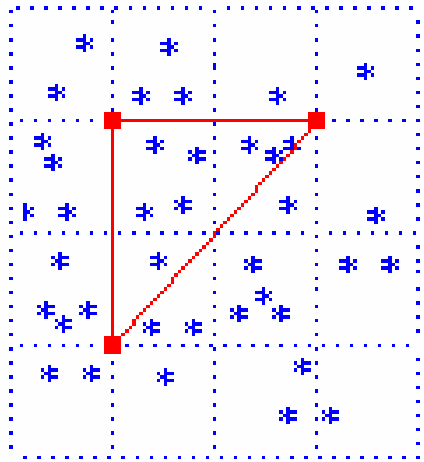
Description of the simulation (SBAS)

- Set of vTEC values at IGPs employed to estimate vTEC values at user IPPs with basis on interpolation schemes in WAAS MOPS Document [RTCA/DO-229];
- vTEC values at these IPPs mapped into user sTEC;
- sTEC values at these IPPs also from RBMC/PIM.





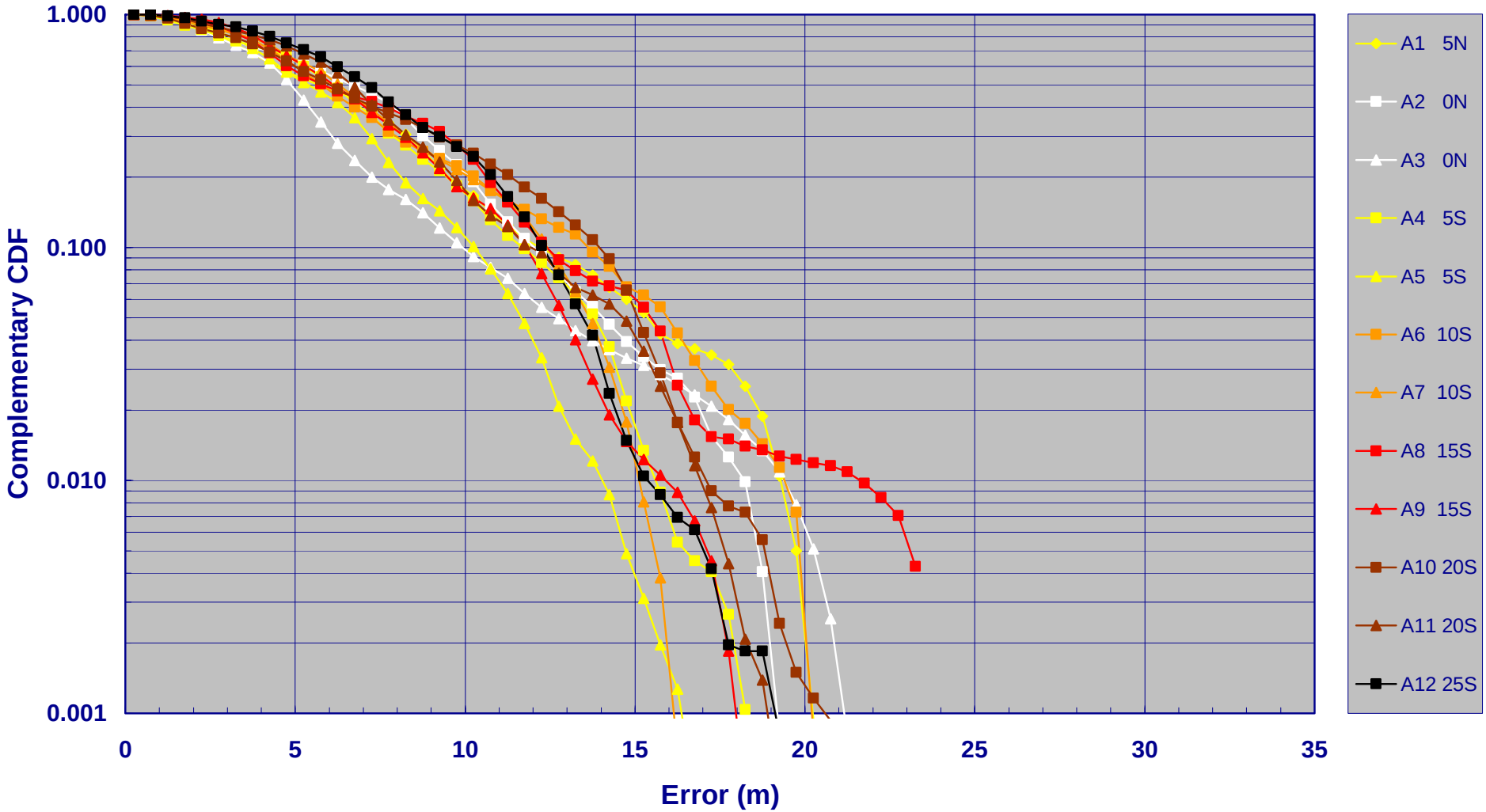




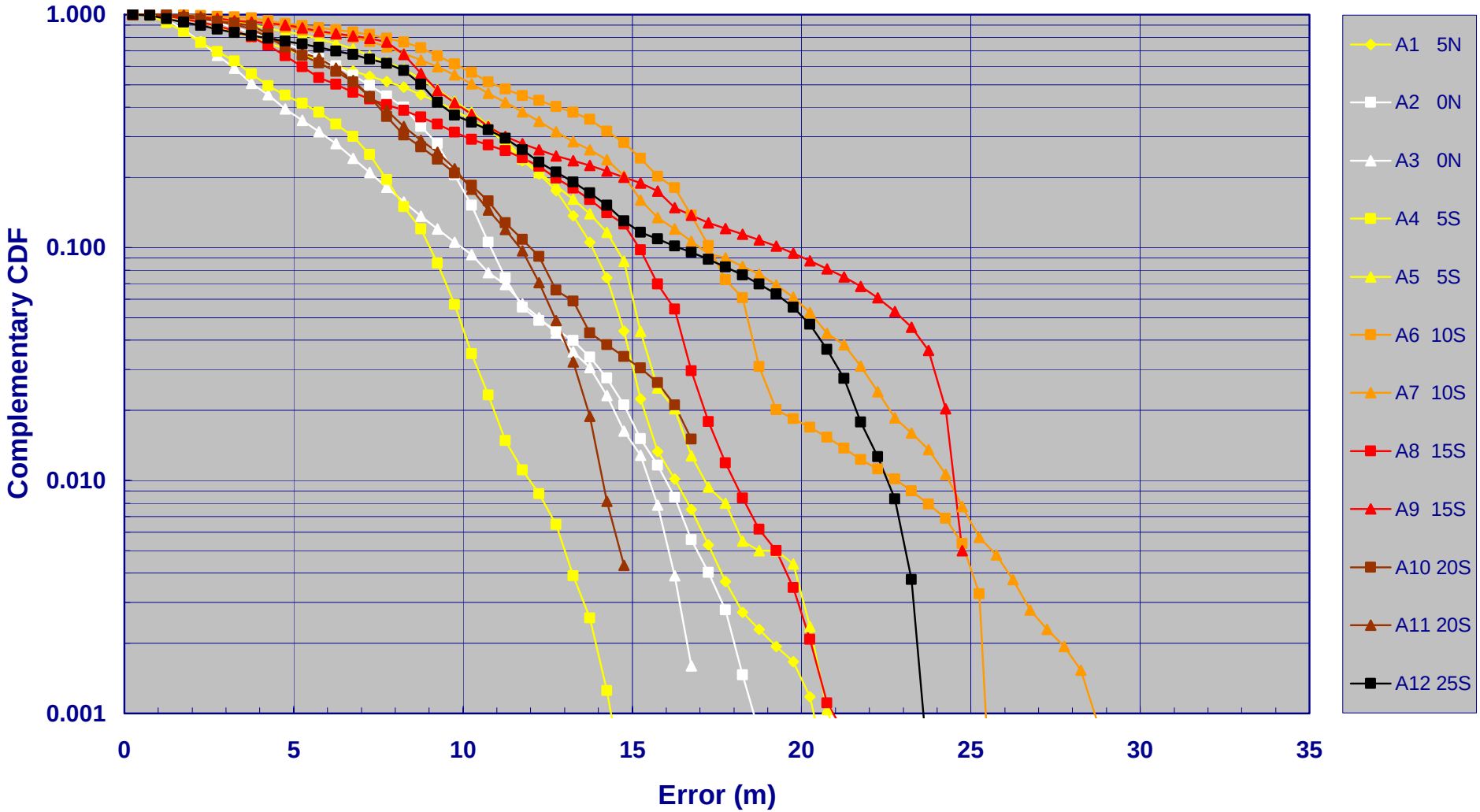
Description of the simulation

- Simulation restricted to days 18 to 27 October, 2001 (10 days under equinoctial and solar maximum conditions) with 1-min increments in time (total of 14400 steps), but with vTEC at IGPs updated only at every 3 minutes (approximate time interval between consecutive WAAS message updates);
- Reference to previous results, corresponding to January 2002 (30 days under summer and solar maximum conditions), using PIM alone.

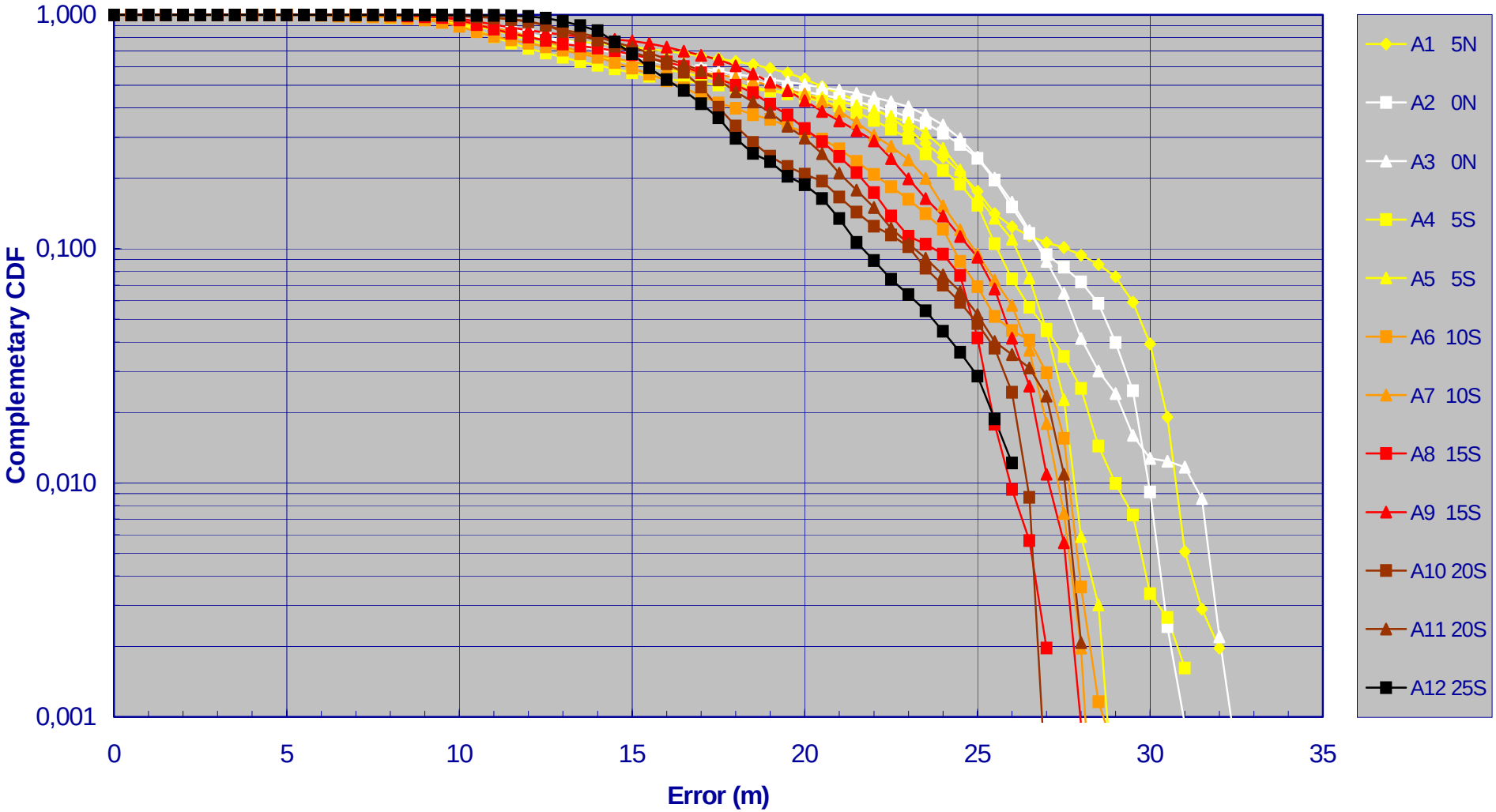
User Horizontal Error – GPS alone (Jan 2002 – PIM)



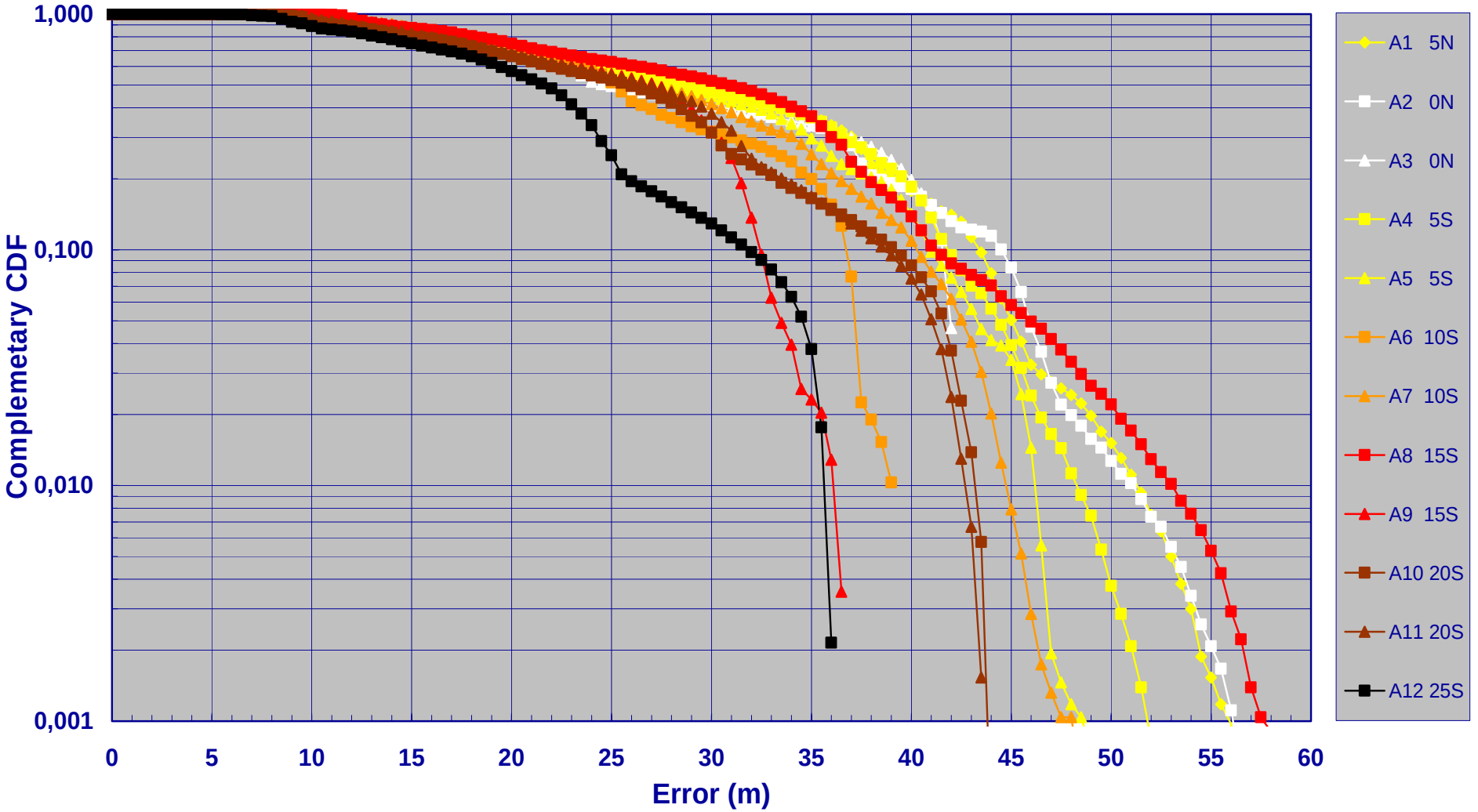
User Horizontal Error – GPS alone (Oct 2001 – RBMC/PIM)



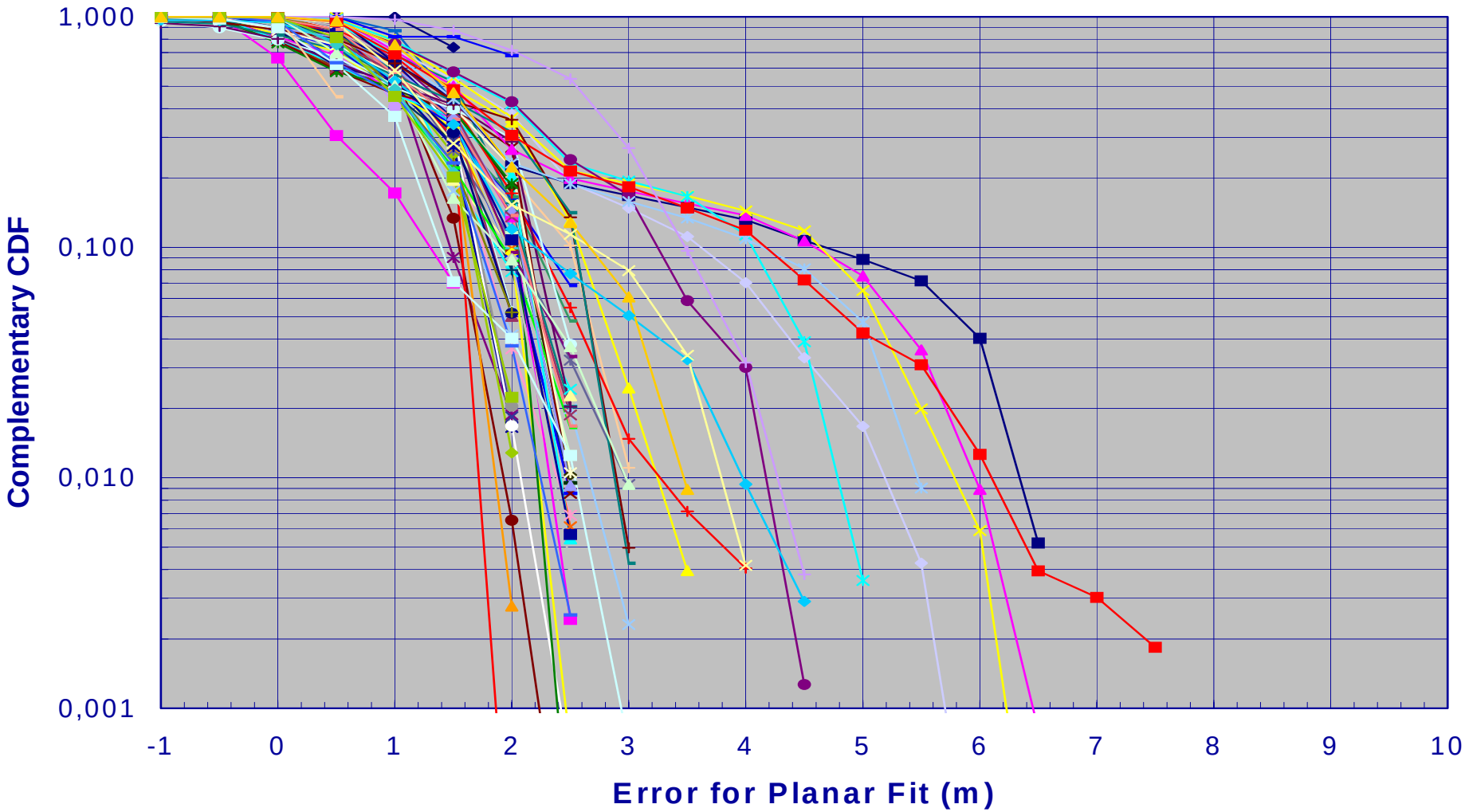
User Vertical Error – GPS alone (Jan 2002 – PIM)



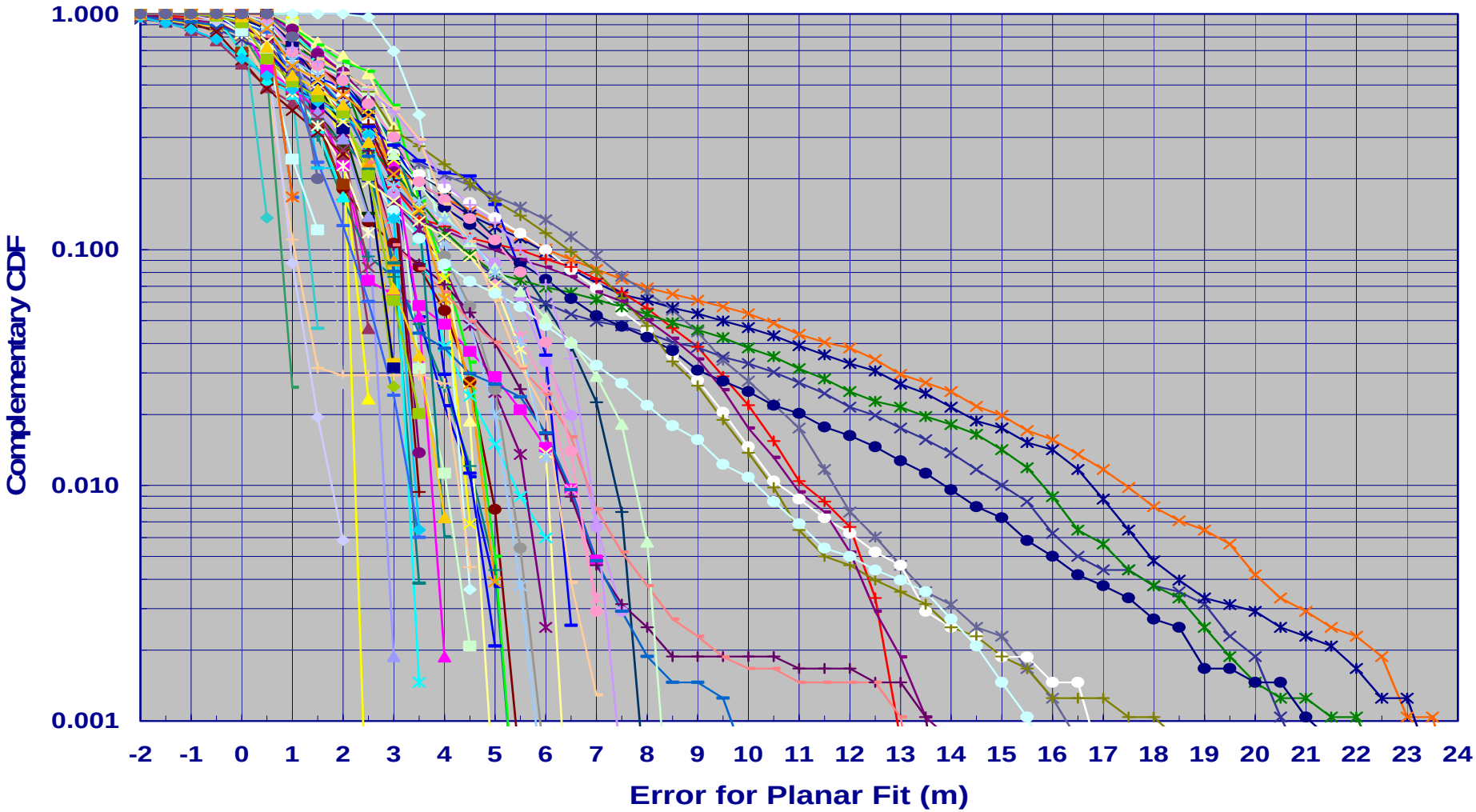
User Vertical Error – GPS alone (Oct 2001 – RBMC/PIM)



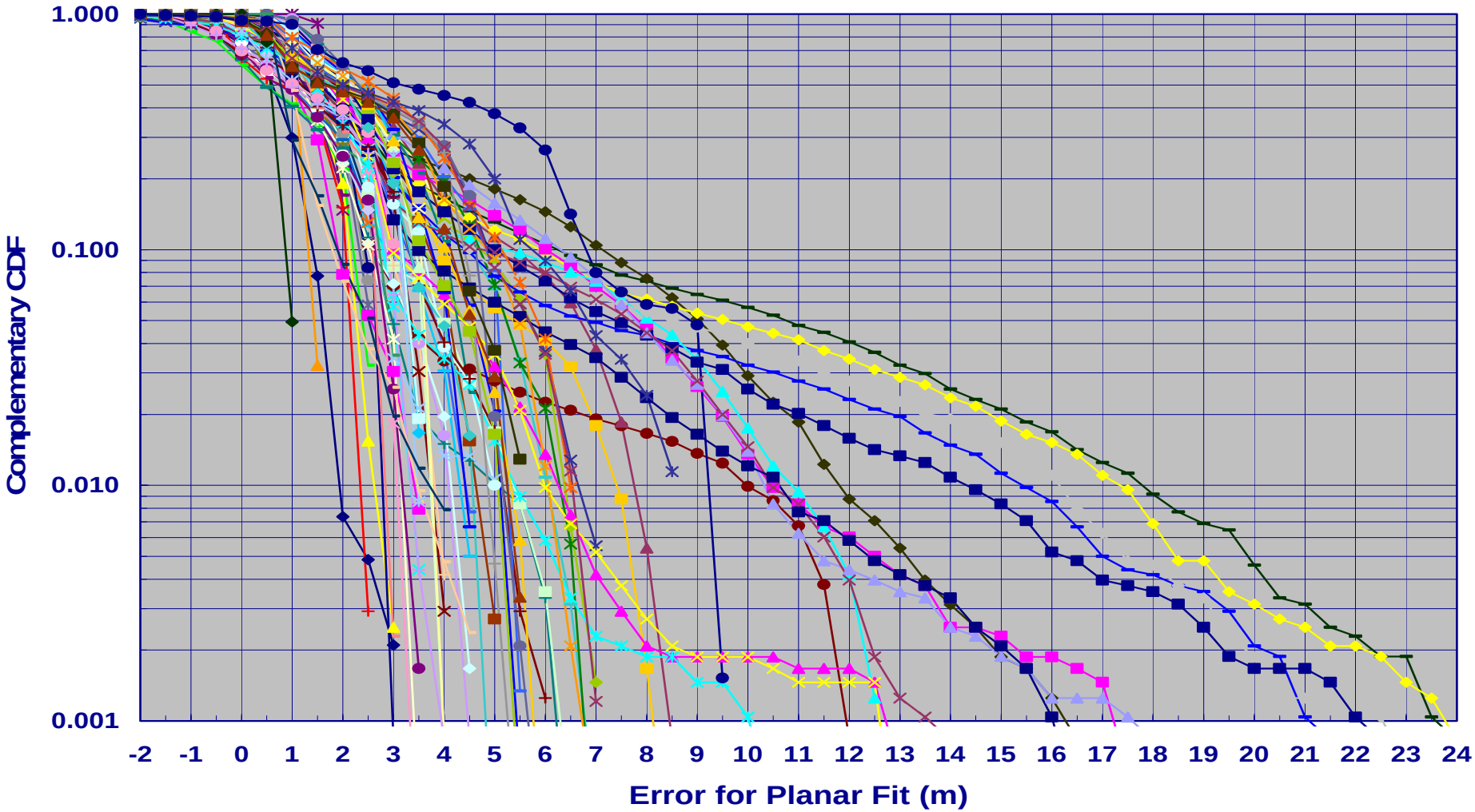
Error in vTEC at Grid Points – 14 Ref. Stations (Jan 2002, PIM)



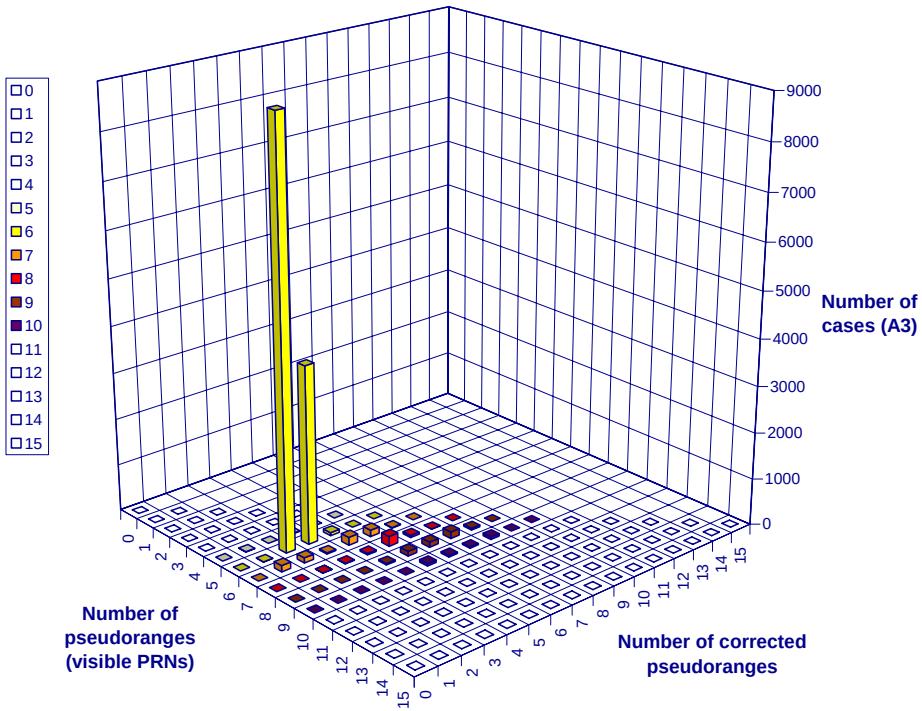
Error in vTEC at Grid Points – 14 Ref. Stations (Oct 2001, RBMC/PIM)

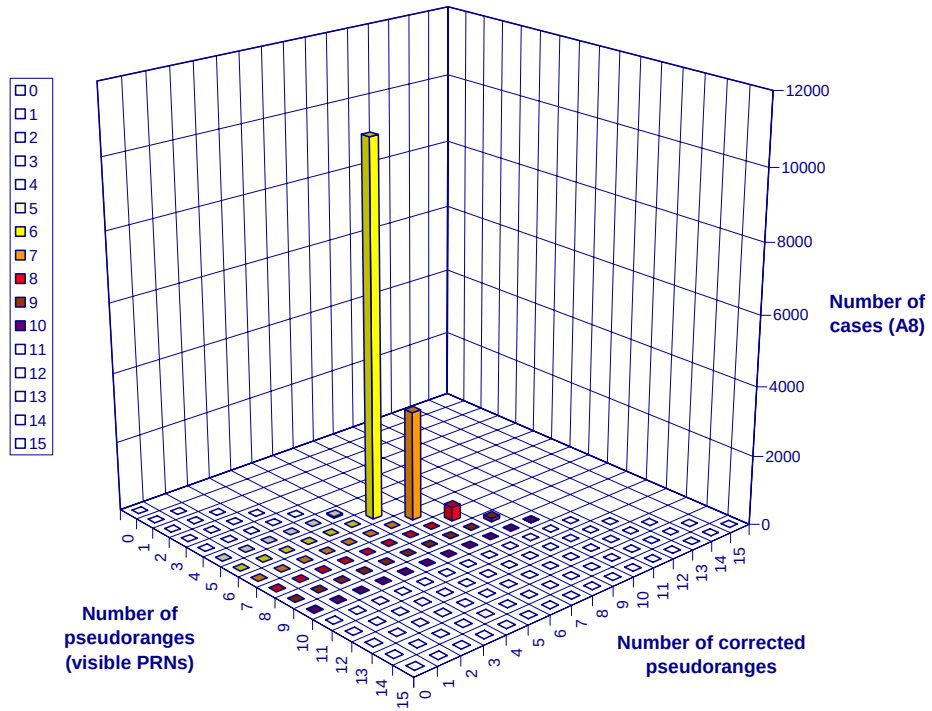


Error in vTEC at Grid Points – 29 Ref. Stations (Oct 2001, RBMC/PIM)



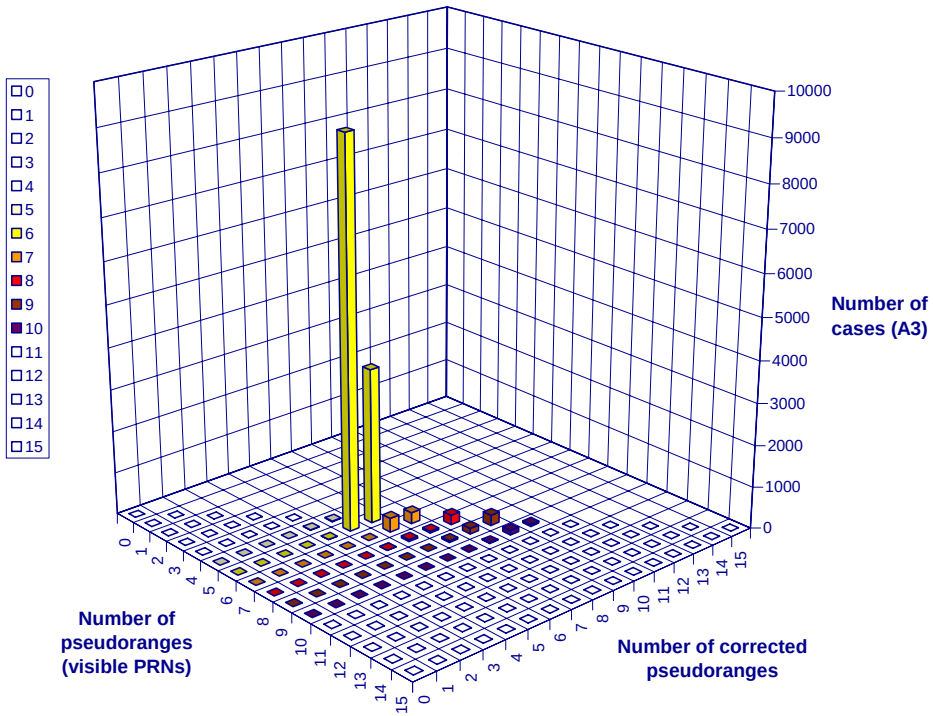
Distributions of number of pseudoranges and number of corrected pseudoranges

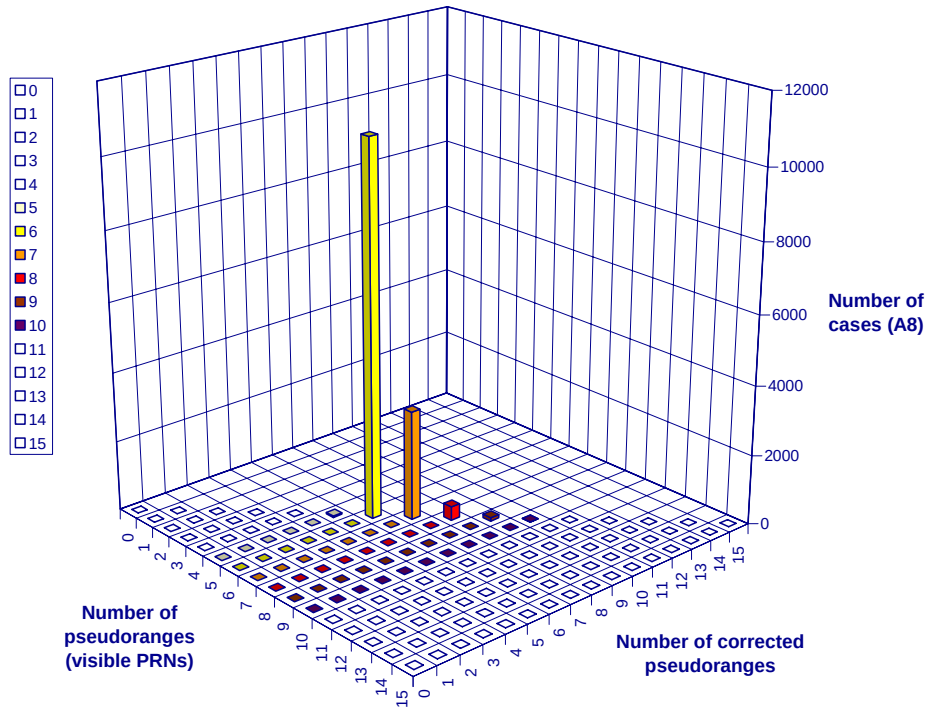




14 Reference Stations (Planar Fit, Oct 2001, RBMC/PIM)

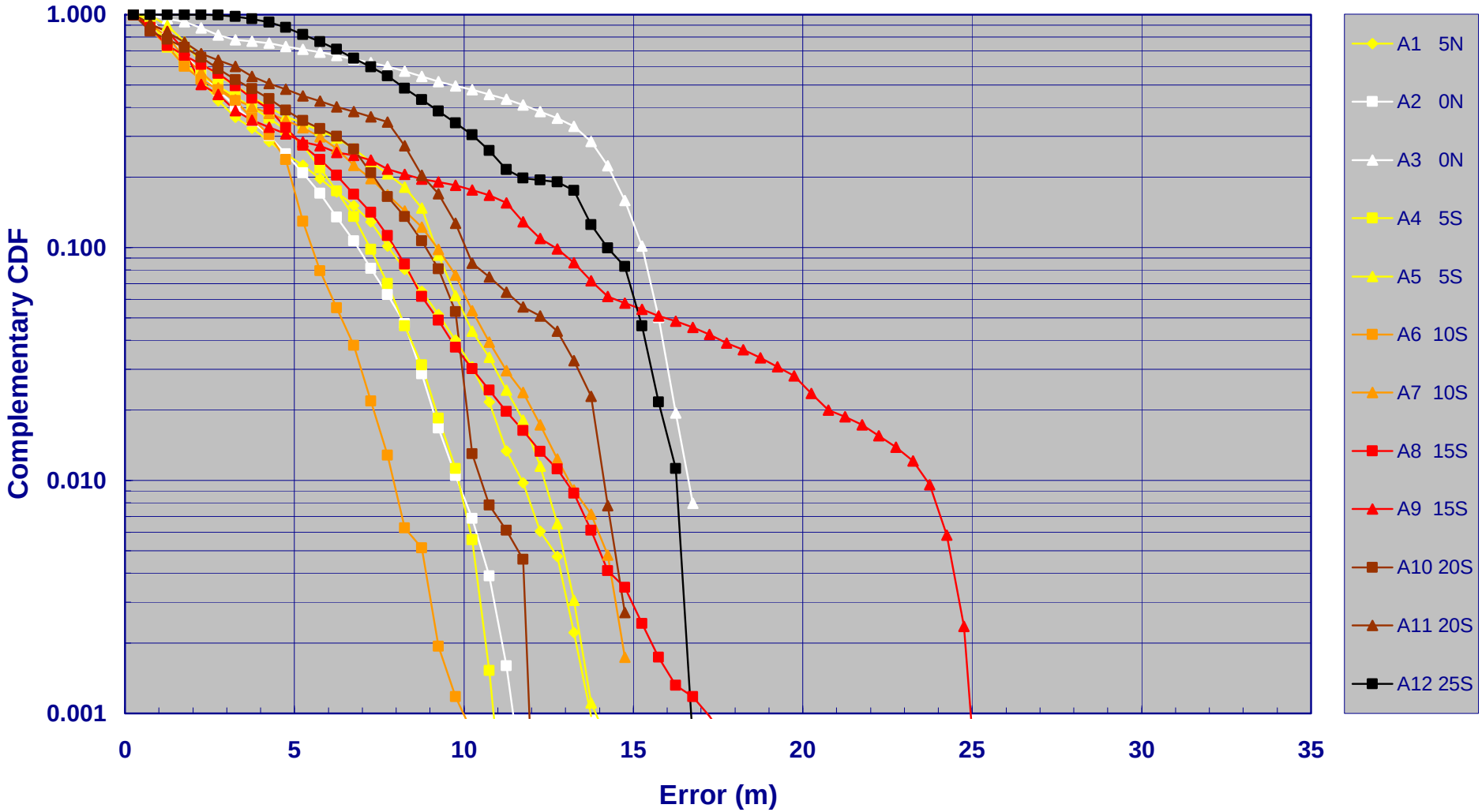
Distributions of number of pseudoranges and number of corrected pseudoranges



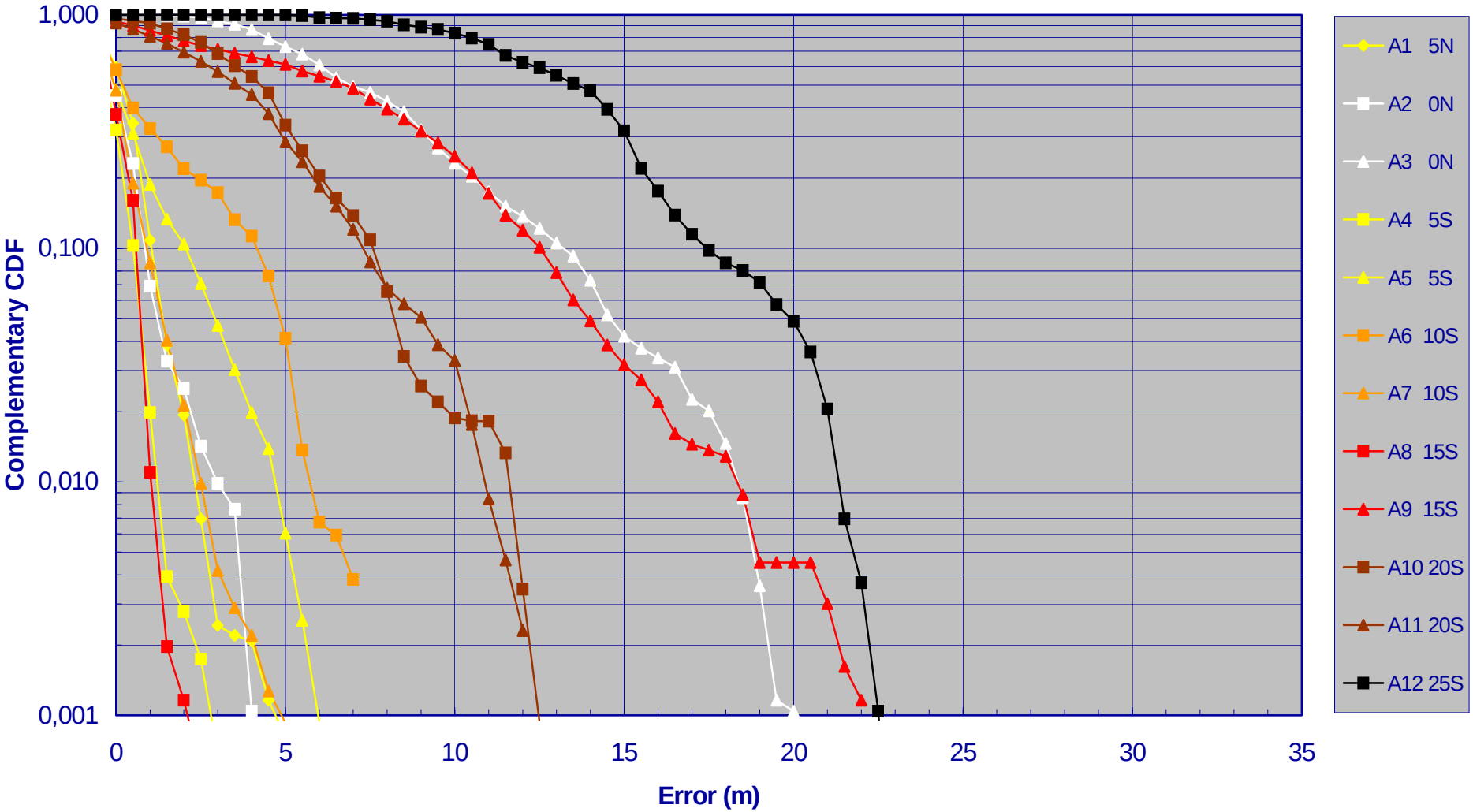


29 Reference Stations (Planar Fit, Oct 2001, RBMC/PIM)

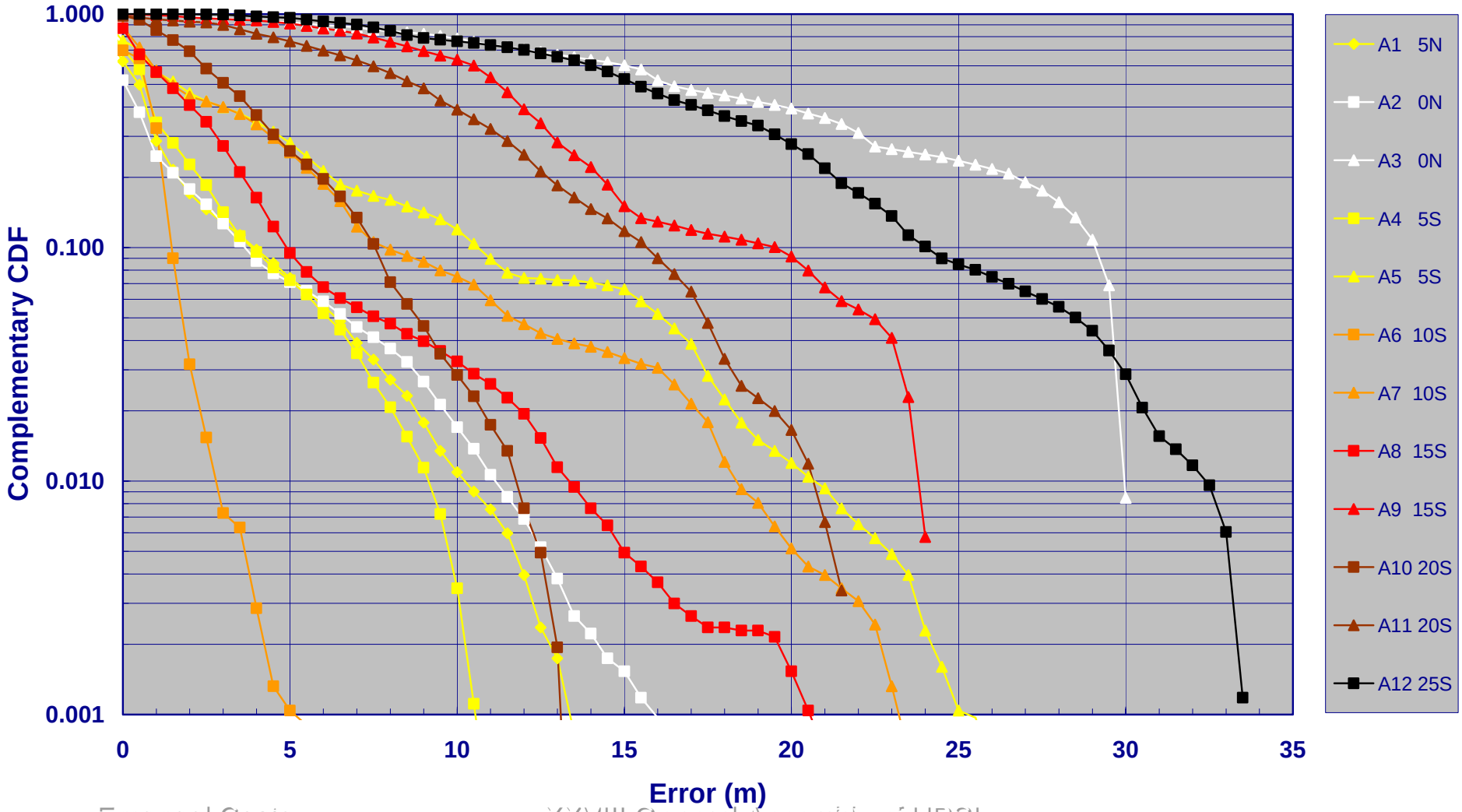
User Horizontal Error – GPS/SBAS 29 Ref. Stations – Planar Fit (Oct 2001, RBMC/PIM)



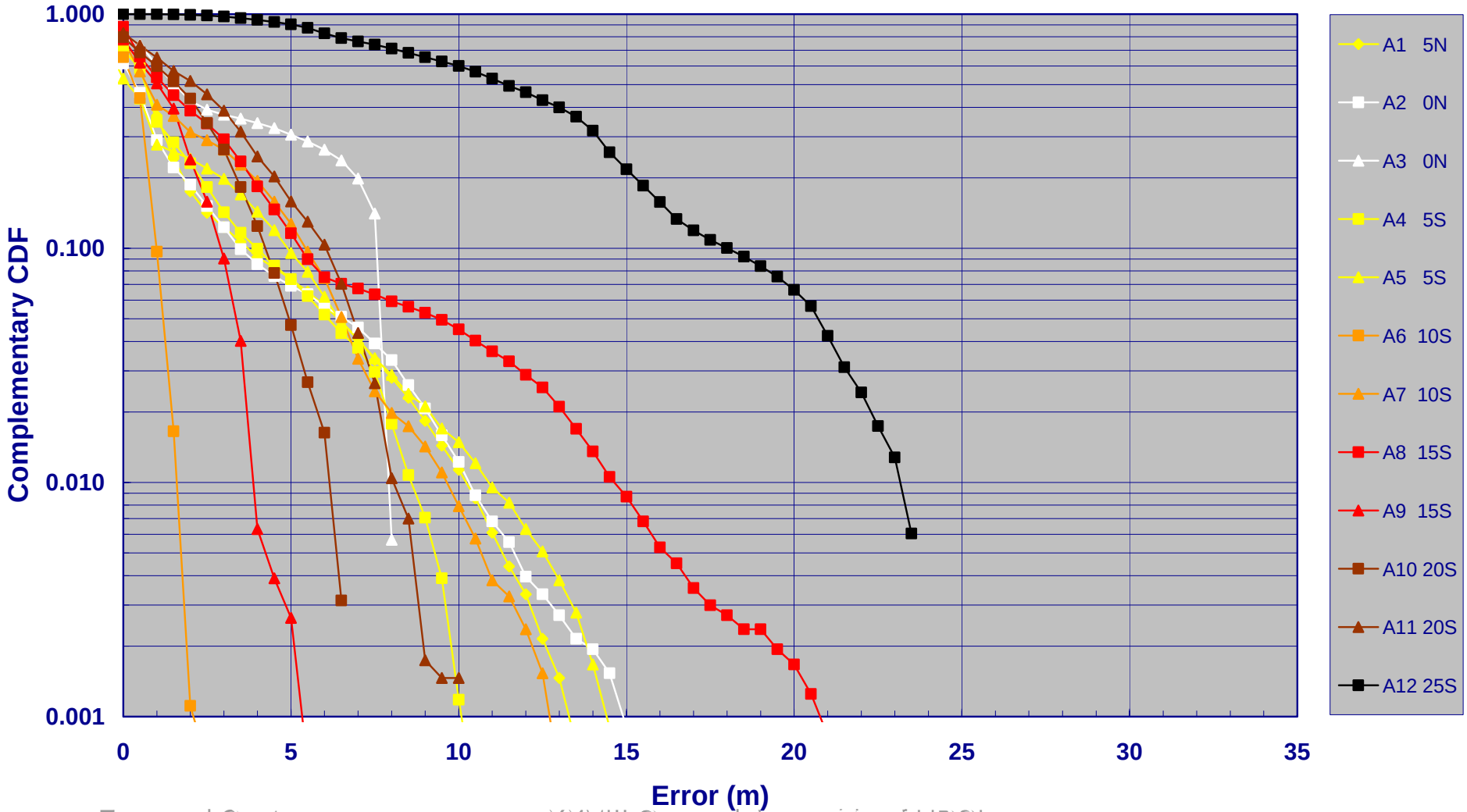
User Vertical Error – GPS/SBAS 14 Ref. Stations – Planar Fit (Jan 2002, PIM)



User Vertical Error – GPS/SBAS 14 Ref. Stations – Planar Fit (Oct 2001, RBMC/PIM)



User Vertical Error – GPS/SBAS 29 Ref. Stations – Planar Fit (Oct 2001, RBMC/PIM)



Conclusion

- Effects of season, of the equatorial anomaly and of plasma bubbles observed on vTEC errors at IGPs and on user horizontal and vertical errors;
- Errors decrease with the number of reference stations;
- For a network of 29 uniformly-distributed reference stations, vTEC errors at IGPs due to the low-latitude ionosphere exceed 23 m with probability 0.001;
- For selected users (not necessarily worst case study), the horizontal and vertical position errors due to the low-latitude ionosphere exceed 25 m with probability 0.001.