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The Effect of Ionospheric Models on Electromagnetic Pulse Locations

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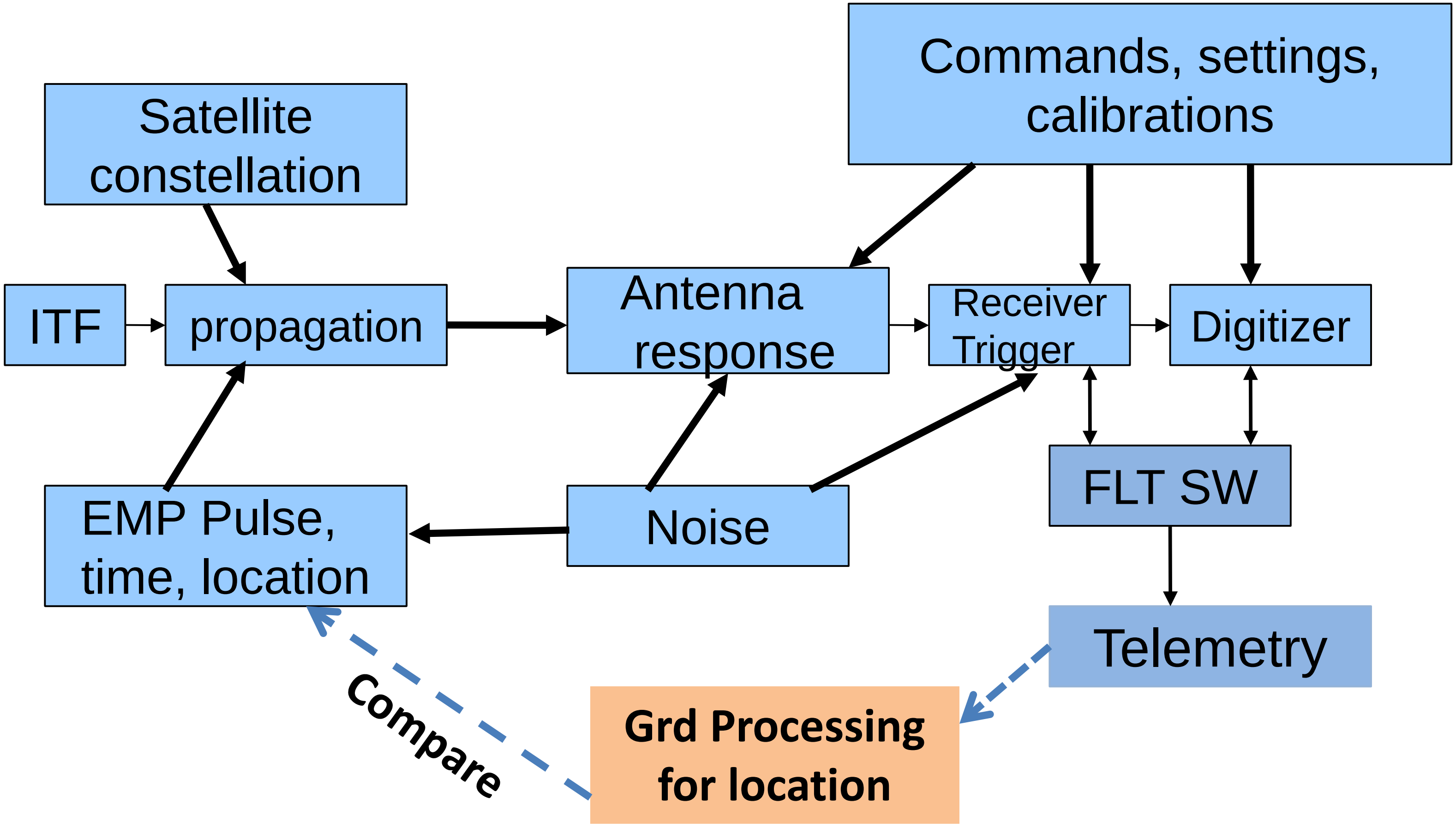
Abstract

Locations of electromagnetic pulses (EMPs) determined by time-of-arrival (TOA) often have outliers with significantly larger errors than expected. In the past, these errors were thought to arise from high order terms in the Appleton-Hartree equation. We simulated 1000 events randomly spread around the Earth into a constellation of 22 GPS satellites. We used four different ionospheres: “simple” where the time delay goes as the inverse of the frequency-squared, “full Appleton-Hartree”, the “BobRD integrals” and a full raytracing code. The simple and full Appleton-Hartree ionospheres do not show outliers whereas the BobRD and raytracing do. This strongly suggests that the cause of the outliers is not additional terms in the Appleton-Hartree equation, but rather is due to the additional path length due to refraction. A method to fix the outliers is suggested based on fitting a time to the delays calculated at the 5 GPS frequencies with BobRD and simple ionospherse. The difference in time is used as a correction to the TOAs.

CONSIM EMP Architecture



Commands, settings, calibrations

Satellite constellation

ITF

propagation

Antenna response

Receiver Trigger

Digitizer

FLT SW

EMP Pulse, time, location

Noise

Telemetry

Grd Processing for location

Compare

Investigate the effect of the ITF on how well locations can be determined

Use 4 of CONSIM’s options for the ITF:
simple, Full A-H, BobRD, and raytrace

Can use 4 of CONSIM’s options for “time at satellite”:
(1) the true time (should always give best answer)
(2) time from flight software (i. e., a $1/f^2$ fit)
(3) time from fits to signal in receiver ($1/f^2$ fit so tests how well the flight software does)
4) time from the arrival time of set frequencies at the satellite (corrects for group vs phase velocity, etc)

Processing to find location

Input: Location and Time-of-arrival (TOA) for N satellites

Method: First a crude location by DTOA, then best fit to find event's X, Y, Z, and time.

Compare with the truth for various ITF models and sources of time-at-satellite.

DTOA solution with respect to satellite #1: Aθ=B

$$A = \begin{bmatrix} x_2 - x_1 & y_{2-}y_1 & z_2 - z_1 & c(T_2 - T_1) \\ x_3 - x_1 & y_3 - y_1 & z_3 - z_1 & c(T_3 - T_1) \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ x_N - x_1 & y_N - y_1 & z_N - z_1 & c(T_N - T_1) \end{bmatrix} \qquad \theta = \begin{bmatrix} X_{EMP} - x_1 \\ Y_{EMP} - y_1 \\ Z_{EMP} - z_1 \\ c(T_{EMP} - T_1) \end{bmatrix}$$

$$B = \frac{1}{2} \begin{bmatrix} (x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2 - c^2(T_2 - T_1)^2 \\ (x_3 - x_1)^2 + (y_3 - y_1)^2 + (z_3 - z_1)^2 - c^2(T_3 - T_1)^2 \\ . \\ . \\ . \\ (x_N - x_1)^2 + (y_N - y_1)^2 + (z_N - z_1)^2 - c^2(T_N - T_1)^2 \end{bmatrix}$$

First, find crude location (θ):

$$A\theta = B$$

$$\theta = (A^T A)^{-1} A^T B$$

Second, find best fit location using crude location as starting point:

$$\chi^2 = \sum_{i=1}^{N} \{(x_i - X_{EMP})^2 + (y_i - Y_{EMP}) + (z_i - Z_{EMP})^2 - c(T_{EMP} - T_i)^2\}^2$$

χ^2 minimization by 4-D Golden search. No gradients, convergence is found to a specified accuracy, not some condition on χ^2. The best-fit method gives ~3 times better locations.

Simulations

Picked 1000 random locations at altitude = 2 km between -60 and +60 latitude

Propagated into a GPS constellation of 22 BDW-2R satellites

Did "round trip" simulation: simulated event through the flight software to the telemetry, processed the telemetry to get a location and compared to the true location.

Did for 4 ionospheres: simple, Full A-H, BobRD, and raytrace

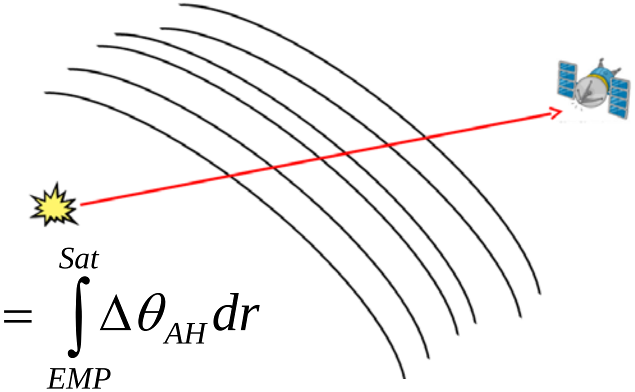
Four ionospheres in CONSIM

SIMPLE IONOSPHERE

$$\Delta\theta \propto \frac{TEC}{f}$$

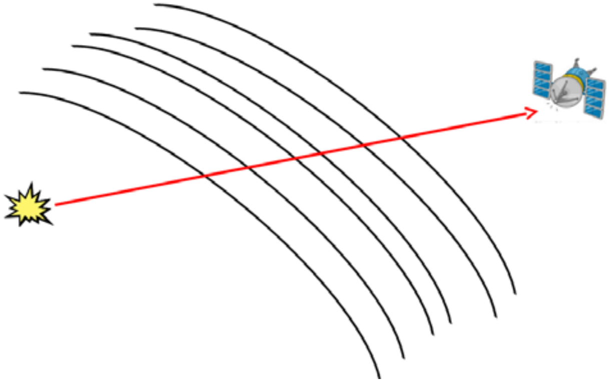
1st term of AH Eq

FULL APPLETON-HARTREE EQ



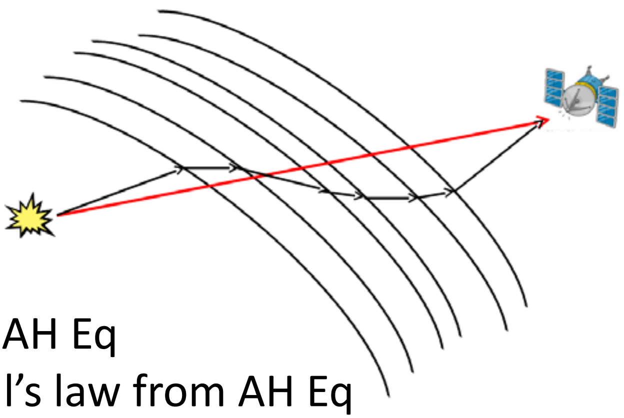
$$\Delta\theta = \int_{EMP}^{Sat} \Delta\theta_{AH}\, dr$$

Bob RD INTEGRAL



1st 3 terms of AH Eq

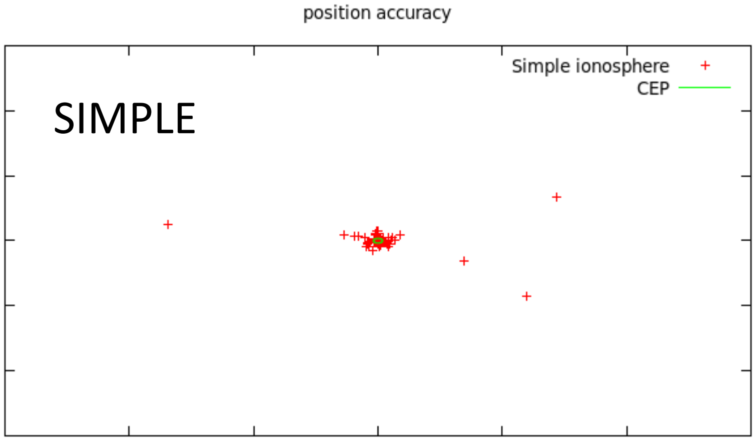
RAYTRACE

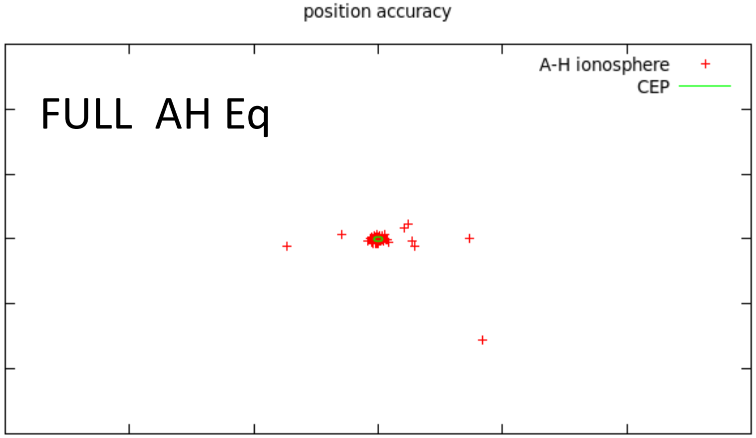


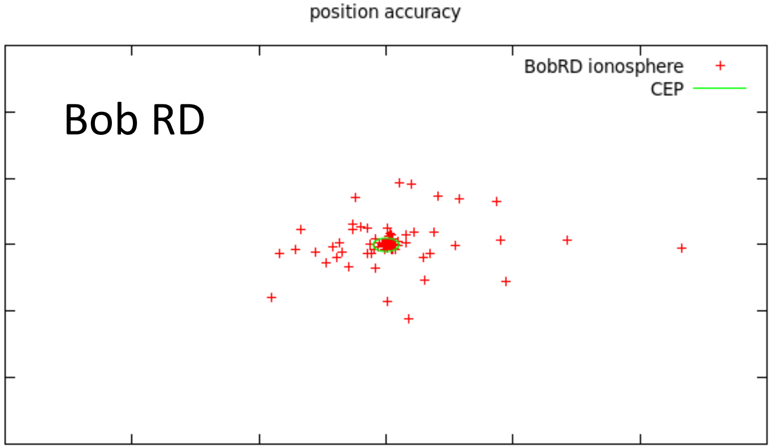
Full AH Eq

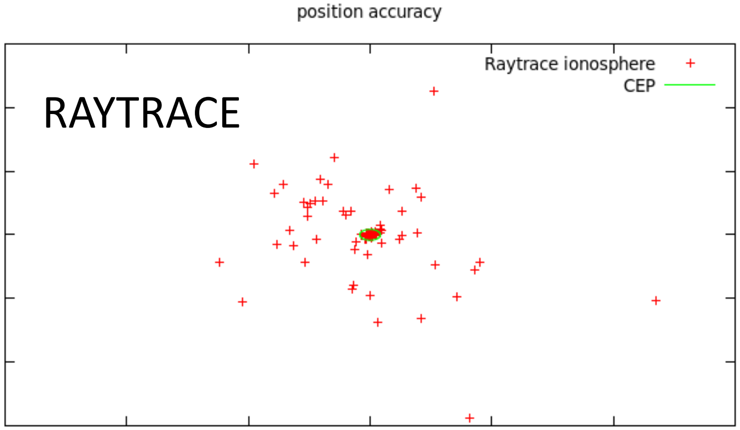
Snell’s law from AH Eq

Results of round-trip analysis





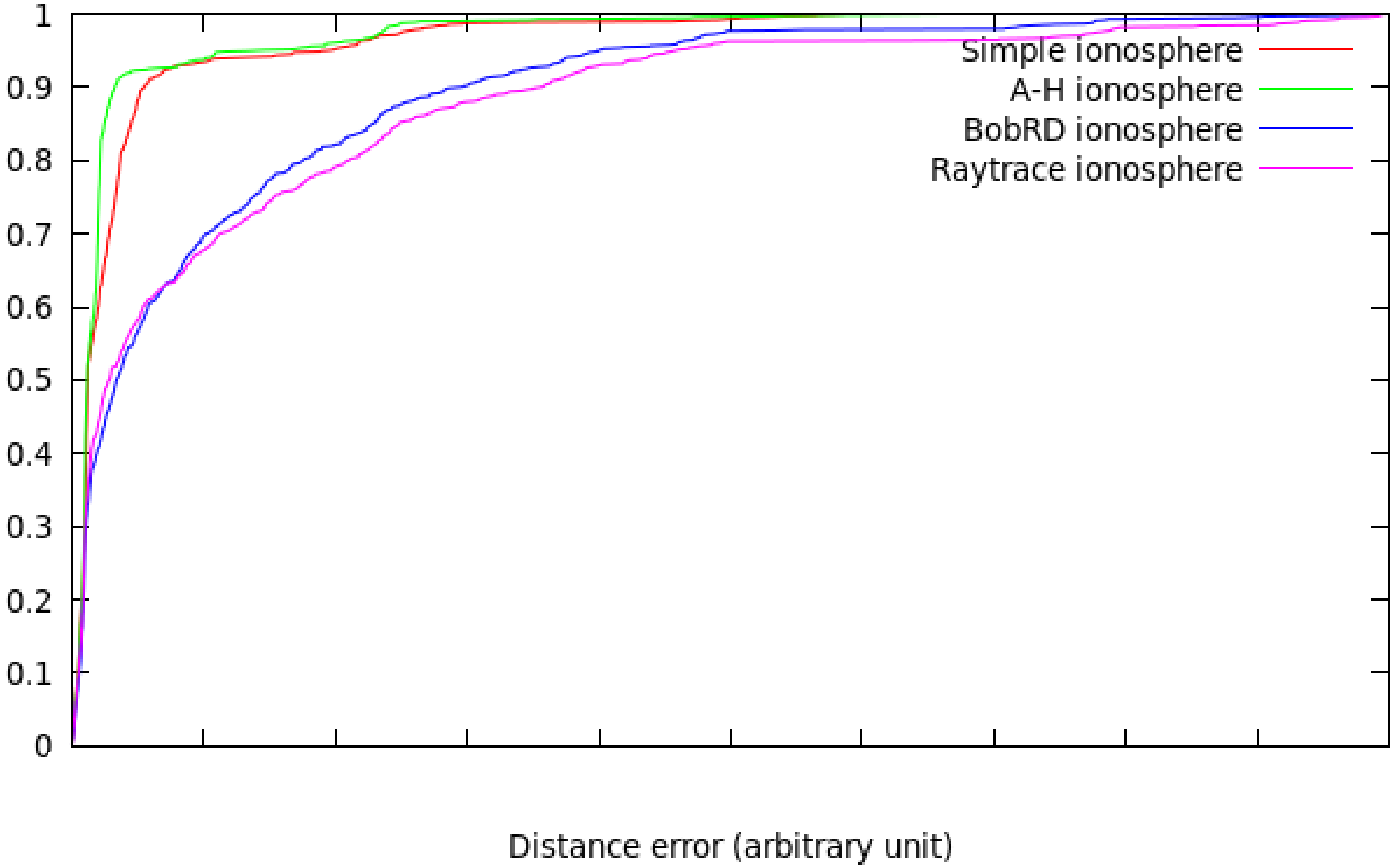




Note when using a full, realistic simulation (i. e., raytrace) there are many events which are found accurately such that the CEP is small, but there are outliers where the error in the location is large.

CEP = circular error probable, the radius that includes 50% of the events

Integral probability functions for error



Conclusion

Since the "Full Appleton-Hartree" simulations effectively uses an infinite series expansion yet does not produce the outlier locations, the outliers are not due to higher order terms in the A-H equation.

The fact that the "BobRD" ionosphere simulations does produce the outliers indicates that the cause of the outliers is the additional path length due to refraction.

A suggestion to correct the outliers

Currently:

Flt SW 1/f^2 fit

$$\chi^2 = \sum_{i=1}^{N} \{(x_i - X_{EMP})^2 + (y_i - Y_{EMP}) + (z_i - Z_{EMP})^2 - c(T_{EMP} - T_i)^2\}^2$$

Instead:

$$\chi^2 = \sum_{i=1}^{N} \{(x_i - X_{EMP})^2 + (y_i - Y_{EMP}) + (z_i - Z_{EMP})^2 - c(T_{EMP} - (T_i - \Delta T_i)\ )^2\}^2$$

Correction of additional path length due to refraction

The BobRD integrals include the effect of 3rd order terms in the A-H eq, ($1/f^2$, $1/f^3$, $1/f^4$) but also includes the time delay due to the longer path caused by refraction.

The BobRD integrals are faster to calculate and do not have the convergence issues in raytracing.

Method 1:

(1) Use NeQuick2 to set electron density profile for each satellite

(2) Use “special_freq” option in CONSIM to find time-of-arrival of the 5 BDW-2R frequencies for the “simple” ITF and the “BobRD” ITF.

(3) Fit T_{simple} to the 5 “simple” time-of-arrival

(4) Fit T_{BobRD} to the 5 “BobRD” time-of-arrival

$$\Delta T_i = T_{BobRD} - T_{Simple}$$

Valid method but simulations will not validate because the left hand would know what the right hand did unless, for example, one uses an IRI date 11 years apart.

Method 2:

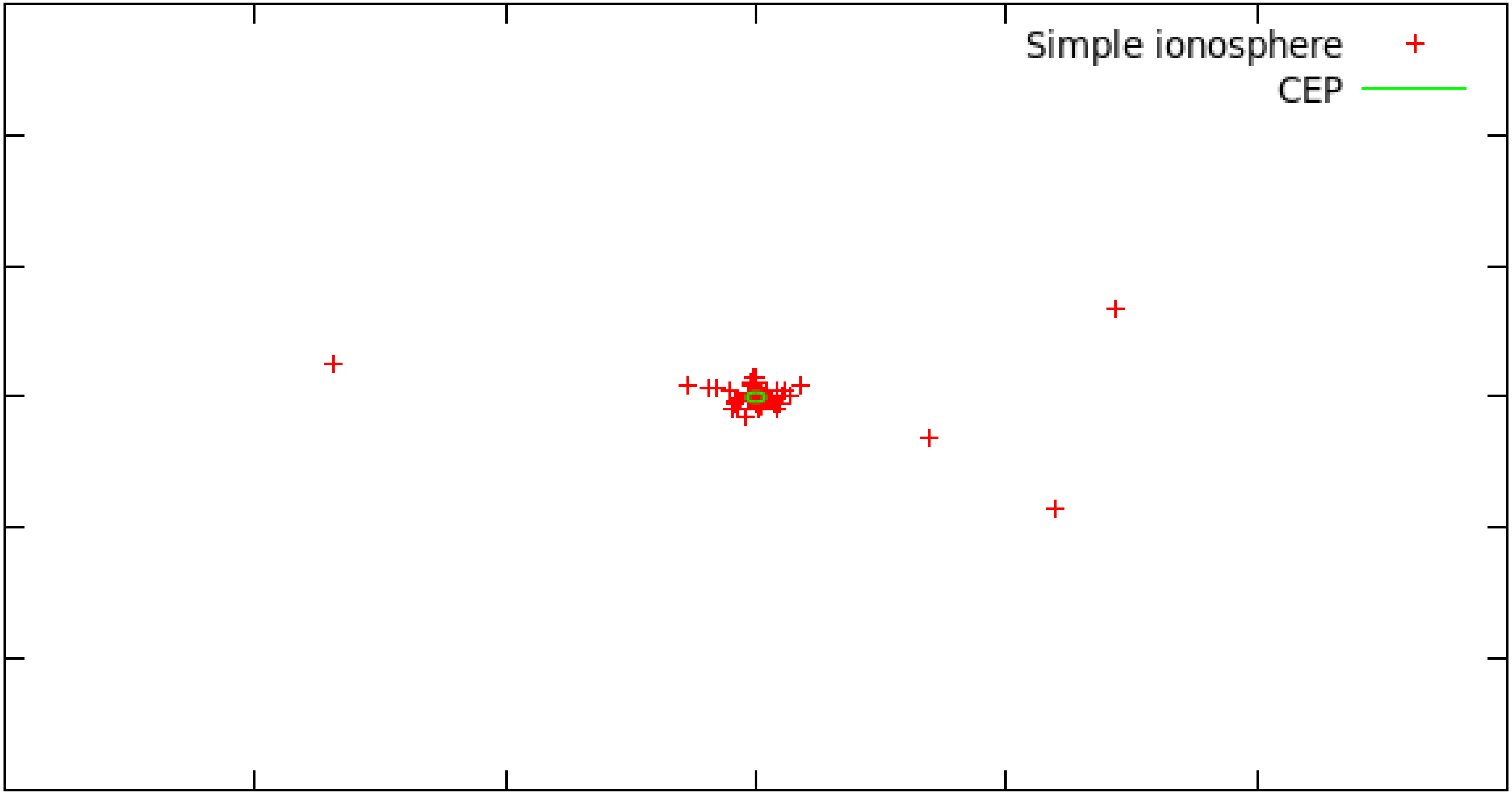
1. (1) **Set up generic electron density as function of height**
2. (2) **Normalize electron density by slant TEC**
3. (3) **Use “special_freq” option in CONSIM to find time-of-arrival of the 5 BDW-2R frequencies for the “simple” ITF and the “BobRD” ITF.**
4. (4) **Fit T_{simple} to the 5 “simple” time-of-arrival**
5. (5) **Fit T_{BobRD} to the 5 “BobRD” time-of-arrival**

$$\Delta T_i = T_{BobRD} - T_{Simple}$$

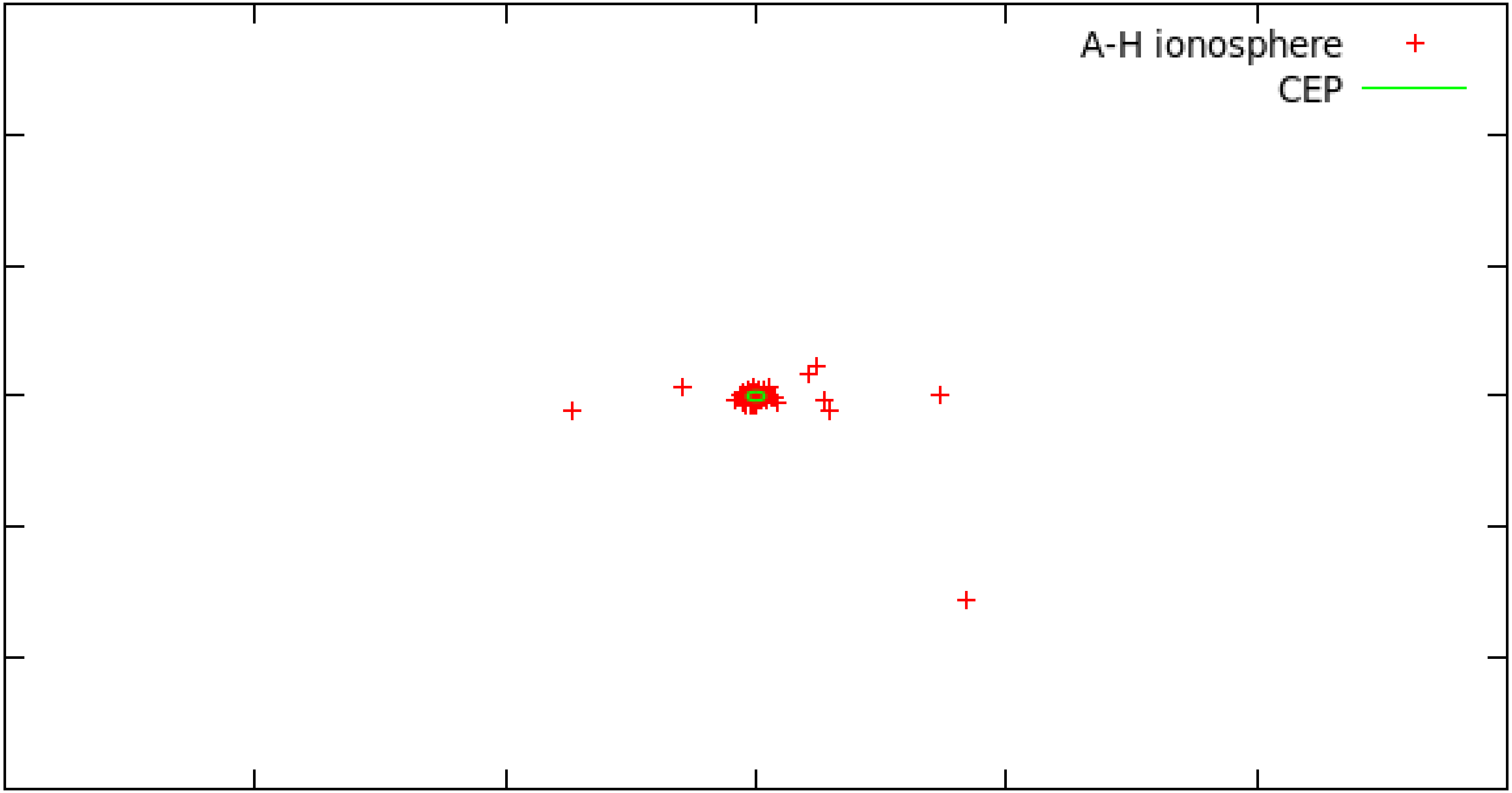
CONSIM has all the pieces and simulation ability to test whether such corrections will fix most outliers. Need to add the ability to switch to a generic ionospheric electron density rather than the current choices of IRI or NeQuick2

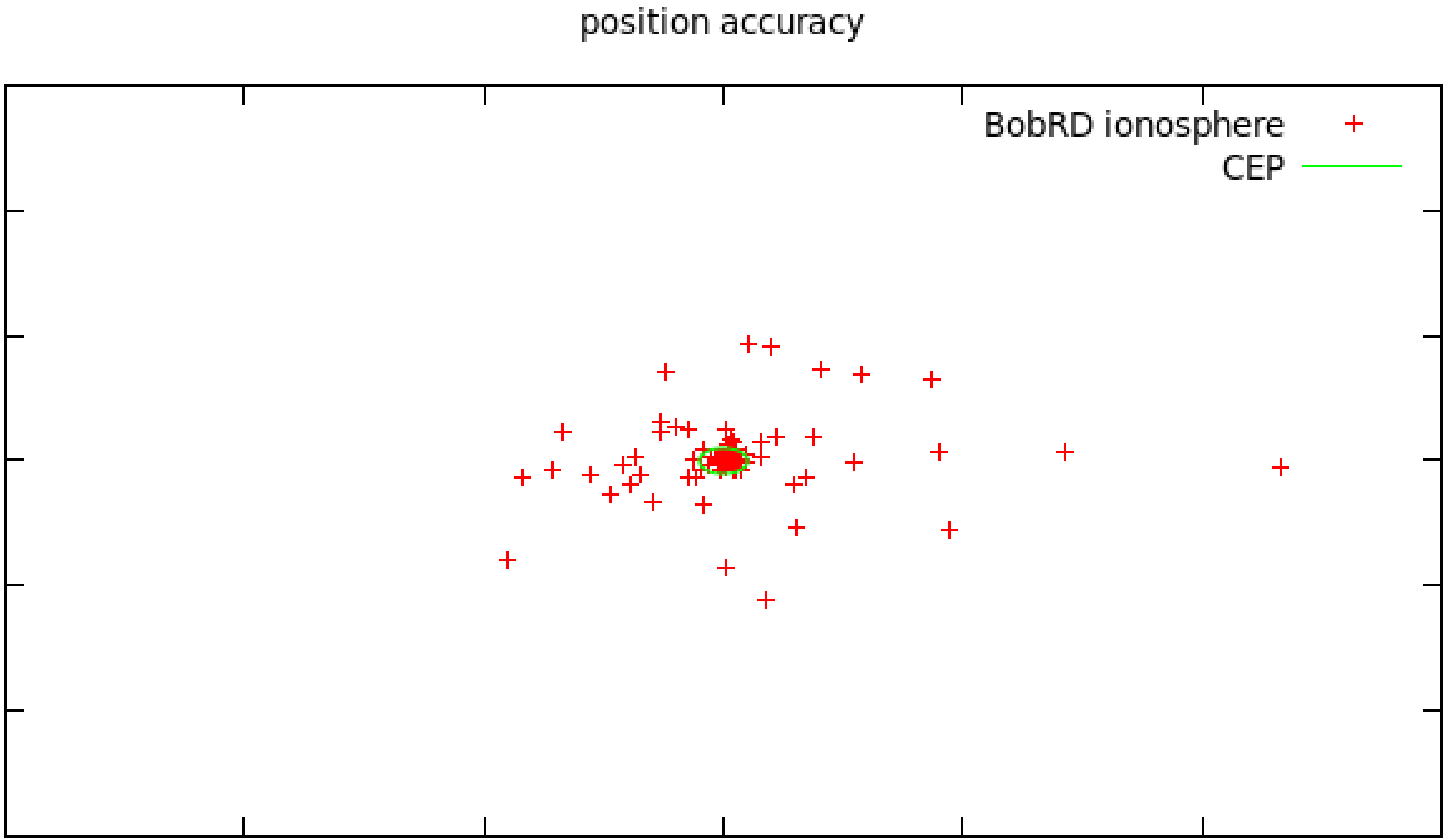
Backup

position accuracy

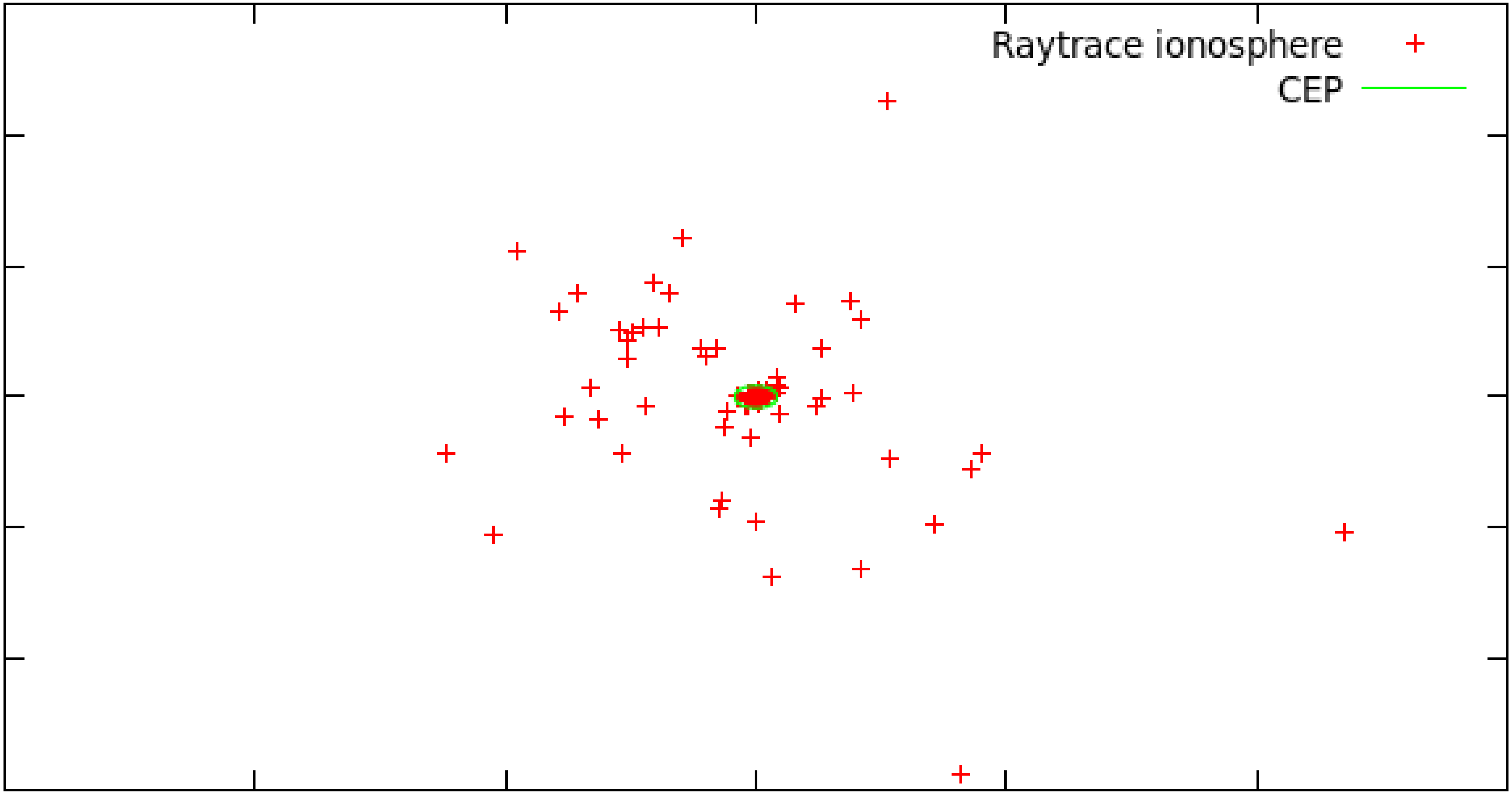


position accuracy




position accuracy
BobRD ionosphere
CEP

position accuracy



Propagation through ionosphere is modeled with multiple shells