The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2333-20

Workshop on Science Applications of GNSS in Developing Countries (11-27 April), followed by the: Seminar on Development and Use of the Ionospheric NeQuick Model (30 April-1 May)

11 April - 1 May, 2012

Challenges for Positioning in Africa

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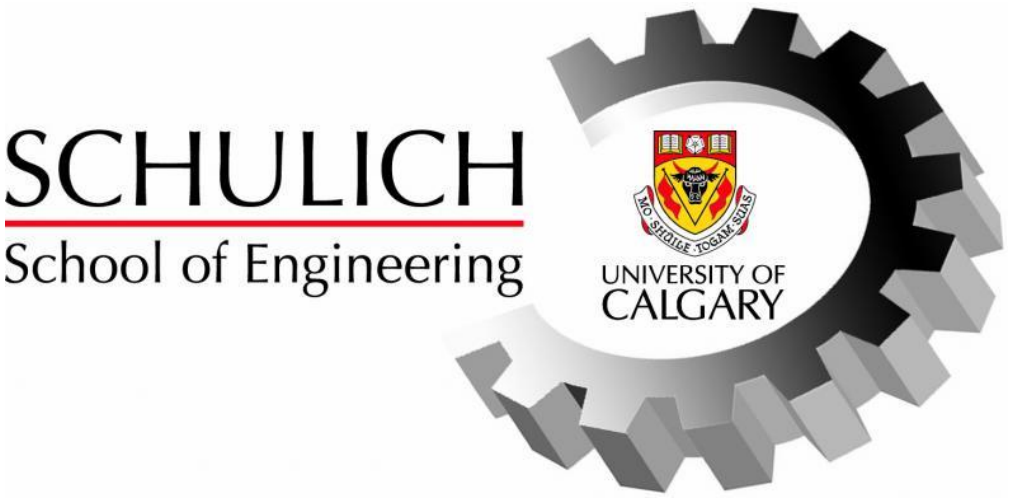
Challenges for Positioning in Africa

S. Skone

Department of Geomatics Engineering

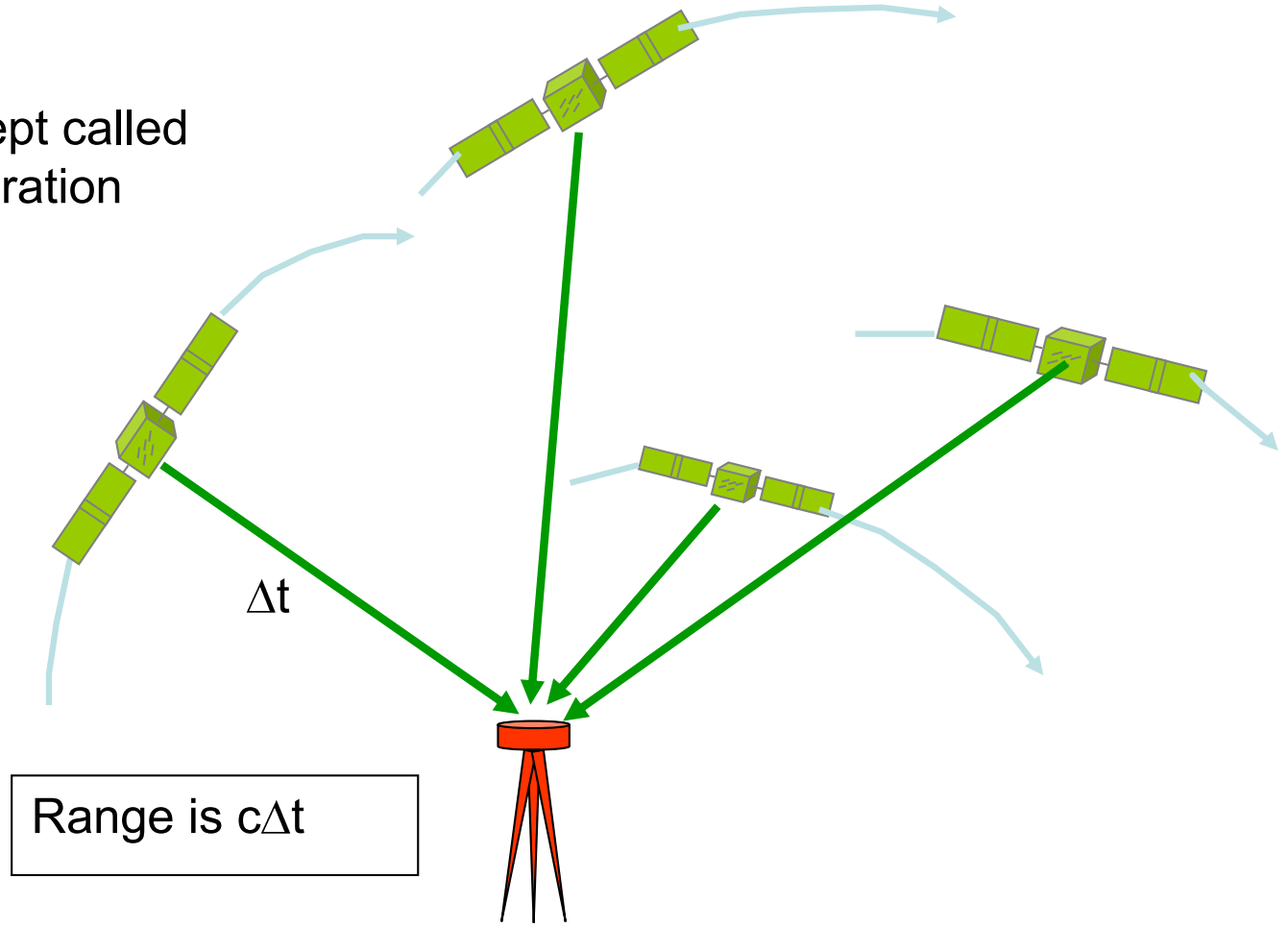


Outline

- GNSS positioning solution and ionosphere range errors
- DGPS & SBAS
- Equatorial anomaly and SED
- Impact on positioning – examples and case studies
- Summary

How does GNSS work?

Concept called
Trilateration



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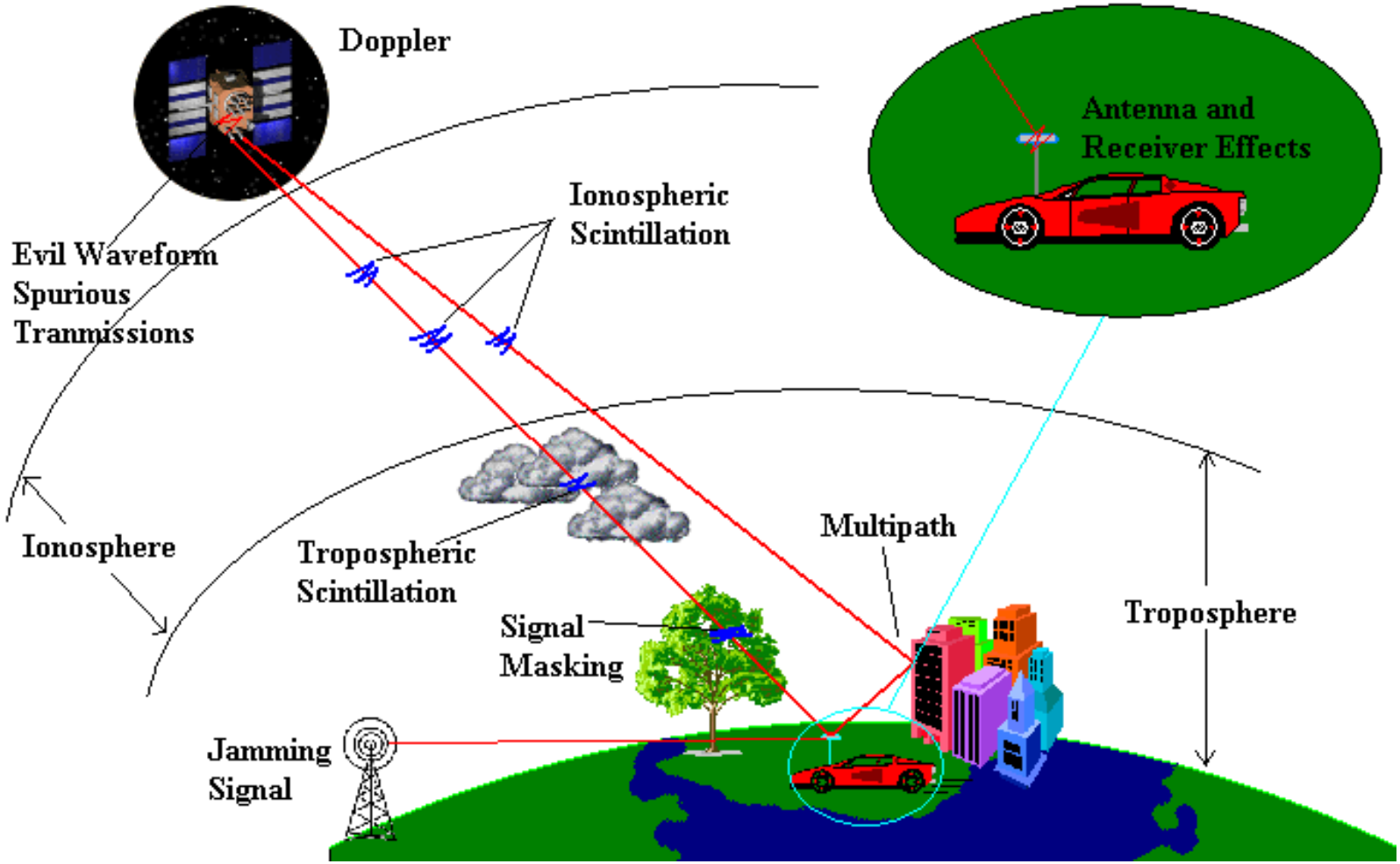
GNSS Ranging Errors

Orbit Error (Δx, Δy, Δz)



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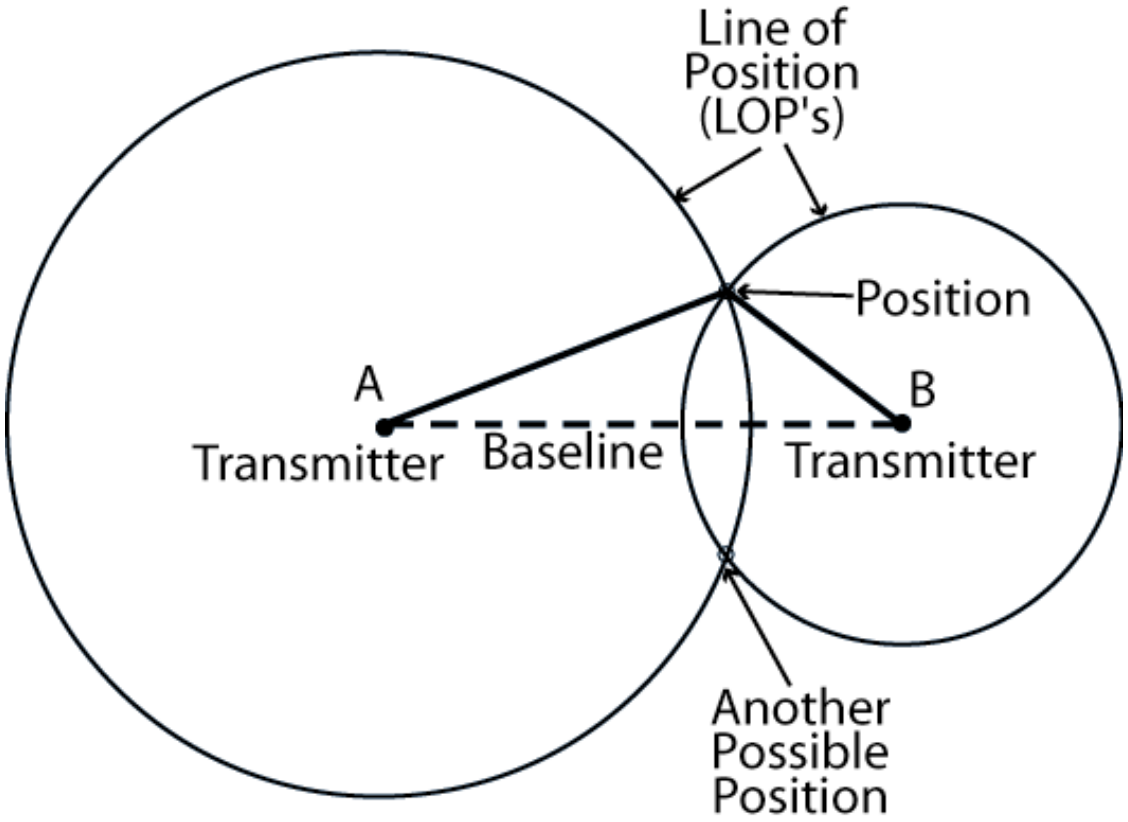
Lines of Position



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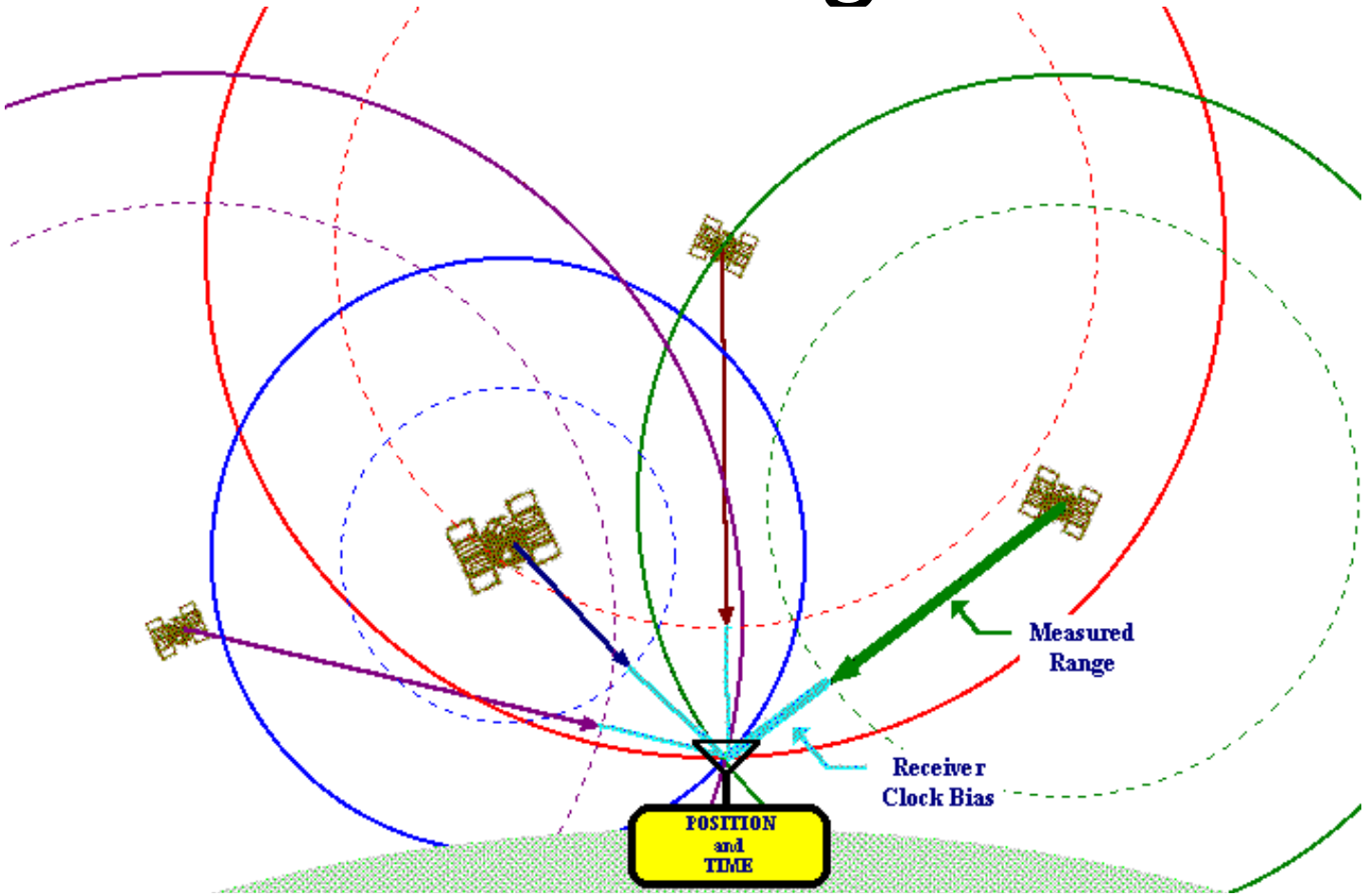
GPS Positioning Solution



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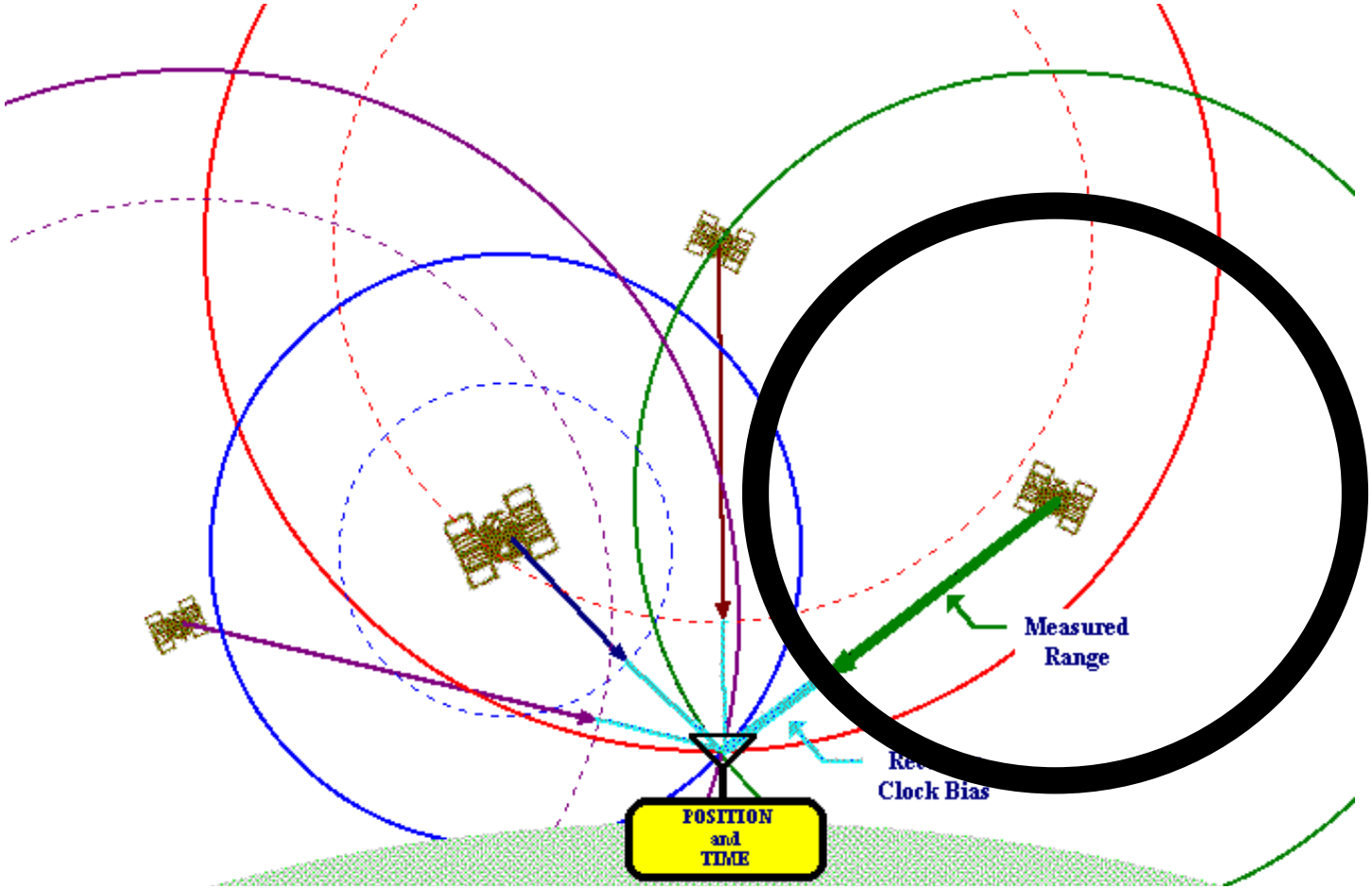

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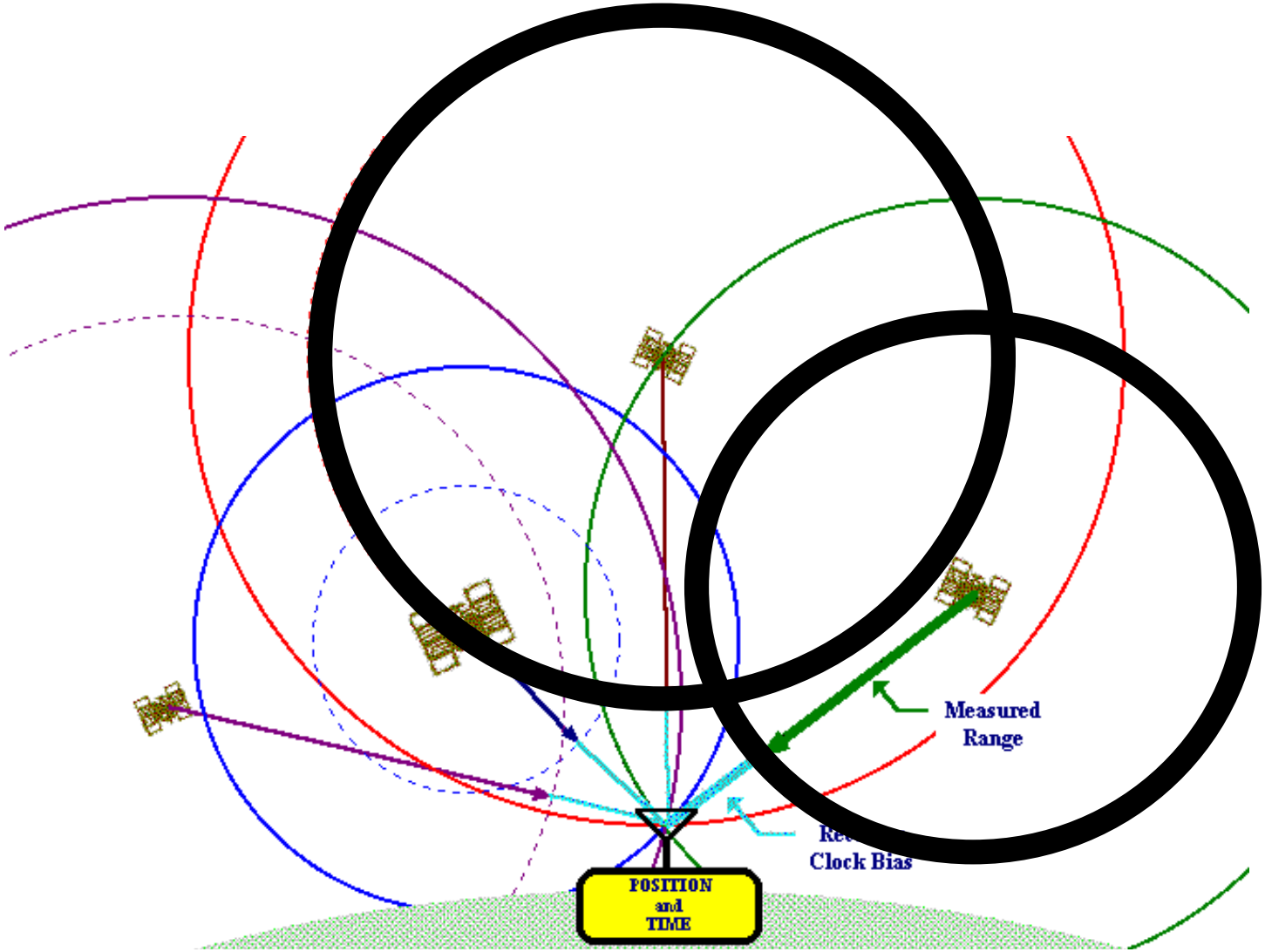

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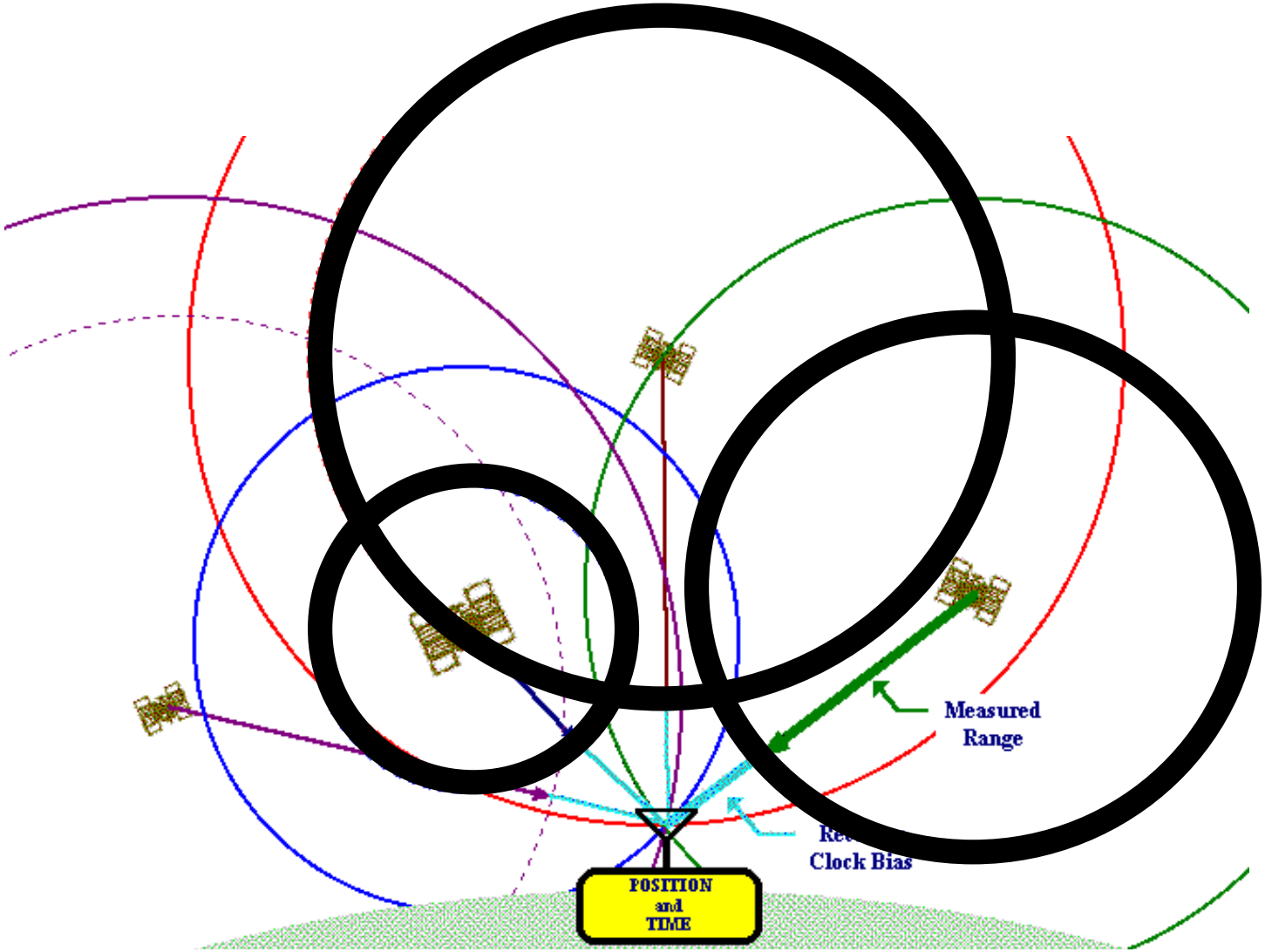

?

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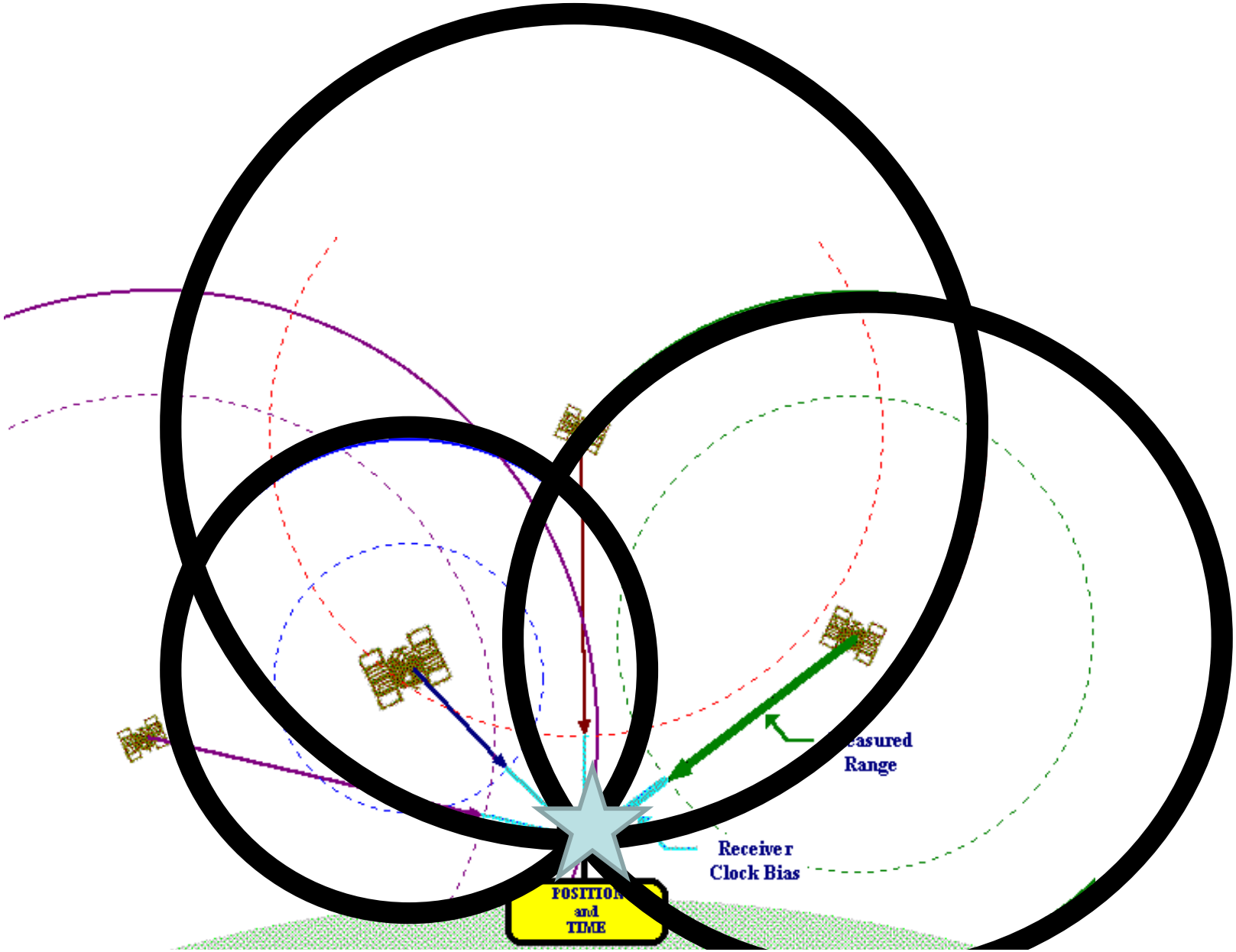

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Receiver computes position in mathematical adjustment

4 range observations required to estimate 4 unknowns.

Receiver reports

X = [x,y,z,t]

and

C_X

Satellite (SV) coordinates in ECEF XYZ from Ephemeris Parameters and SV Time

$SVx_0 := 15524471.175$ $SVy_0 := -16649826.222$ $SVz_0 := 13512272.387$ SV 15

$SVx_1 := -2304058.534$ $SVy_1 := -23287906.465$ $SVz_1 := 11917038.105$ SV 27

$SVx_2 := 16680243.357$ $SVy_2 := -3069625.561$ $SVz_2 := 20378551.047$ SV 31

$SVx_3 := -14799931.395$ $SVy_3 := -21425358.24$ $SVz_3 := 6069947.224$ SV 7

Satellite Pseudoranges in meters (from C/A code epochs in milliseconds)

$P_0 := 89491.971$ $P_1 := 133930.500$ $P_2 := 283098.754$ $P_3 := 205961.742$ Range + Receiver Clock Bias

Receiver Position Estimate in ECEF XYZ

$Rx := -730000$ $Ry := -5440000$ $Rz := 3230000$

For Each of 4 SVs $i := 0..3$

Ranges from Receiver Position Estimate to SVs (R) and Array of Observed - Predicted Ranges

$$R_i := \sqrt{(SVx_i - Rx)^2 + (SVy_i - Ry)^2 + (SVz_i - Rz)^2} \qquad L_i := \mathrm{mod}\left[\left(R_i\right), 299792.458\right] - P_i$$

Compute Directional Derivatives for XYZ and Time

$$Dx_i := \frac{SVx_i - Rx}{R_i} \qquad Dy_i := \frac{SVy_i - Ry}{R_i} \qquad Dz_i := \frac{SVz_i - Rz}{R_i} \qquad Dt_i := -1$$

Solve for Correction to Receiver Position Estimate

$$A := \begin{bmatrix} Dx_0 & Dy_0 & Dz_0 & Dt_0 \\ Dx_1 & Dy_1 & Dz_1 & Dt_1 \\ Dx_2 & Dy_2 & Dz_2 & Dt_2 \\ Dx_3 & Dy_3 & Dz_3 & Dt_3 \end{bmatrix} \qquad dR := \left(A^T \cdot A\right)^{-1} \cdot A^T \cdot L \qquad dR = \begin{bmatrix} -3186.496 \\ -3791.932 \\ 1193.286 \\ 12345.997 \end{bmatrix}$$

Apply Corrections to Receiver XYZ and Compute Receiver Clock Bias Estimate

$Rx := Rx + dR_0$ $Ry := Ry + dR_1$ $Rz := Rz + dR_2$ $Time := dR_3$

$Rx = -733186.496$ $Ry = -5443791.932$ $Rz = 3231193.286$ $Time = 12345.997$

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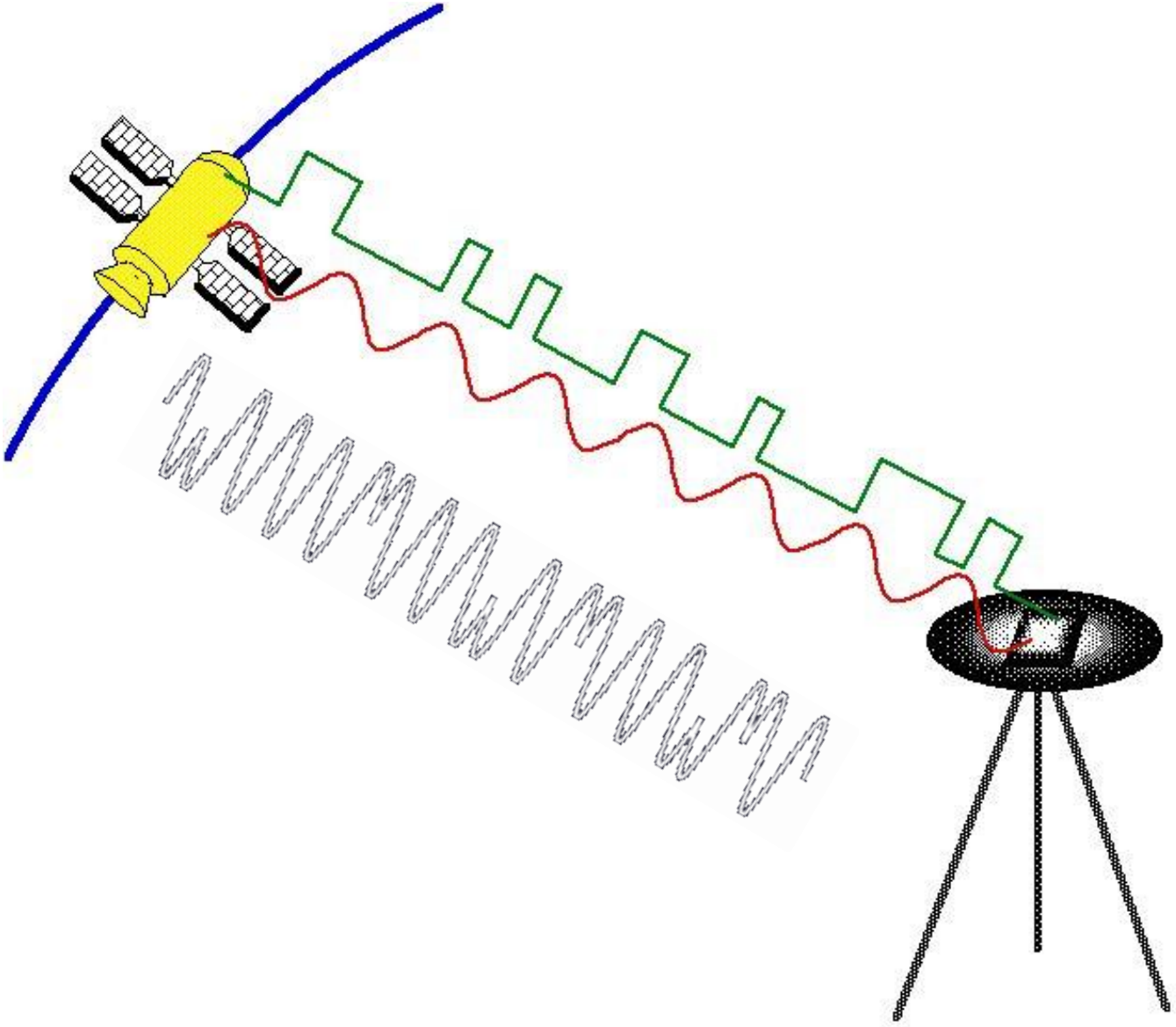
GPS Observations



Receiver Observations

Travel time: Δt

Phase: Φ

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GNSS Ionosphere Range Error

Range computed as $R = c_0 \Delta t$

But GNSS signal velocity is not c_0 (n is not 1)!

$$n^2 = 1 - \frac{X}{1 - iZ - \frac{Y_T^2}{2(1 - X - iZ)} \pm \left[\frac{Y_T^4}{4(1 - X - iZ)^2} + Y_L^2 \right]^{1/2}}$$

$$\Delta R = \int_{path} (n - 1) ds$$

$$\Delta R = \frac{40.3}{f^2} \; TEC \quad [m]$$

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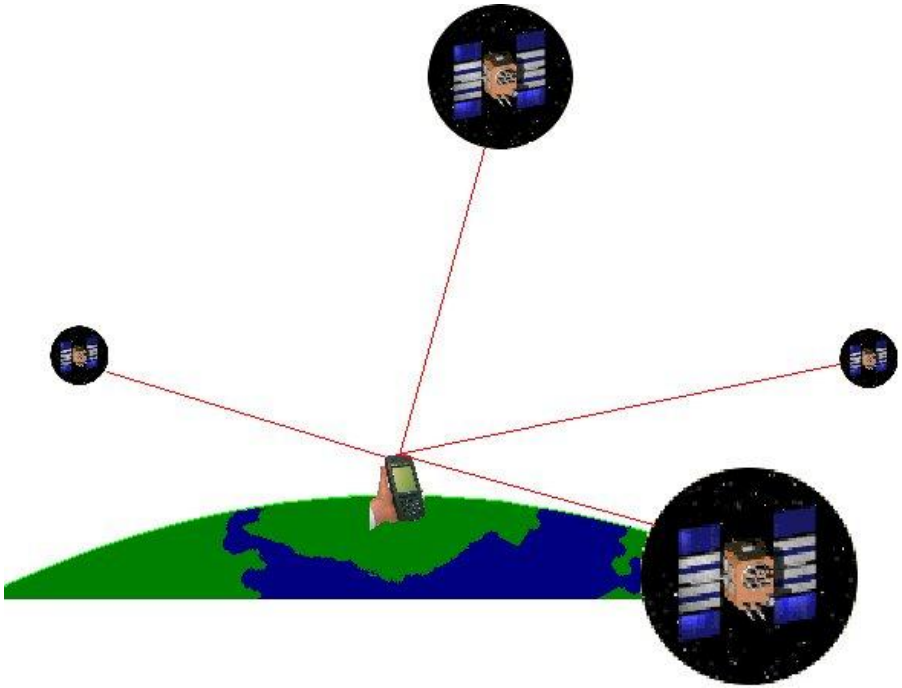
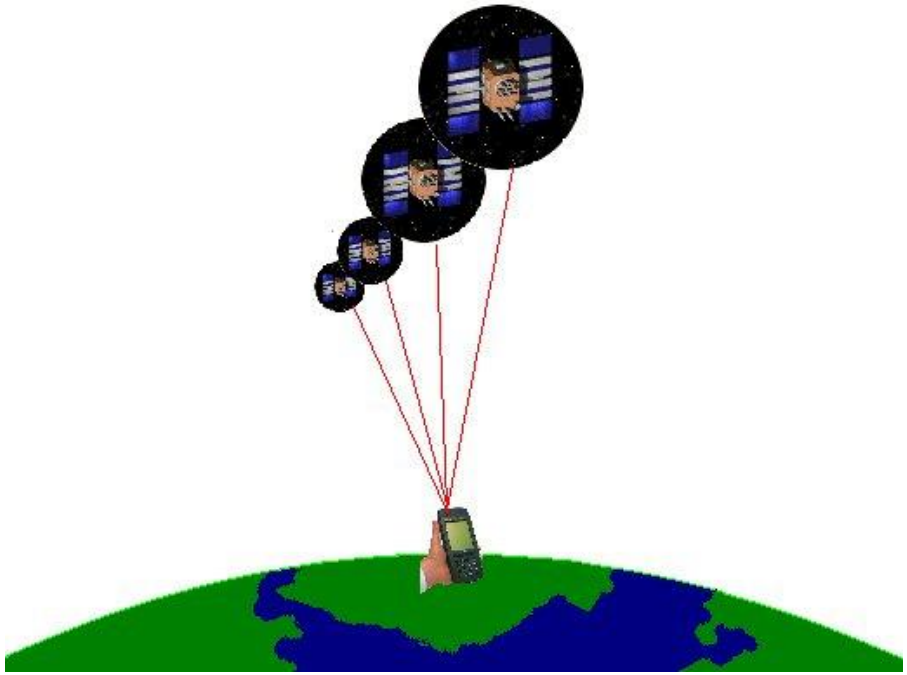
Position Accuracy will depend on the ‘Satellite Geometry’

GOOD
Satellites are dispersed



BAD
Satellites are bunched together



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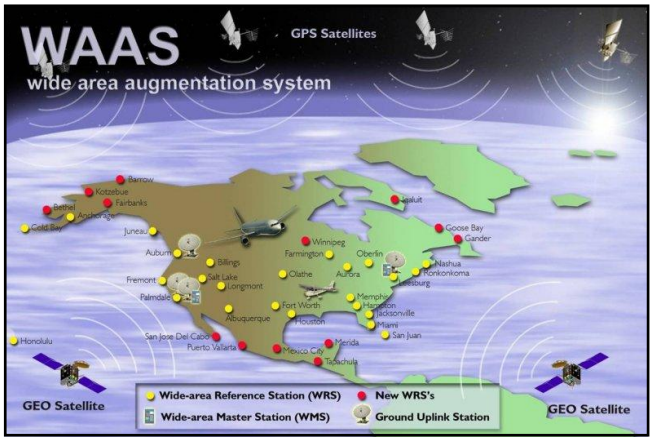
Numbers to Consider

GPS receivers report

- Lat/long and height
- Dilution of Precision (DOP) – measure of satellite geometry and the smaller values are better

Rule-of-Thumb:
Positioning accuracy α DOP x ΔR

GPS Positioning Accuracy



Low

(single frequency, metre-level accuracy)

High

(multiple frequencies, centimetre-level accuracy)

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How can we reduce ionospheric effect for better positioning accuracy?

Calculating TEC (Dual Frequency)

- Assume measurements on two frequencies f_1, f_2 (i.e. GPS)
- Different range errors:

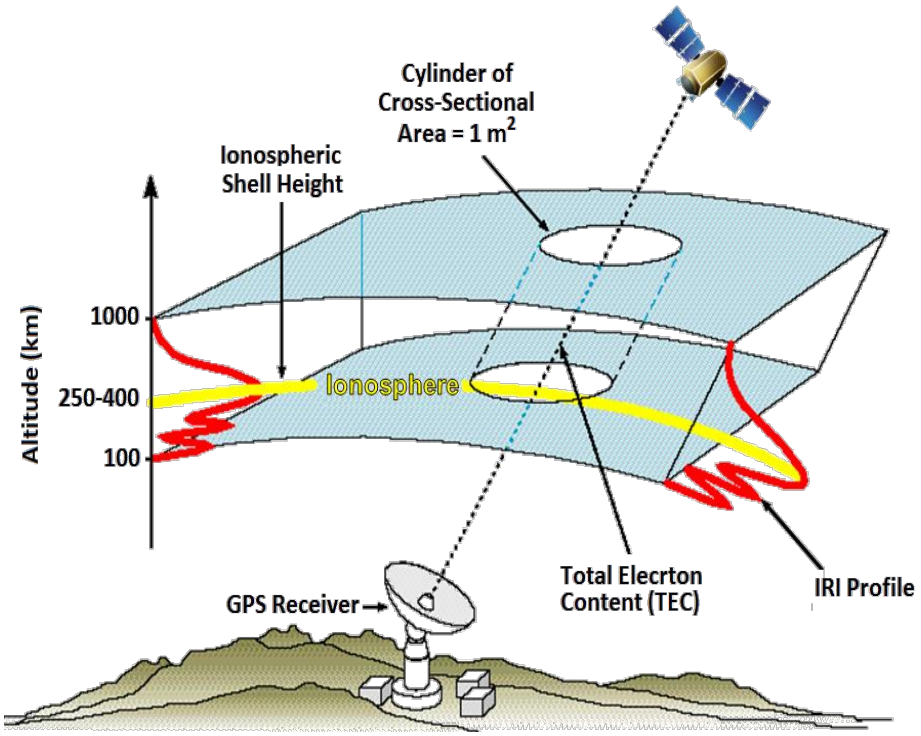
$$\Delta R_1 = \frac{40.3}{f_1^2}\mathrm{TEC} \qquad \Delta R_2 = \frac{40.3}{f_2^2}\mathrm{TEC}$$

- We can compute TEC:

$$R_1 - R_2 = \Delta R_1 - \Delta R_2 = 40.3\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right)\mathrm{TEC}$$

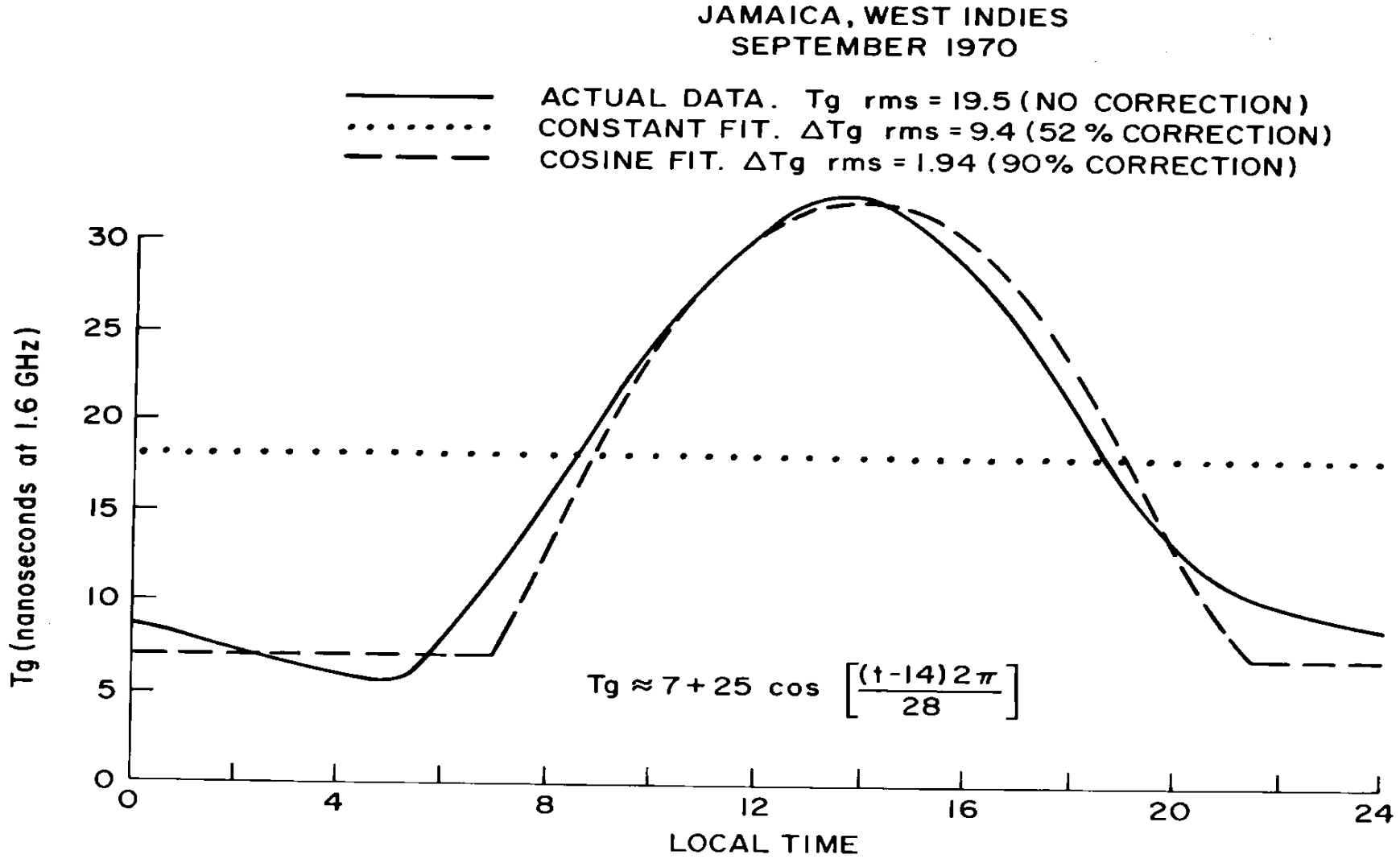
$$\mathrm{TEC} = \frac{1}{40.3}\left(\frac{f_1^2 f_2^2}{f_2^2 - f_1^2}\right)(\Delta R_1 - \Delta R_2)$$

L1 = 1.5 GHz
L2 = 1.2 GHz



[http://www.gnss.be/]

Broadcast (Klobuchar) Ionospheric Correction Algorithm



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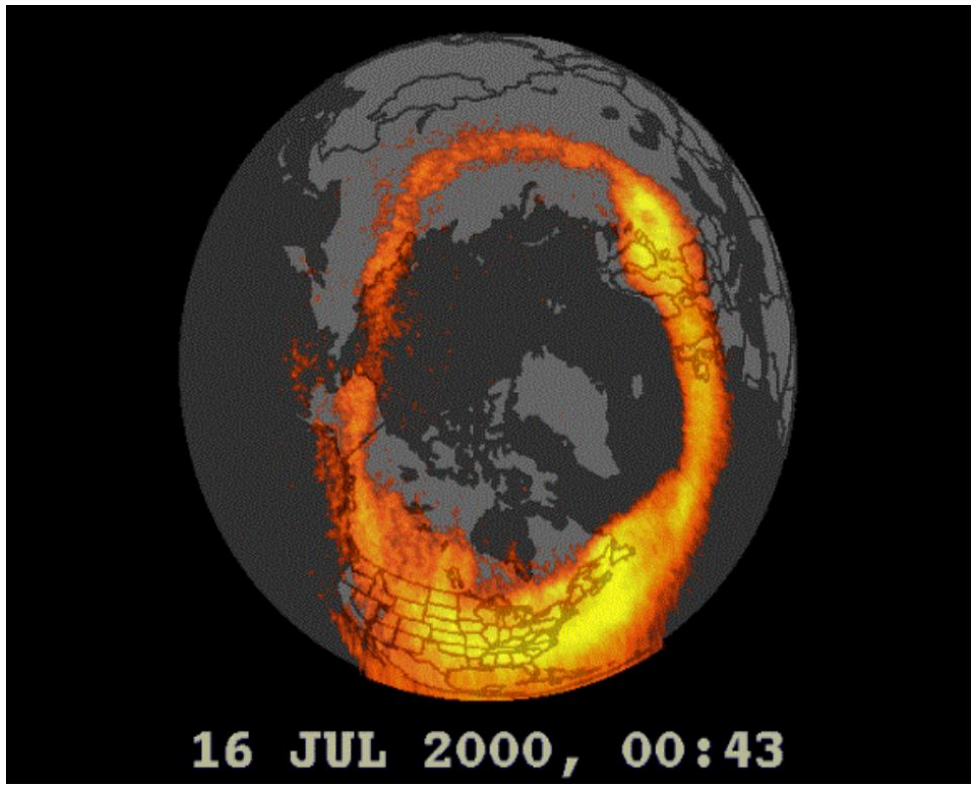
Sample Storm Event



July 15-16 2000
Storm Event

- severe global geomagnetic storm
- bright aurora (geomagnetic substorm)
- large absolute TEC and gradients at mid-latitudes
- storm-enhanced density
- Kp=9

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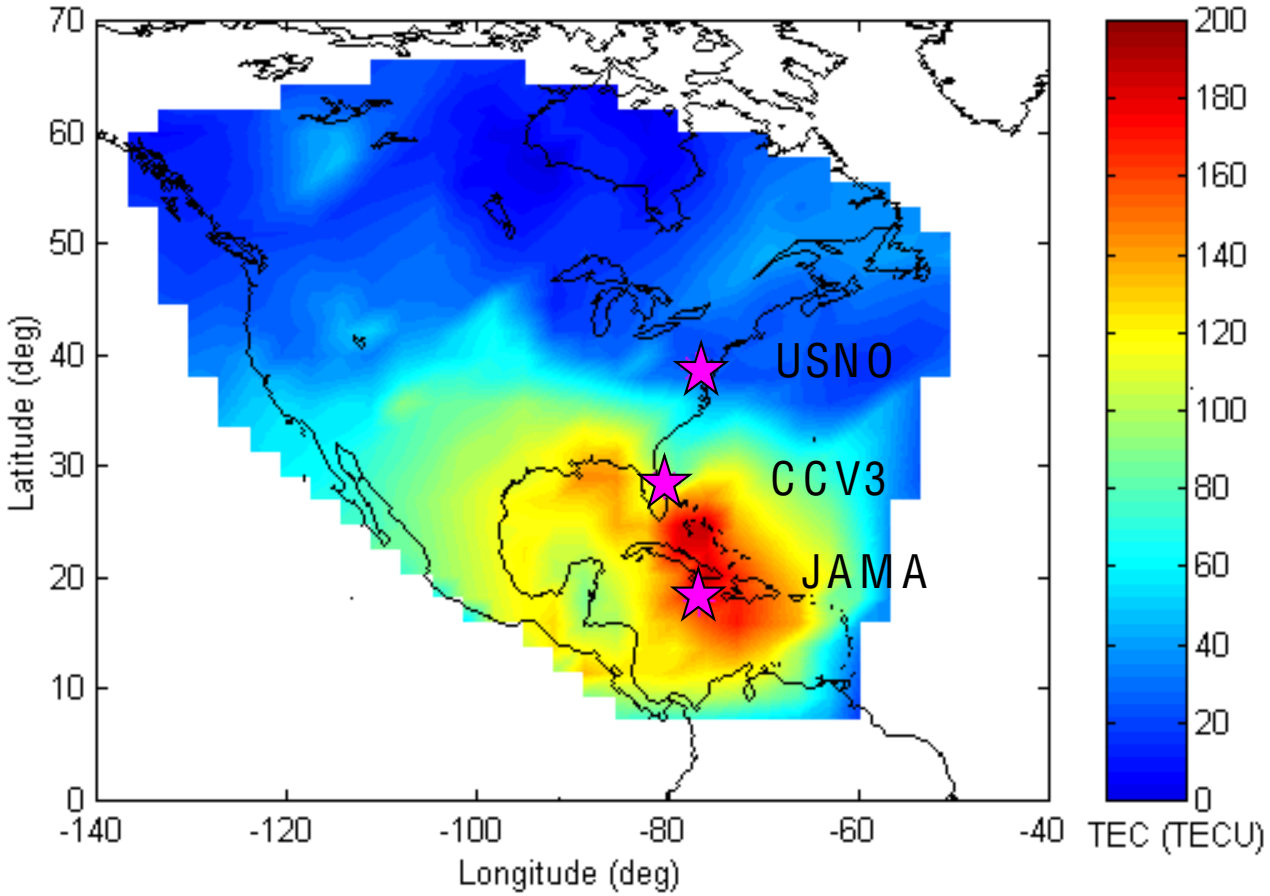
TEC Map July 15, 2000: 22:25 UT



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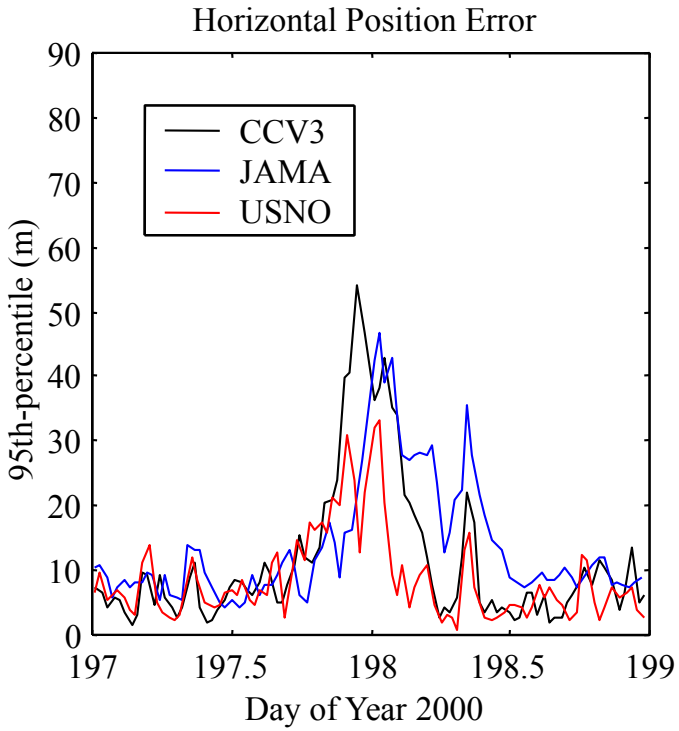
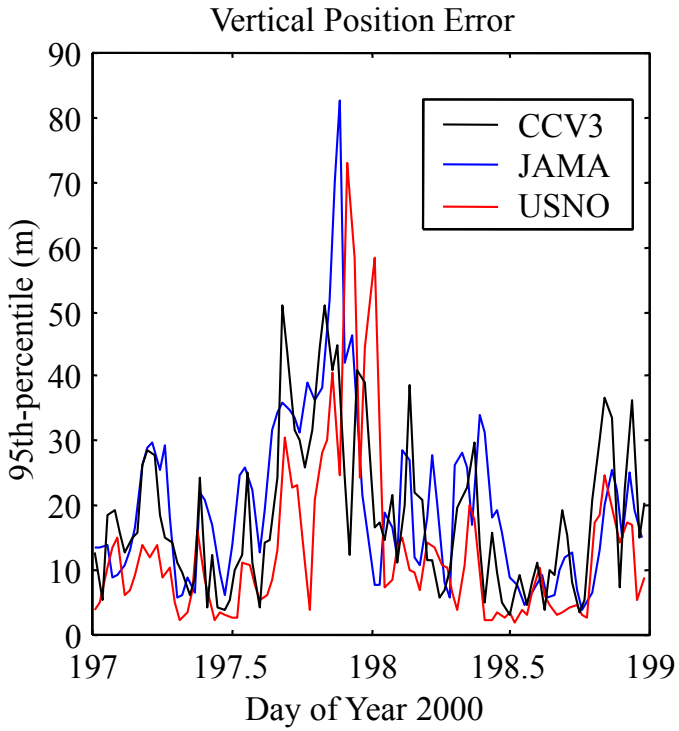
Single Point Positioning Accuracies (Single Frequency)





- Broadcast ionosphere model does not represent storm conditions accurately

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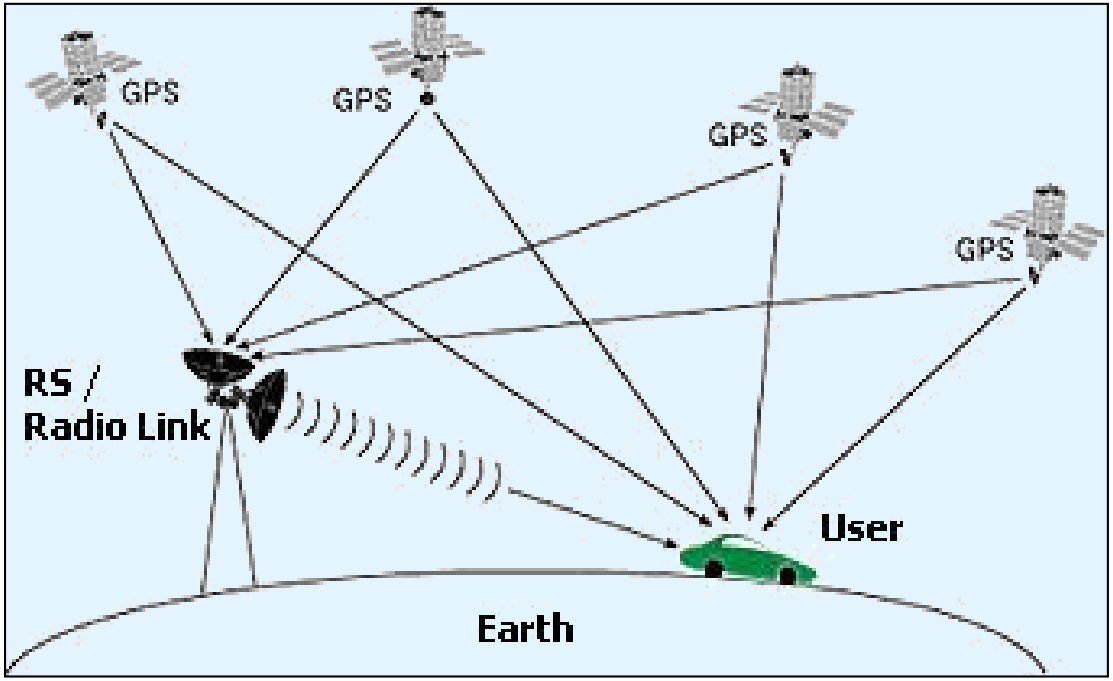
Differential GPS



- Range corrections measured at reference station and sent to remote users
- Without DGPS… your accuracy is 5-10 metres
- With DGPS…your accuracy improves to 0.5 - 2 metres
- Accuracy degrades with baseline distance

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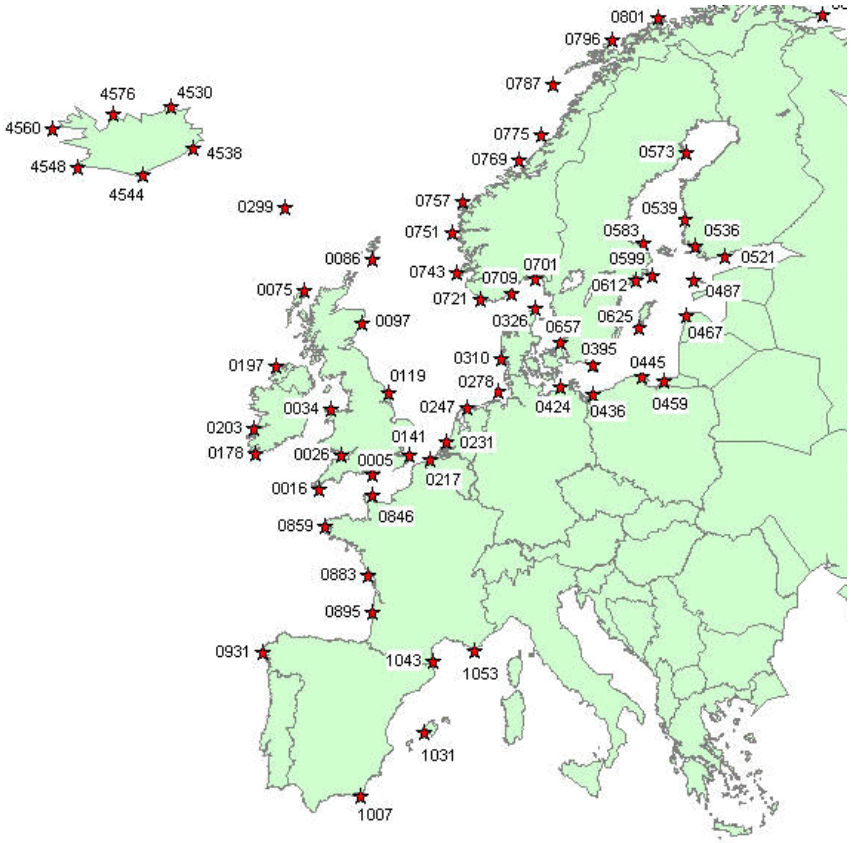
- Many service providers worldwide
- Horizontal positioning accuracies typically 1-2 m



http://www.effective-solutions.co.uk/beacons.html

(Fugro, 2010)

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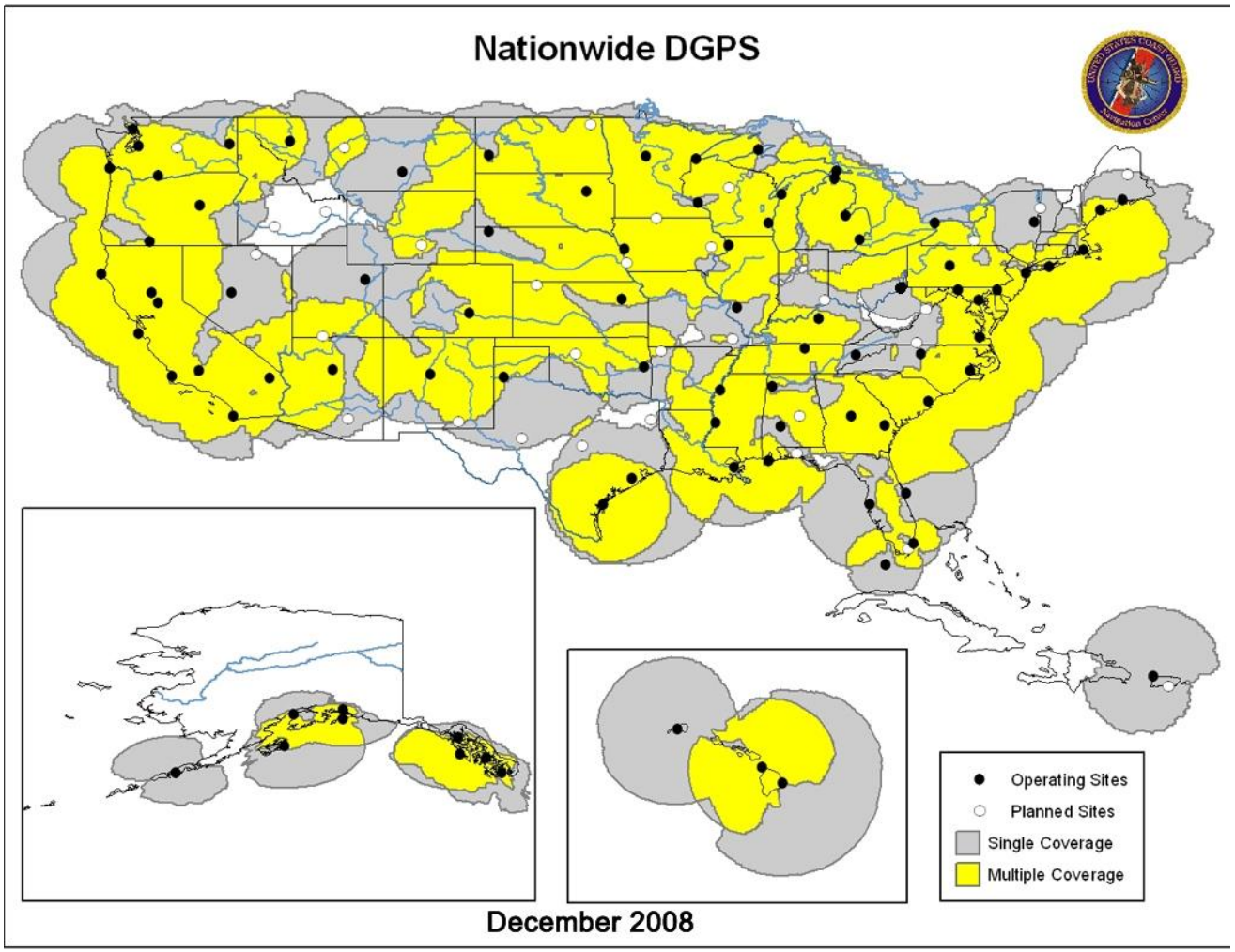
Nationwide DGPS (U.S.)



http://www.navcen.uscg.gov/dgps/coverage/CurrentCoverage.htm

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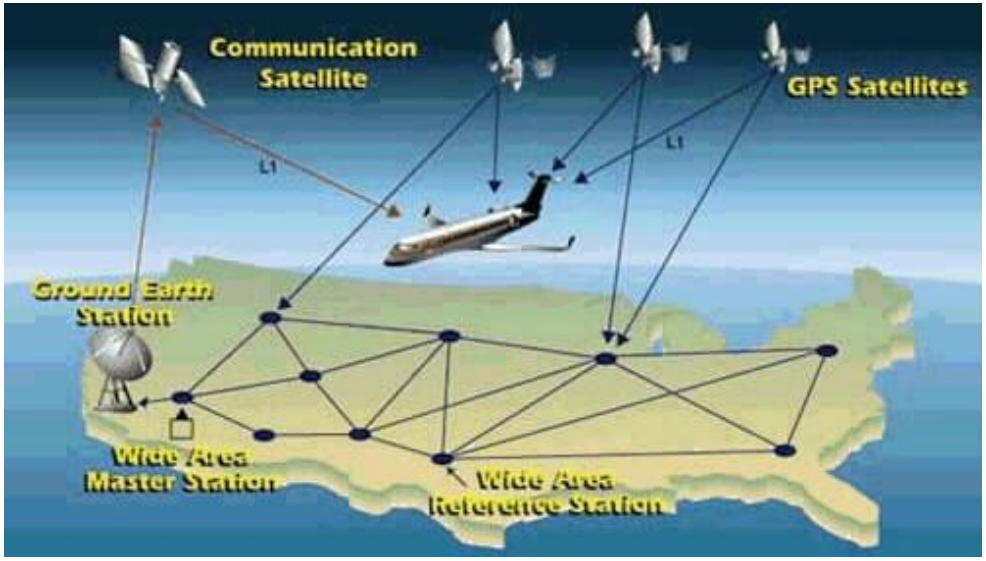
Applications

- Mapping and surveying, including hydrographic surveying
- Natural resource exploration and management
- Agriculture (seeding and harvesting)
- Environmental monitoring (GIS)
- Transportation – asset management, road construction, train control, and truck routing
- Emergency response

Satellite-Based Augmentation System



http://www.nstb.tc.faa.gov

- Satellite clock, orbit and ionosphere corrections estimated using dual-frequency reference network
- Ionosphere corrections defined on (typically) 5 deg by 5 deg grid
- Positioning accuracies typically 1-3 m
- WAAS implemented in United States for commercial aviation; EGNOS in Europe; extension to Africa
- SBAS positioning capabilities in low-cost receivers (marine and land applications)

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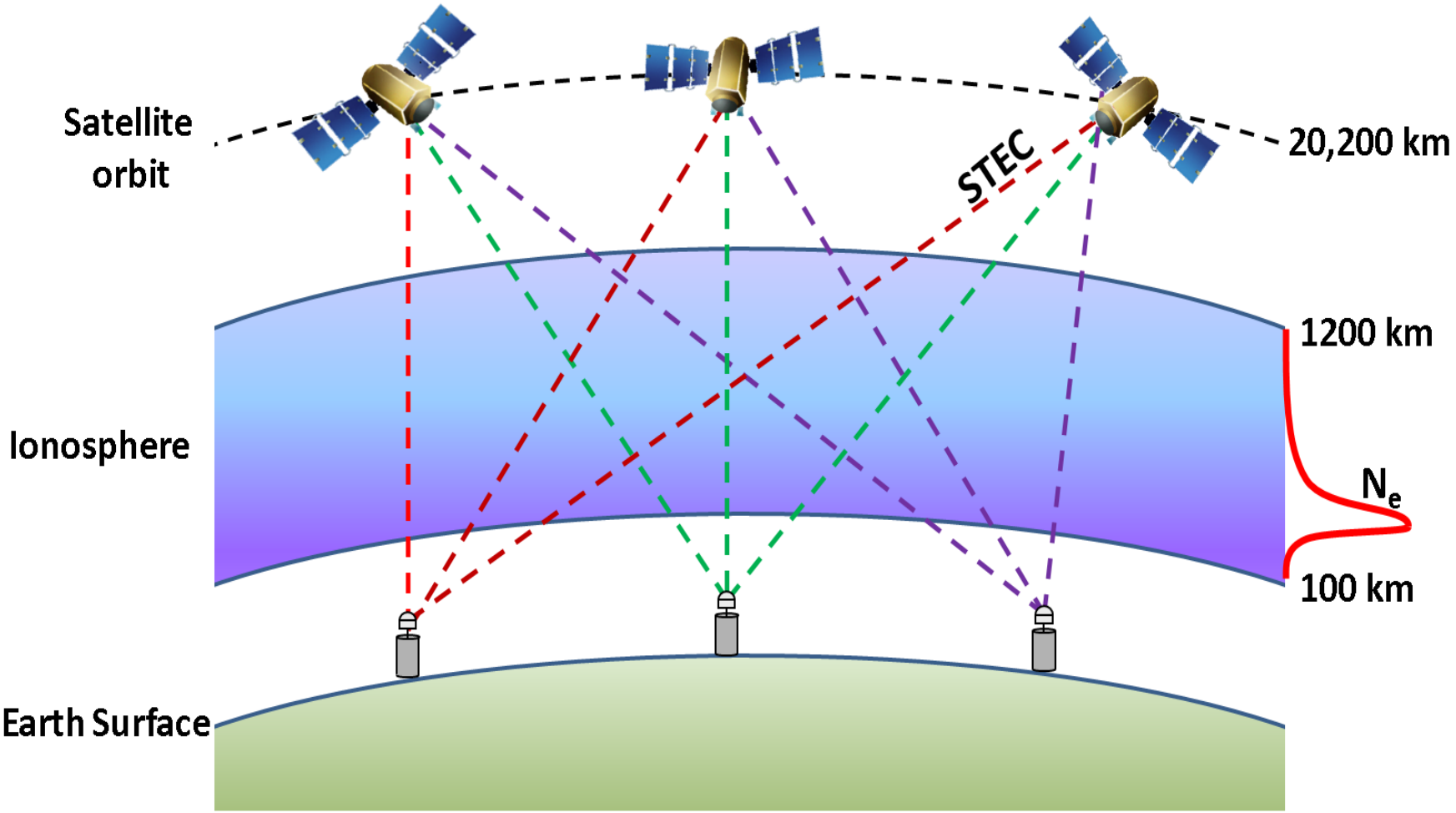
Wide Area Ionosphere Observations



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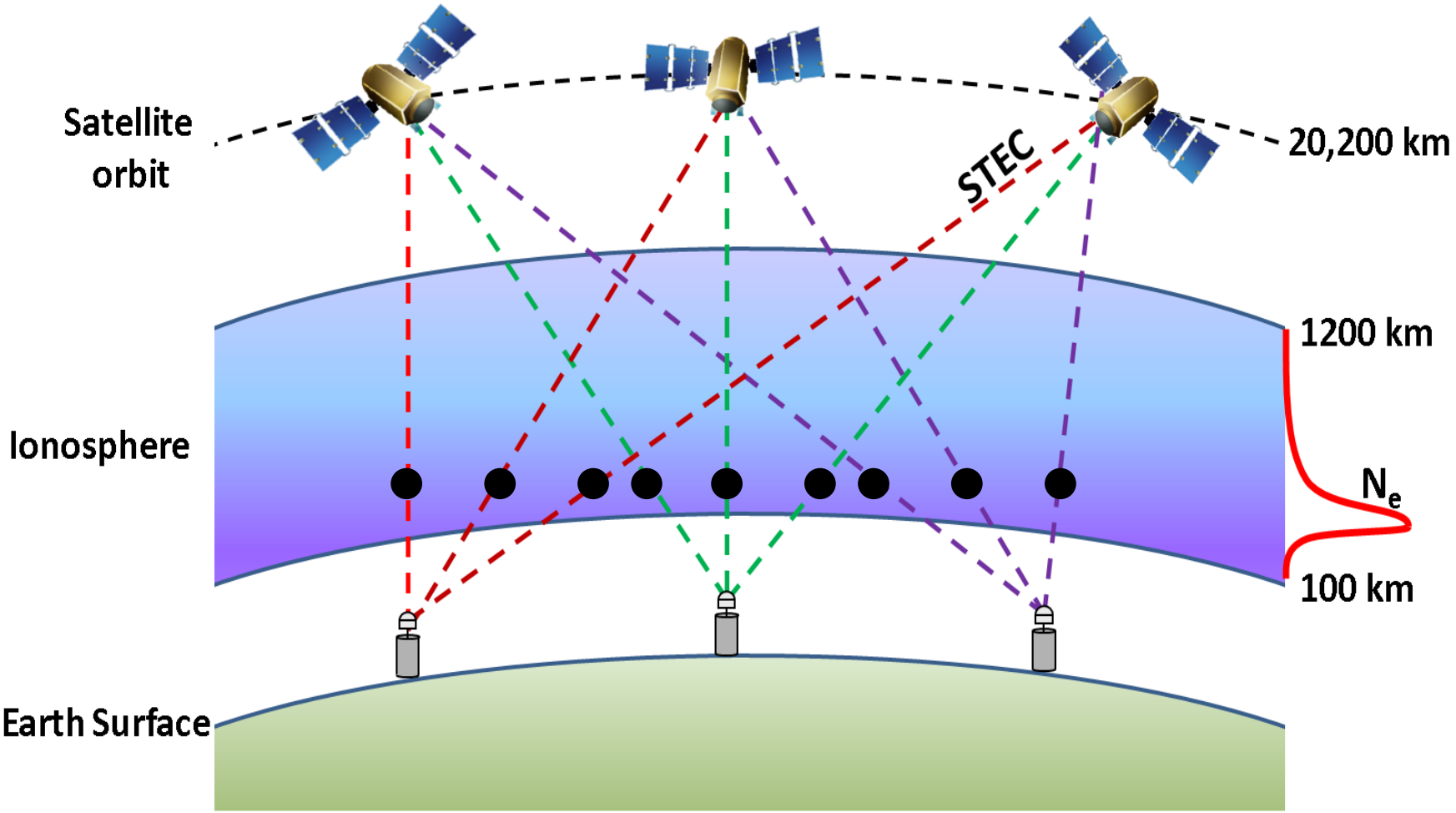
Mapped to Two Dimensions



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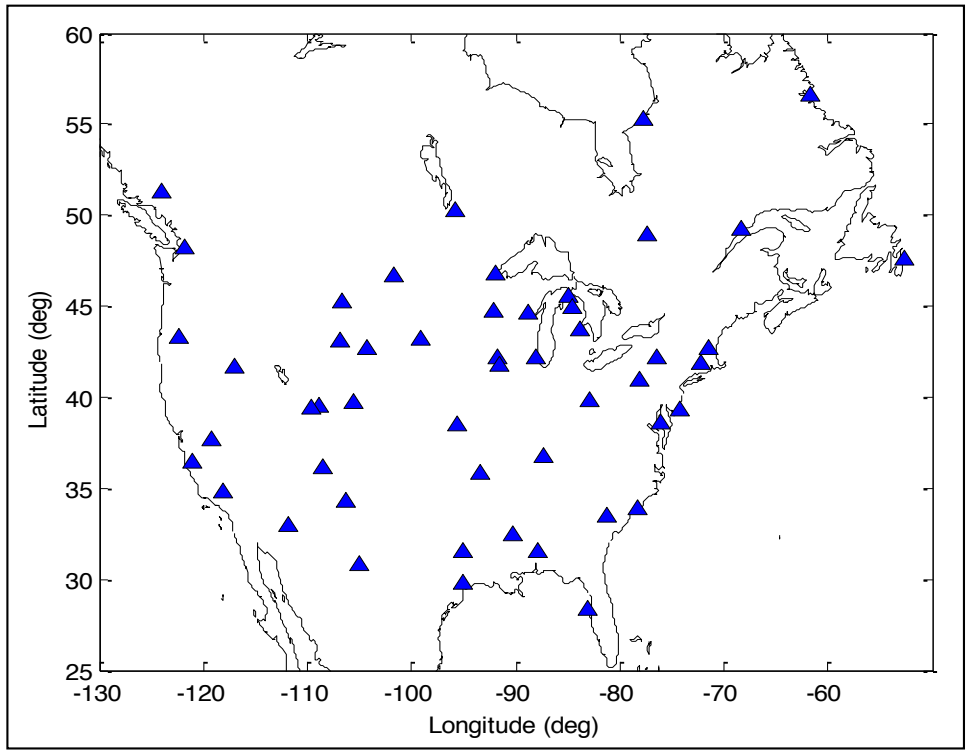
Wide Area Differential GPS Network



Real-time GPS reference stations (dual frequency)

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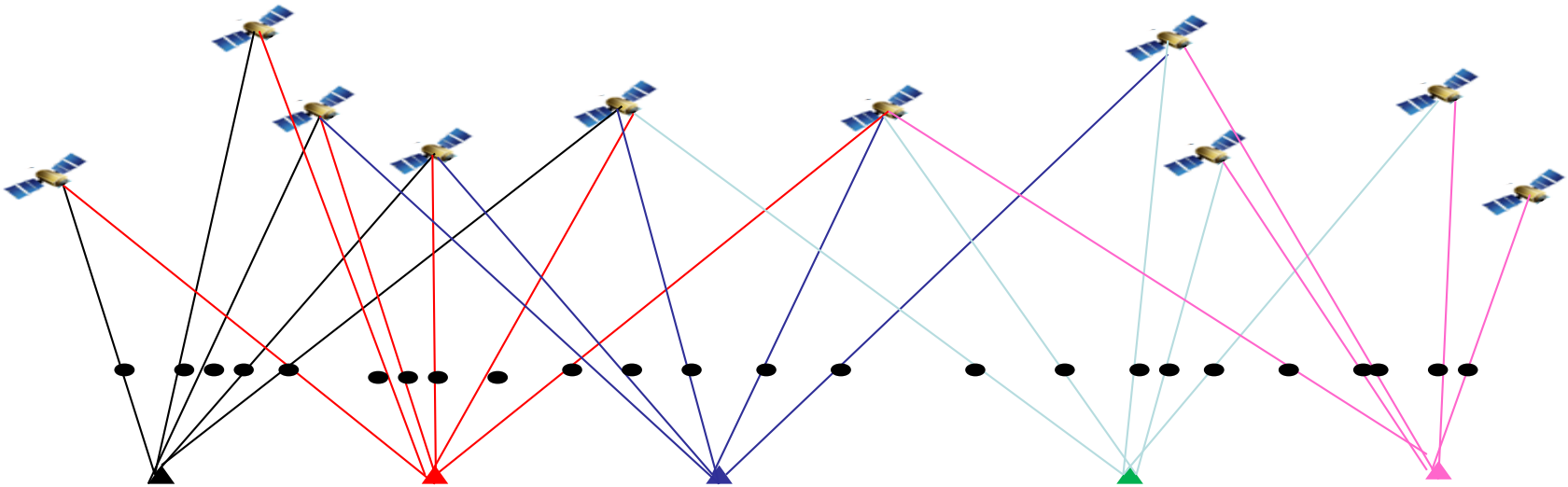
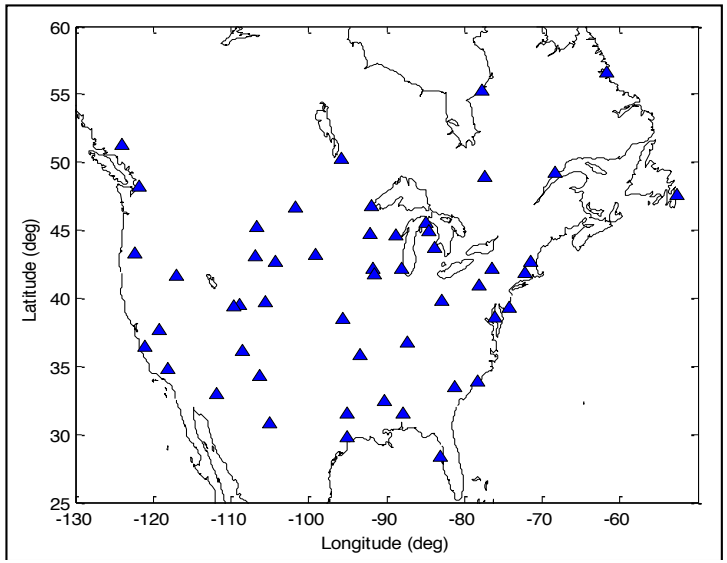
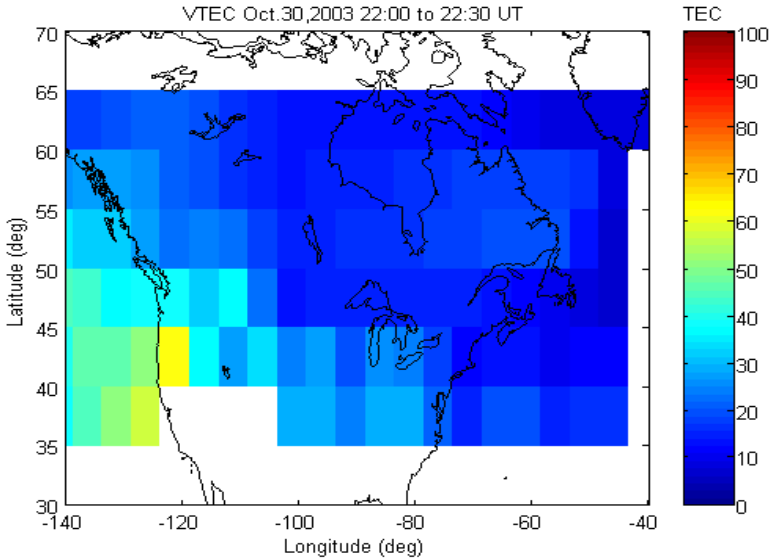
Network Observations and Output



$$F = a_0 + a_1\Delta\lambda + a_2\Delta\phi$$





Wide Area Approach

Broadcast Navigation Message

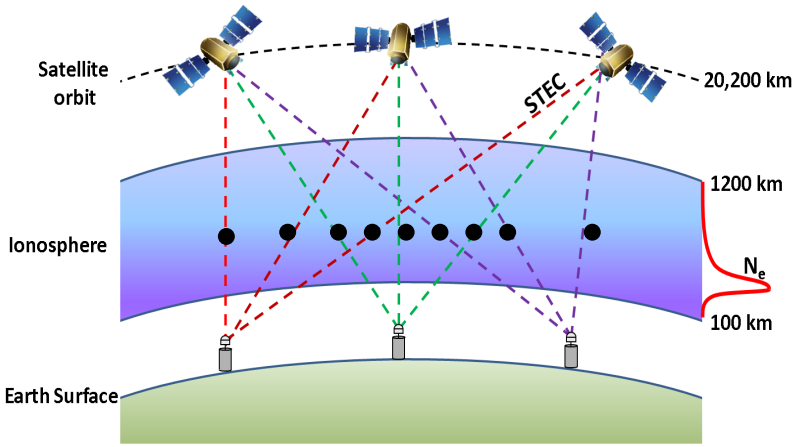
Satellite pseudorange and carrier phase observations

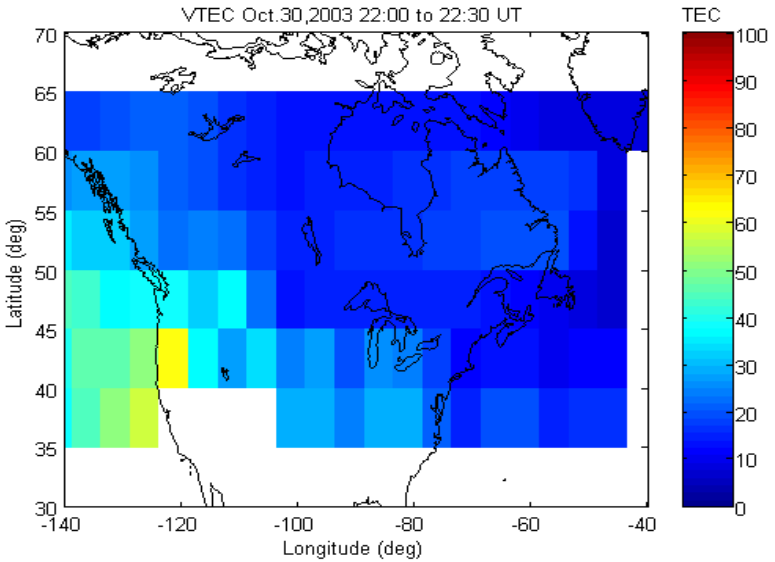
Satellite elevation angles

Derive ionospheric observables

Compute IPPs and mapping functions

Estimate 2D model in latitude and local time





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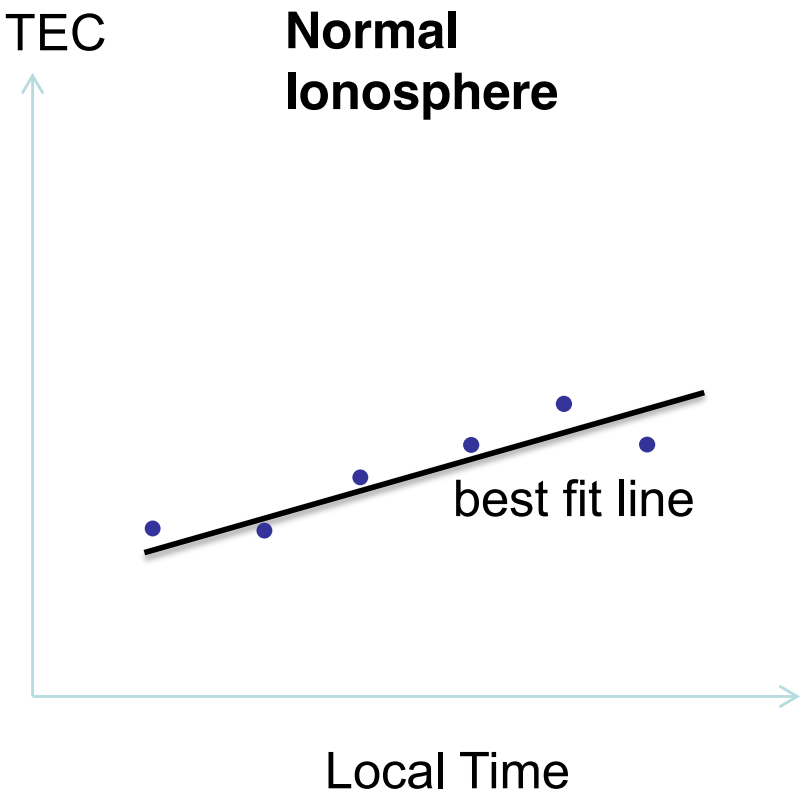
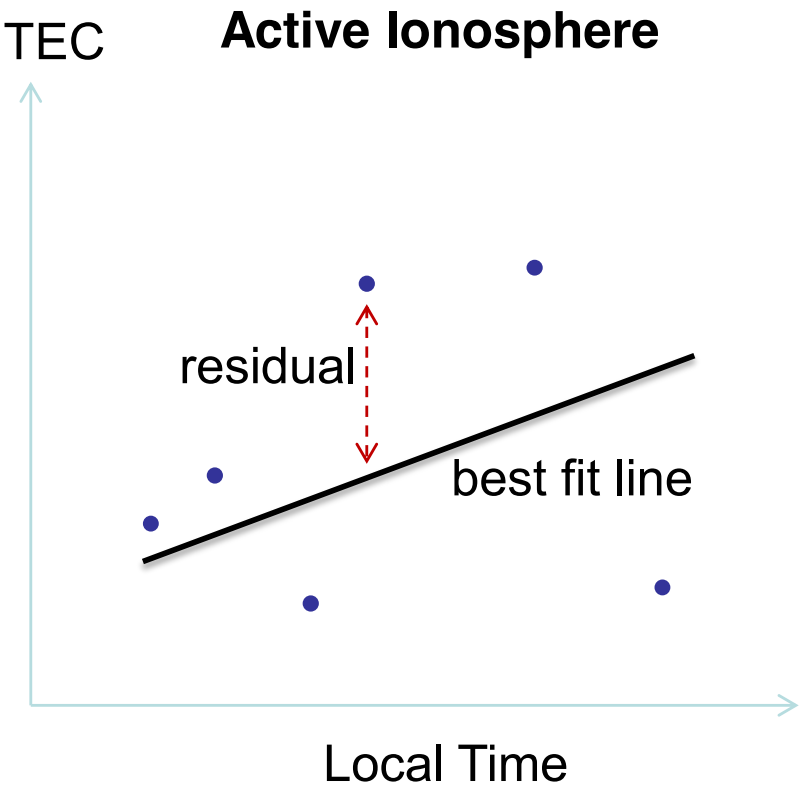
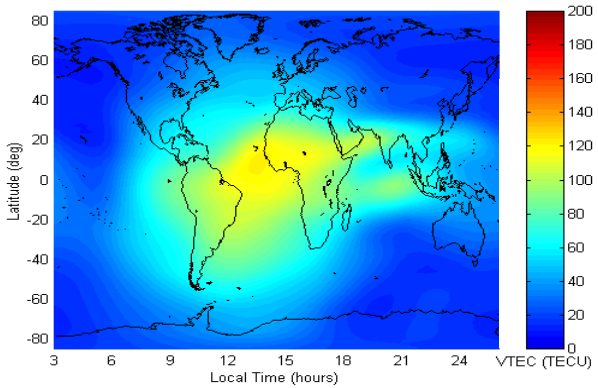
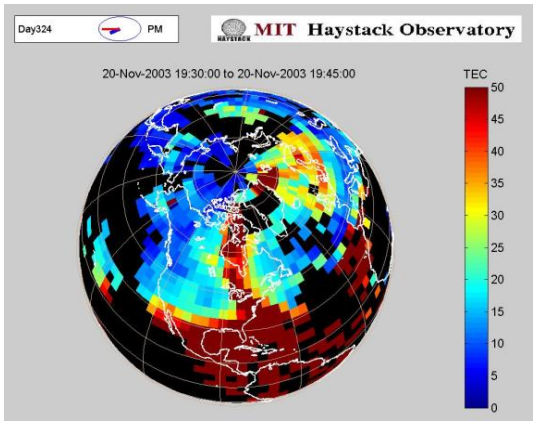
Error Bounds









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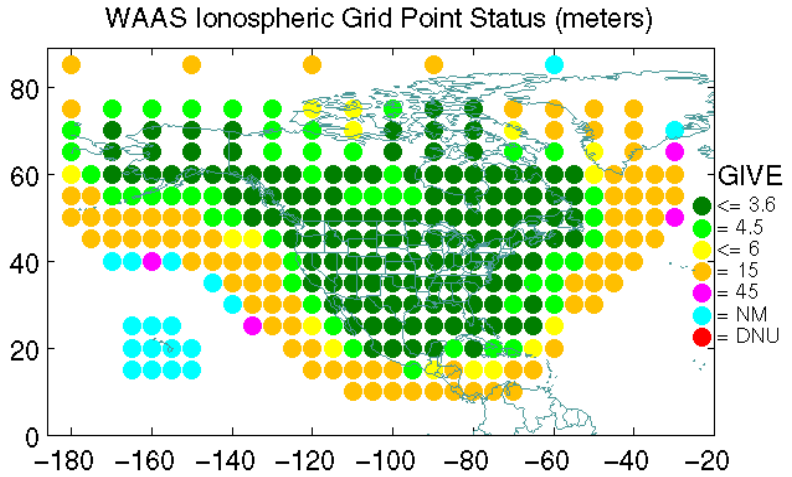
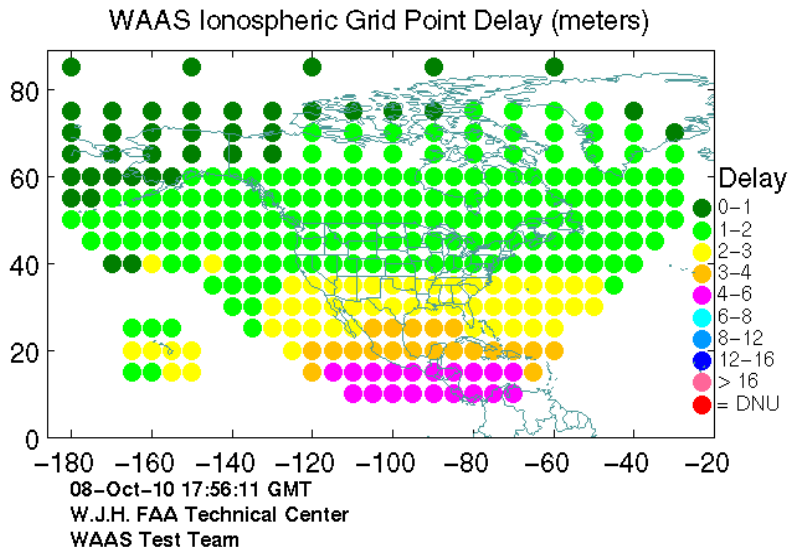
Example: WAAS Error Bounds

Aviation certified receivers make use of GIVE

Low-cost single frequency GPS receivers do NOT make use of GIVE





[http://www.nstb.tc.faa.gov/RT_WaasSIGPStatus.htm]

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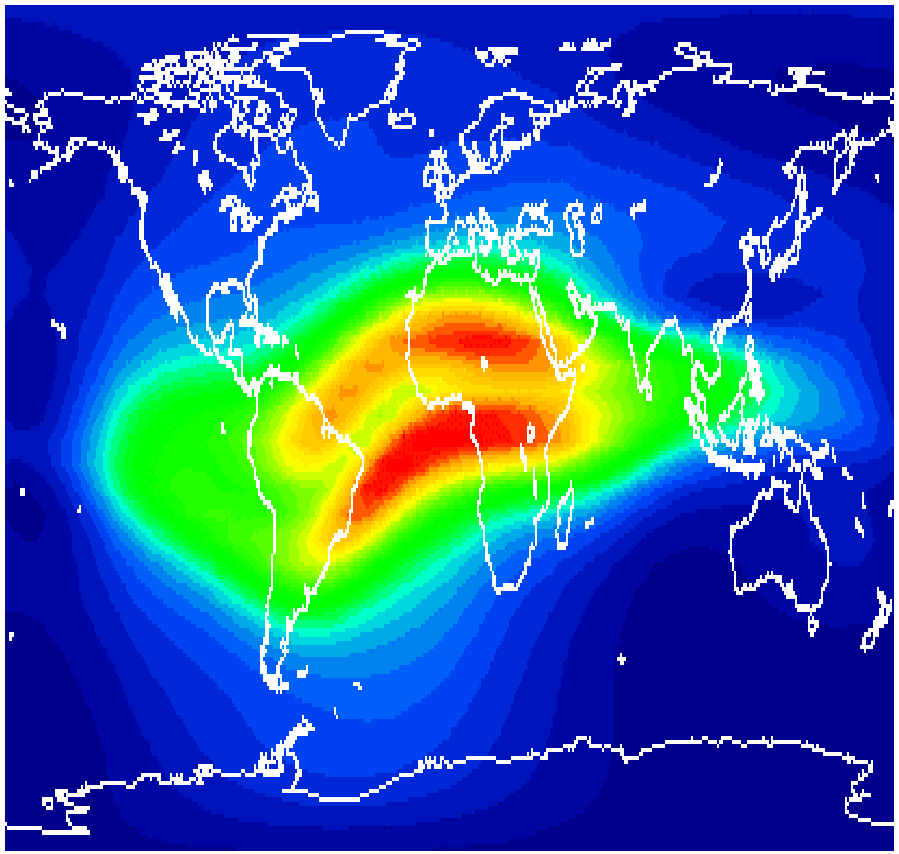
Equatorial Anomaly



- two maxima in TEC (±15° mag)
- primary peak at 1400
- secondary peak at 2100
- large gradients: 30 ppm
- scintillations
- largest peaks observed during equinoxes at solar maximum

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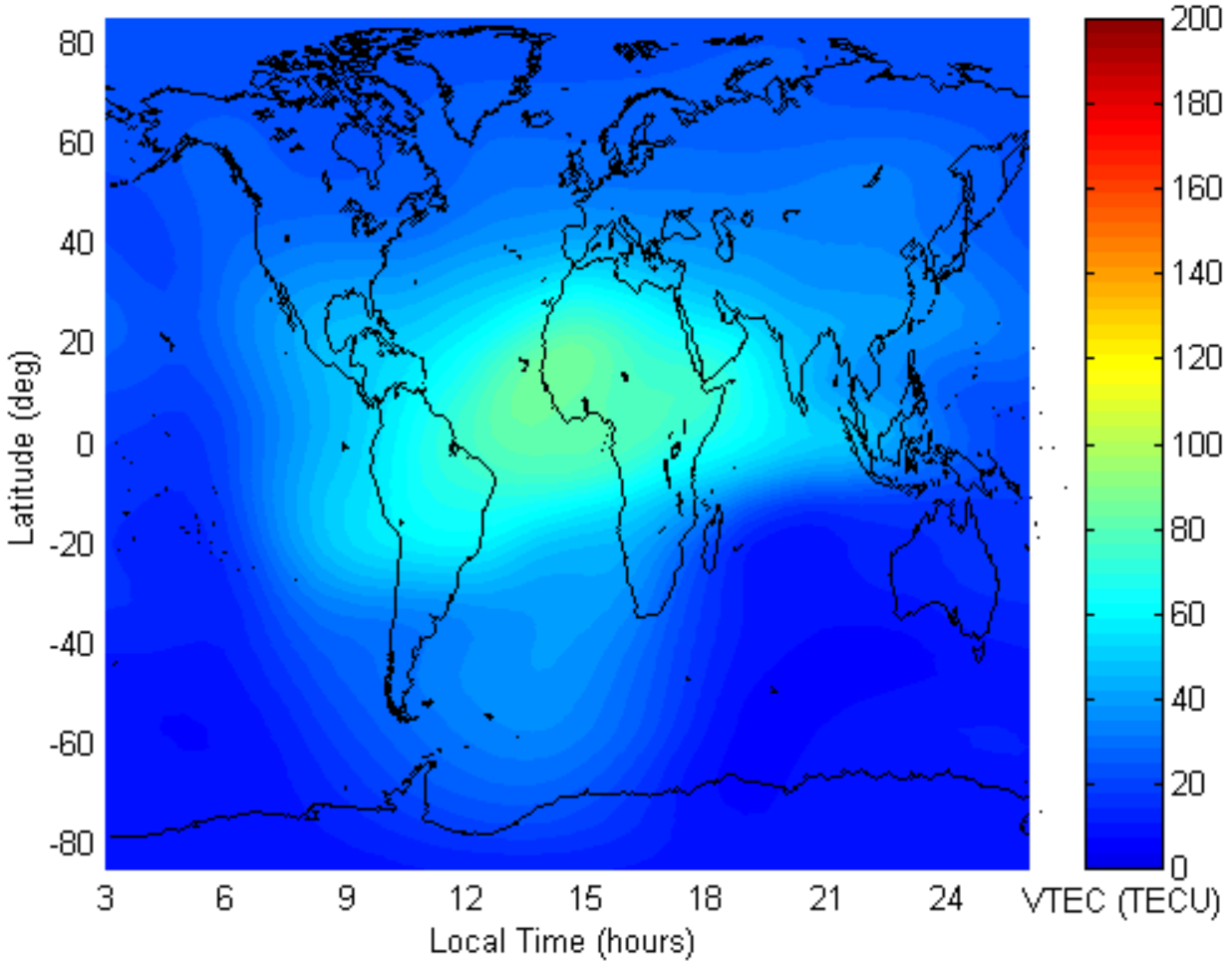
Spatial Distribution of VTEC during Solar Maximum

June 2000



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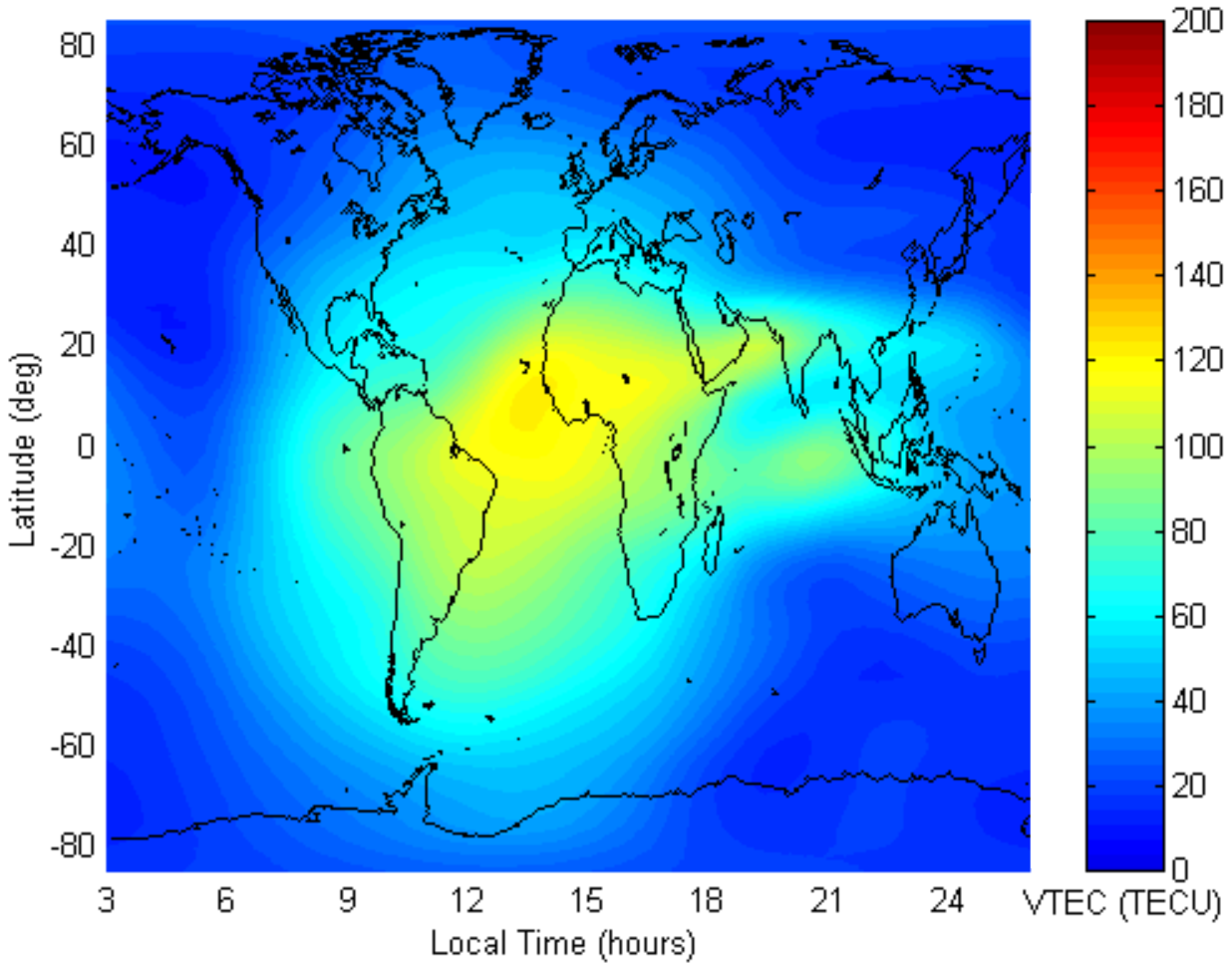
Spatial Distribution of VTEC during Solar Maximum (Equinox)

March 2000



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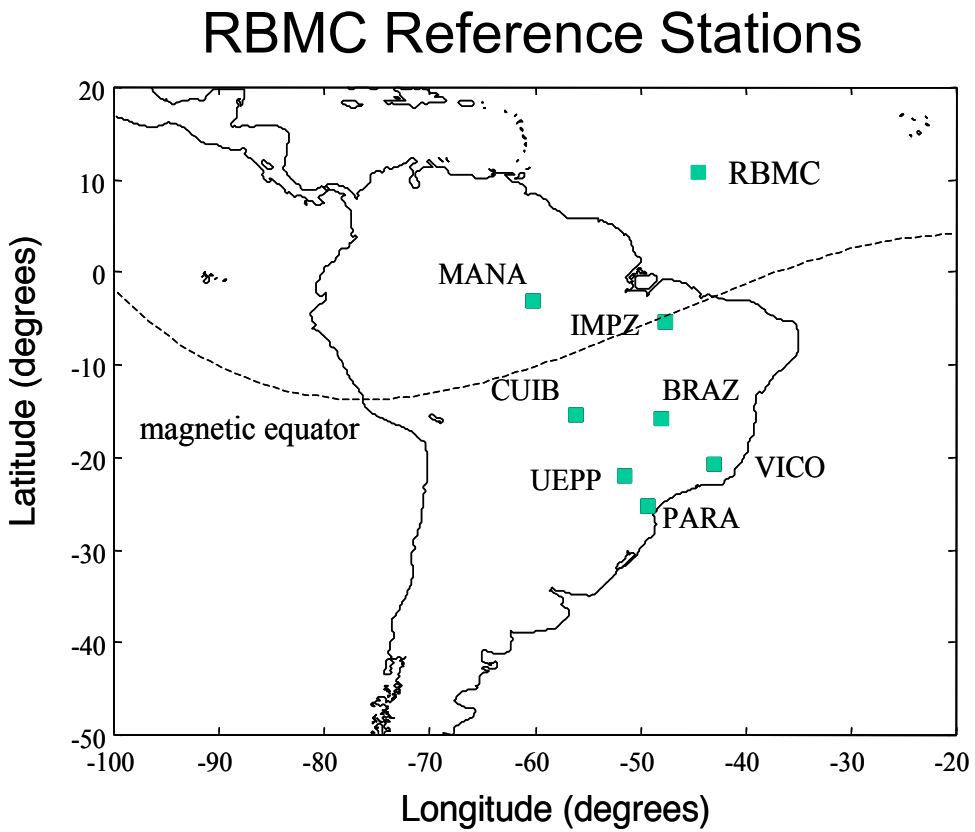
Low Latitude DGPS at Solar Maximum



- DGPS positioning accuracies computed for UEPP-PARA baseline (430 km)

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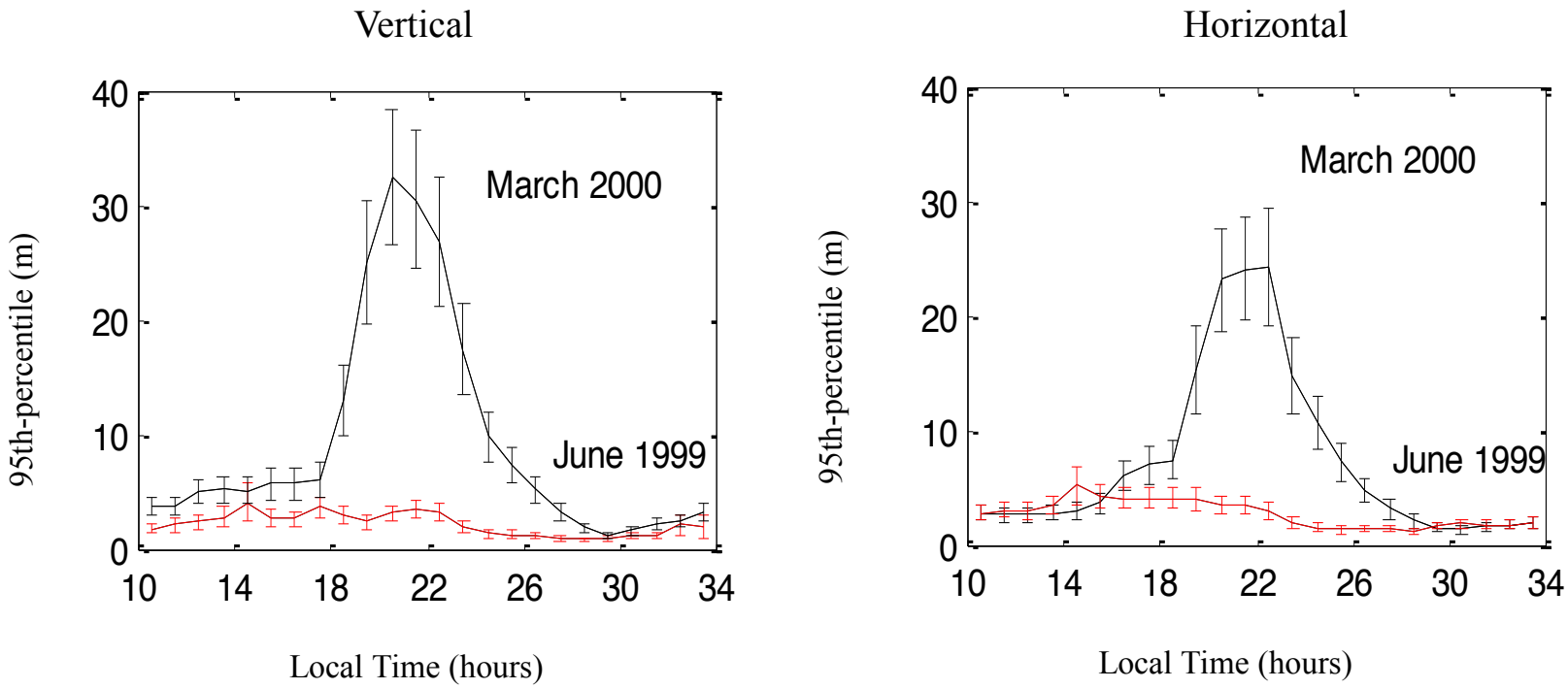
DGPS Positioning Accuracies



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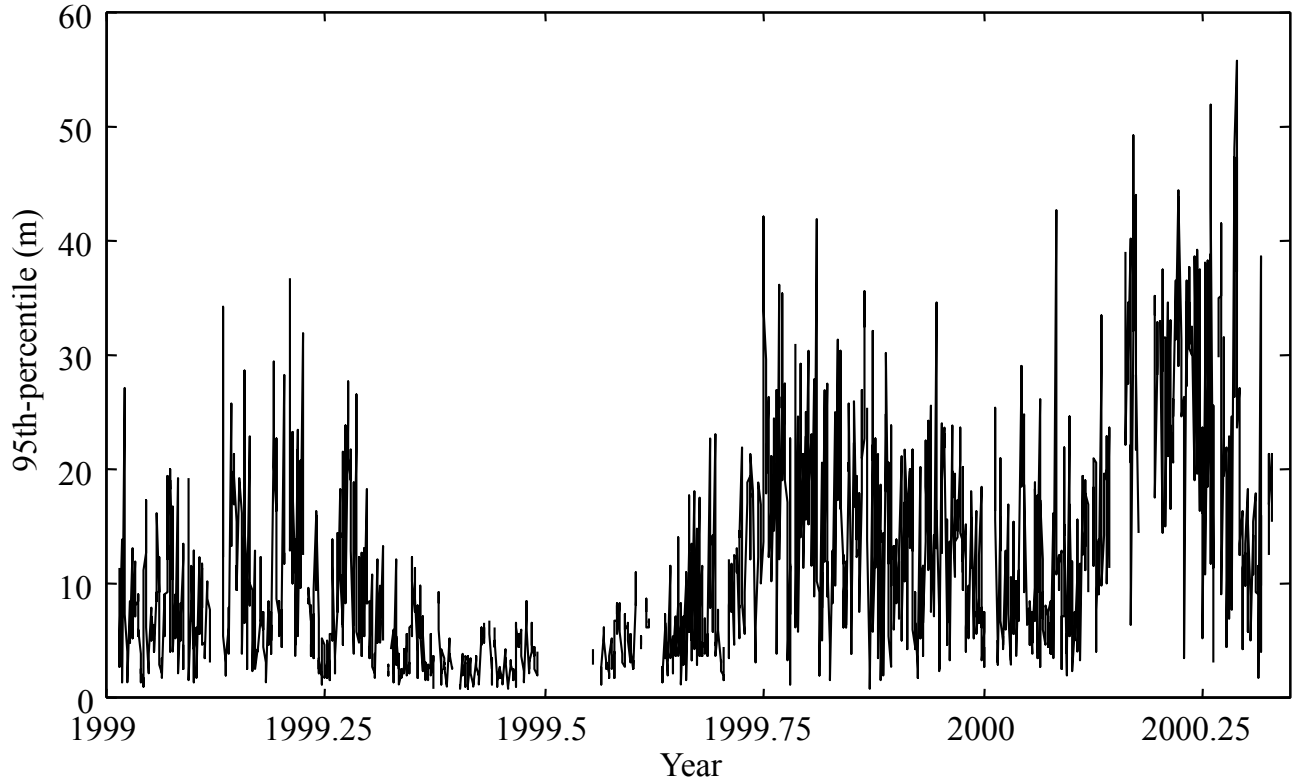
Horizontal DGPS Positioning Accuracies – Evening Sector



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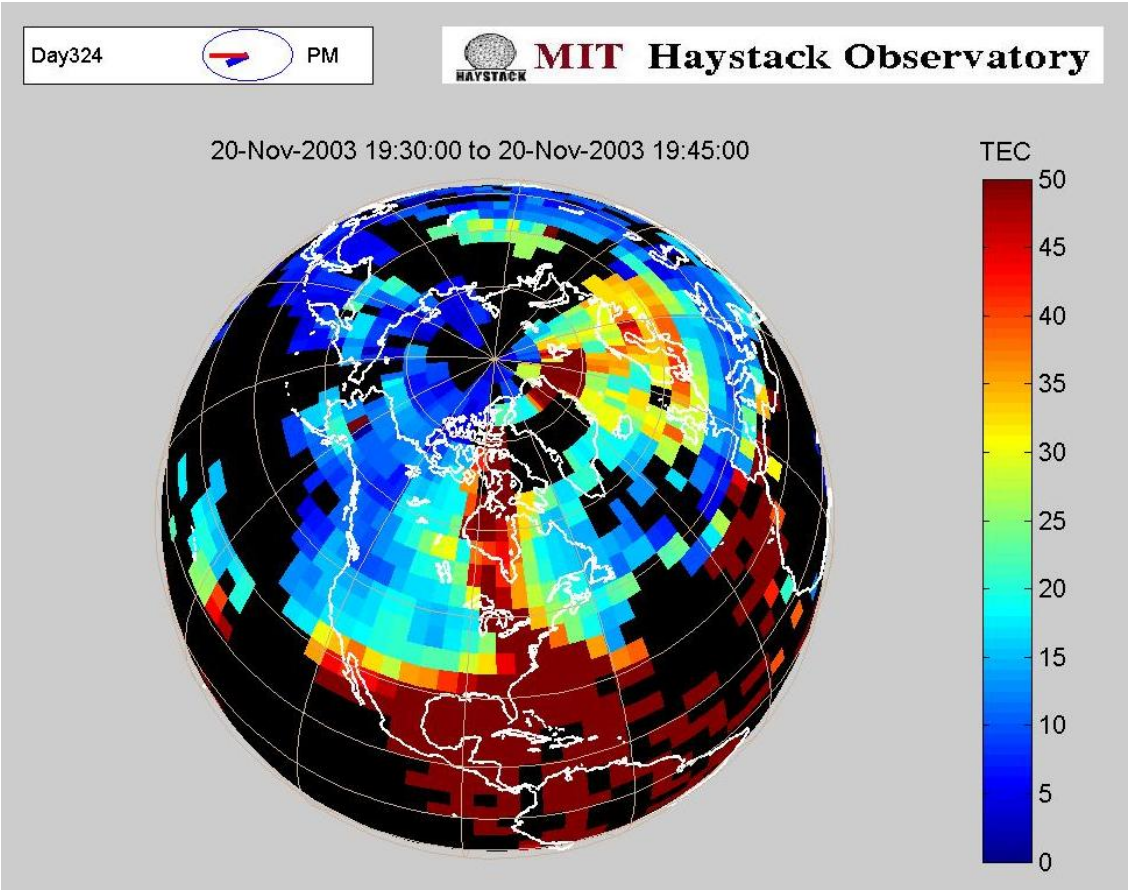
Storm-Enhanced Density



Range Error:

$$I = \pm 40.3 \frac{TEC}{f^2}$$

- Impact on GNSS applications?
- Plume extends 1000 km E-W
- Gradients of 30-50 ppm near edges of plume (E-W) and base of plume (N-S)
- Conjugate effects in northern and southern hemispheres – impact in Africa

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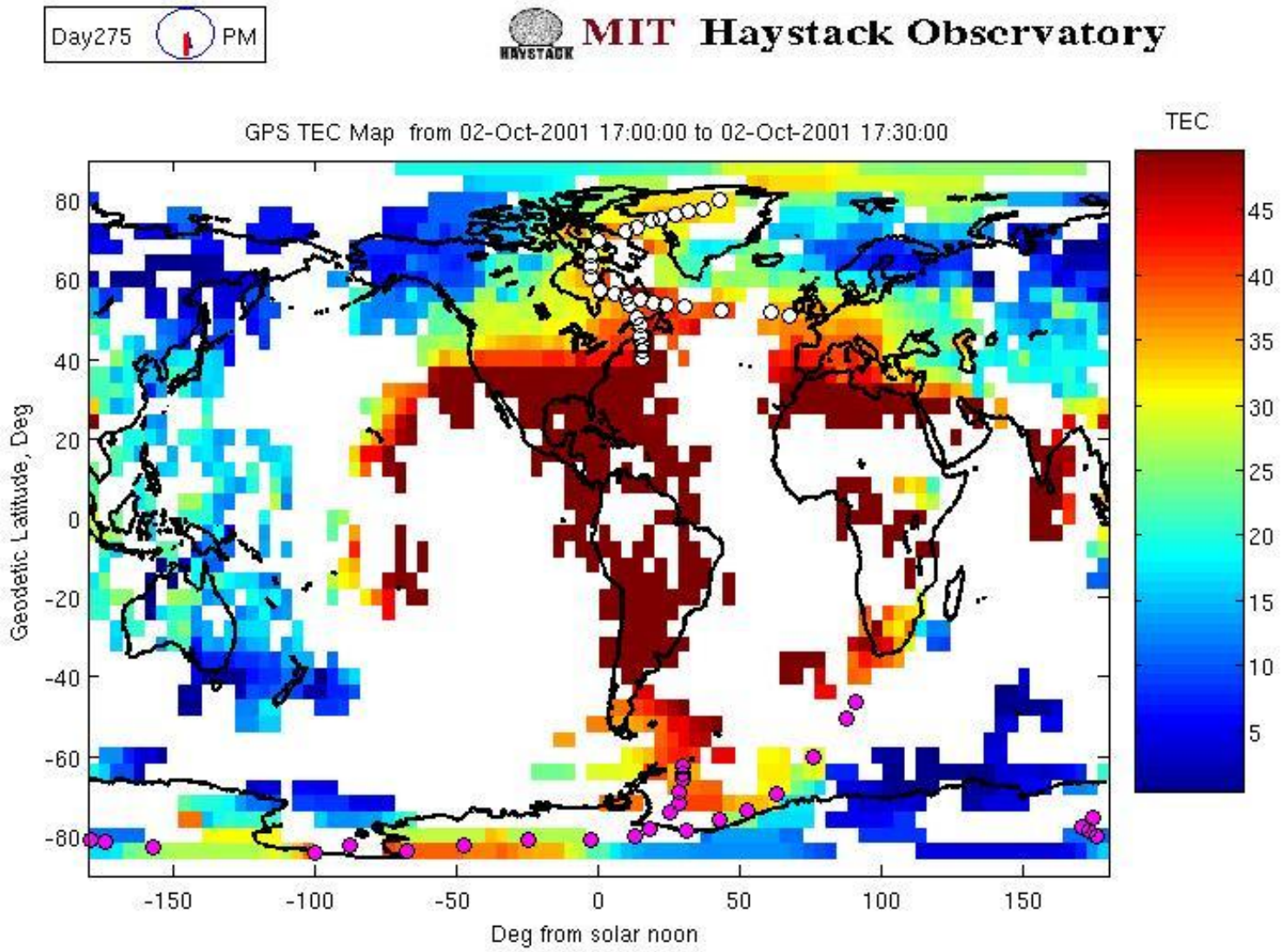
Conjugate Effects: 1730 Oct 2, 2001



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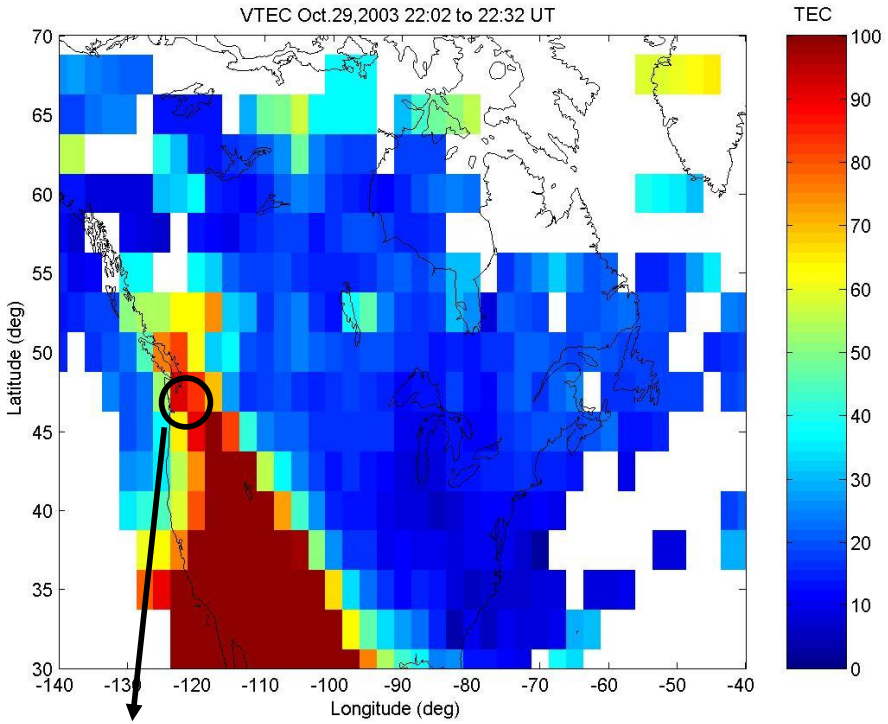
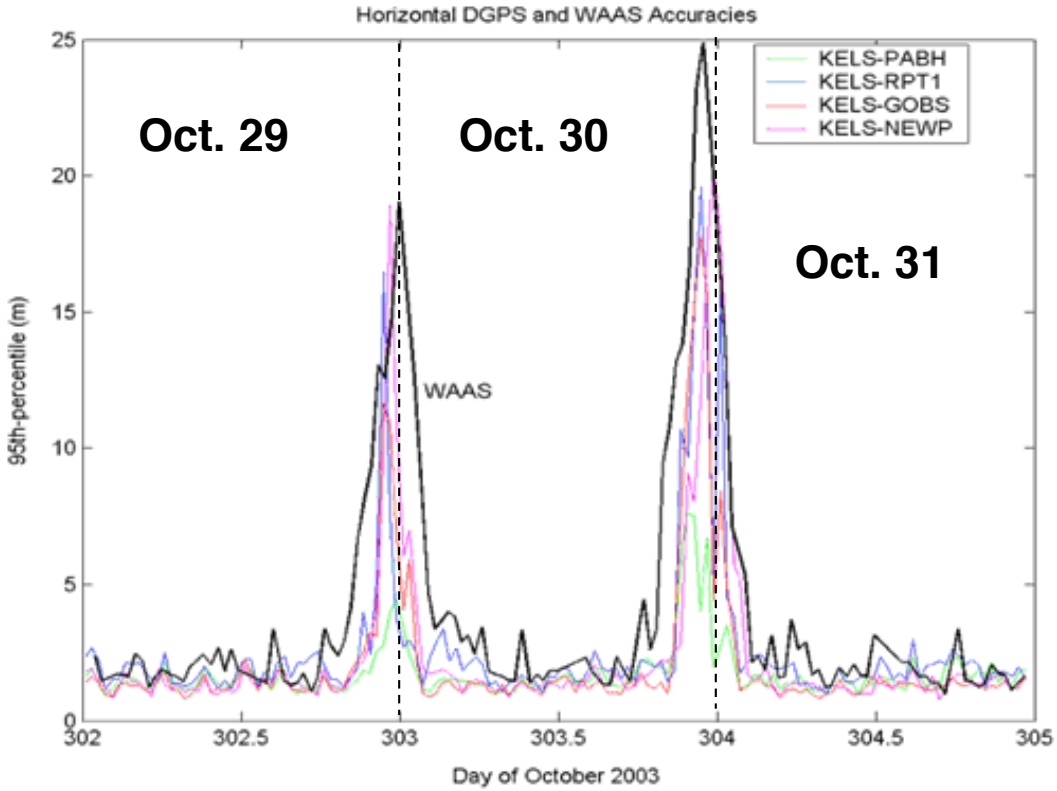
GEOMATICS ENGINEERING

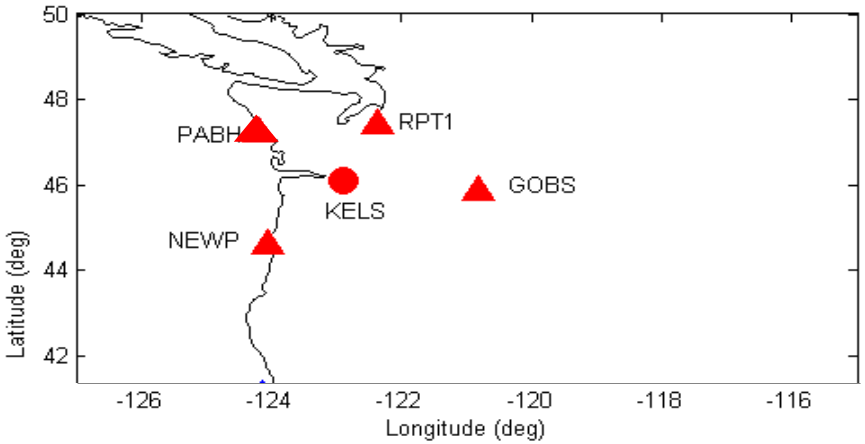
SCHULICH School of Engineering

UNIVERSITY OF CALGARY

SED Event 29-31 October 2003



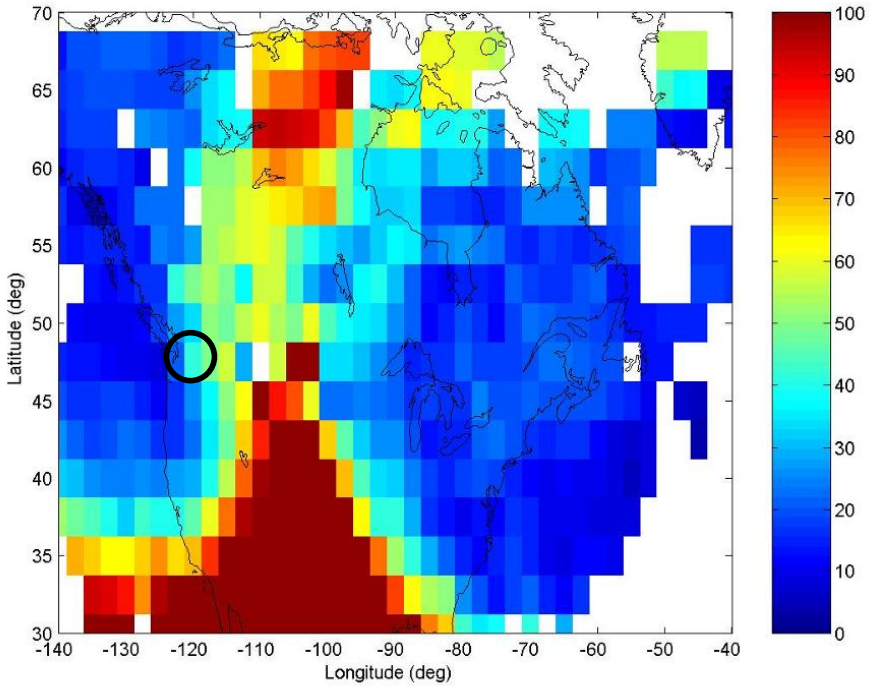




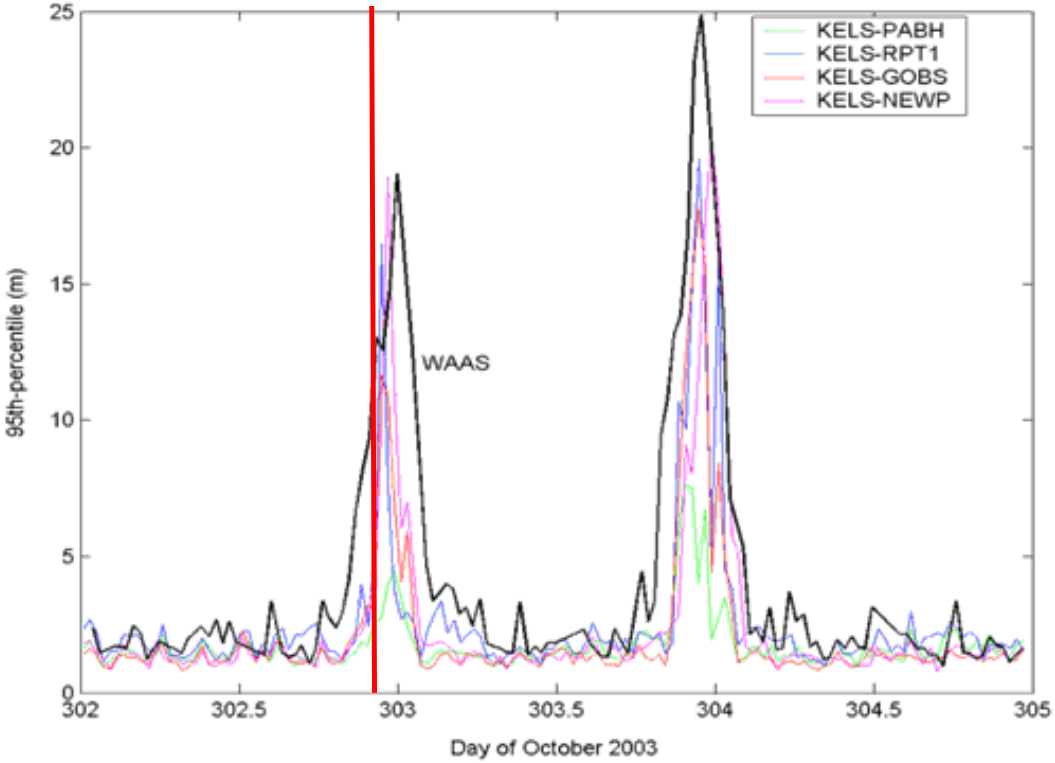
STATION PAIR (USER-REFERENCE)	BASELINE LENGTH (KM)
KELS-PABH	158
KELS-RPT1	147
KELS-GOBS	164
KELS-NEWP	193

DGPS&WAAS Horizontal Positioning Errors: 29 October 2003

Ionosphere Map: 2130 UT



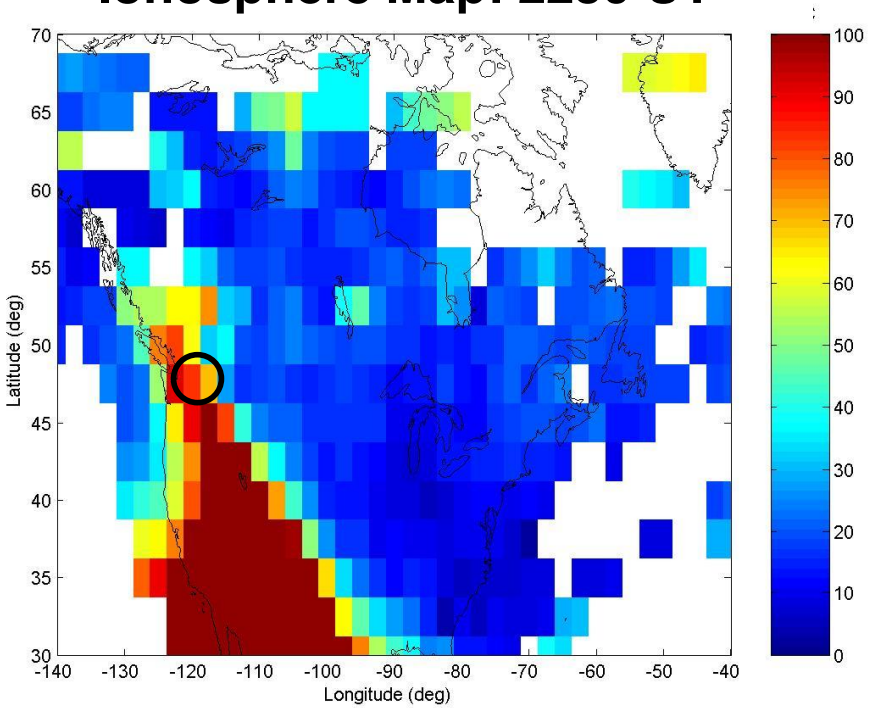
Horizontal Position Errors



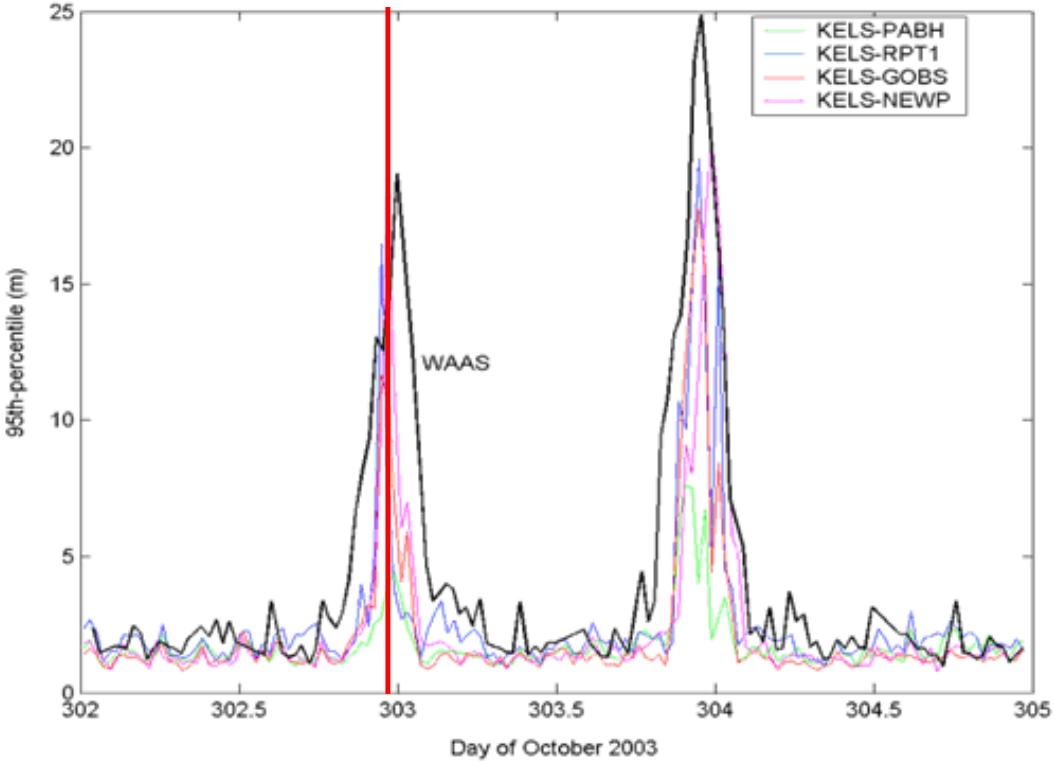
S. Skone/2012

DGPS&WAAS Horizontal Positioning Errors: 29 October 2003

Ionosphere Map: 2230 UT



Horizontal Position Errors



Gradient = 30 ppm

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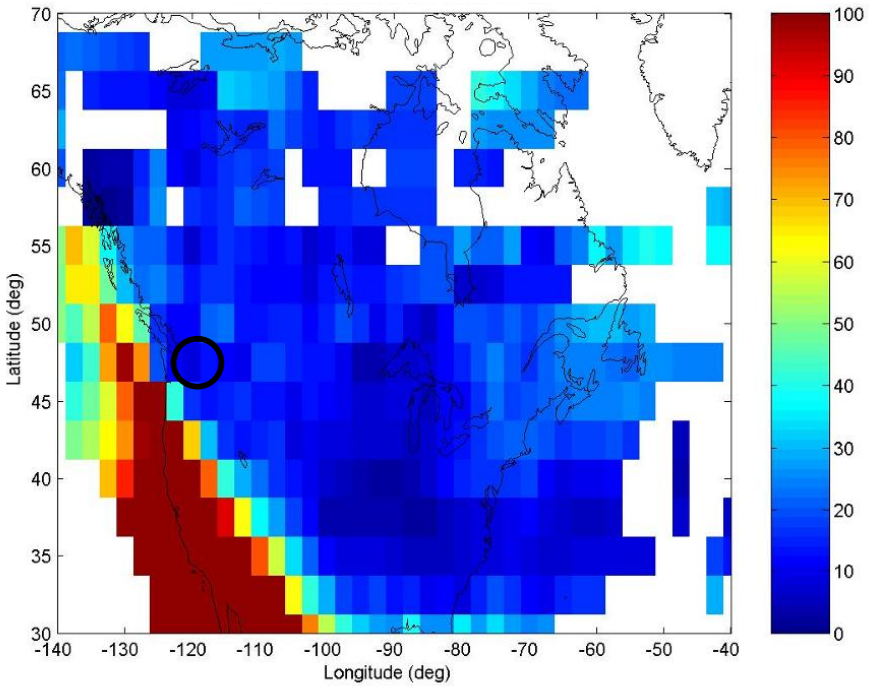
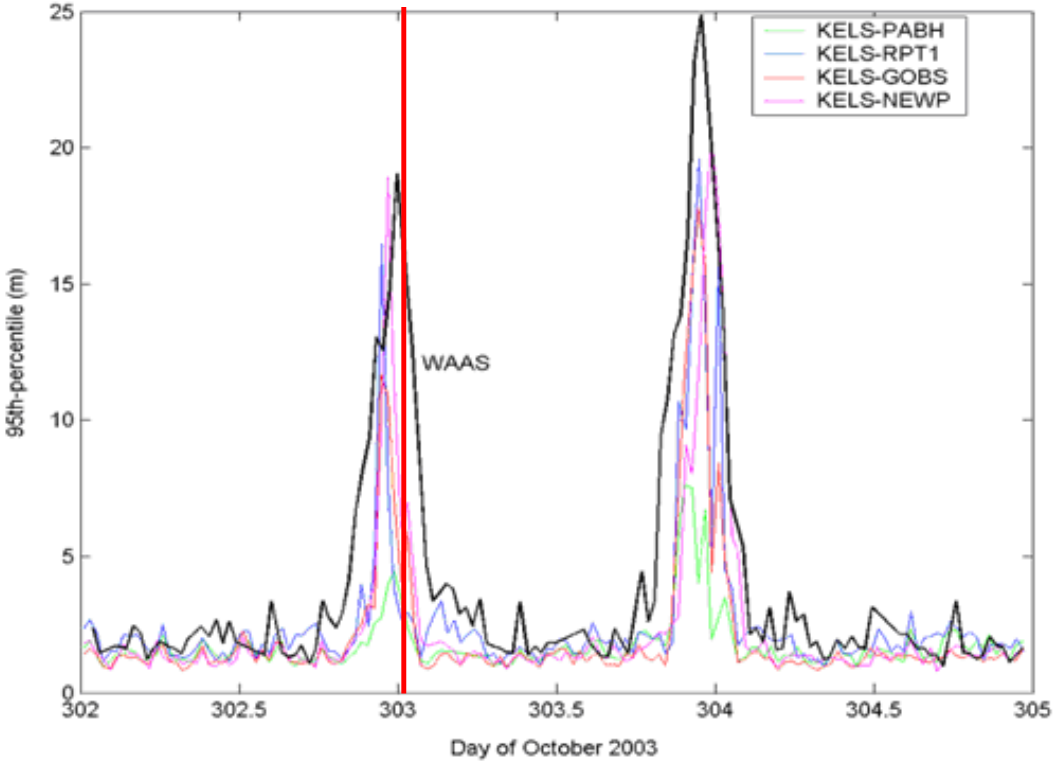
DGPS&WAAS Horizontal Positioning Errors: 29 October 2003

Ionosphere Map: 2330 UT



Horizontal Position Errors



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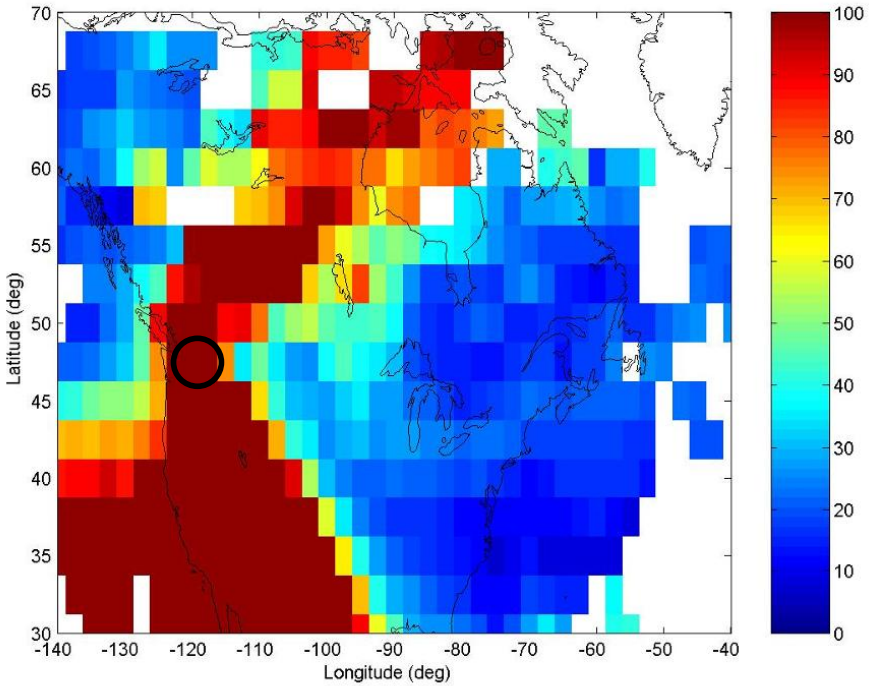
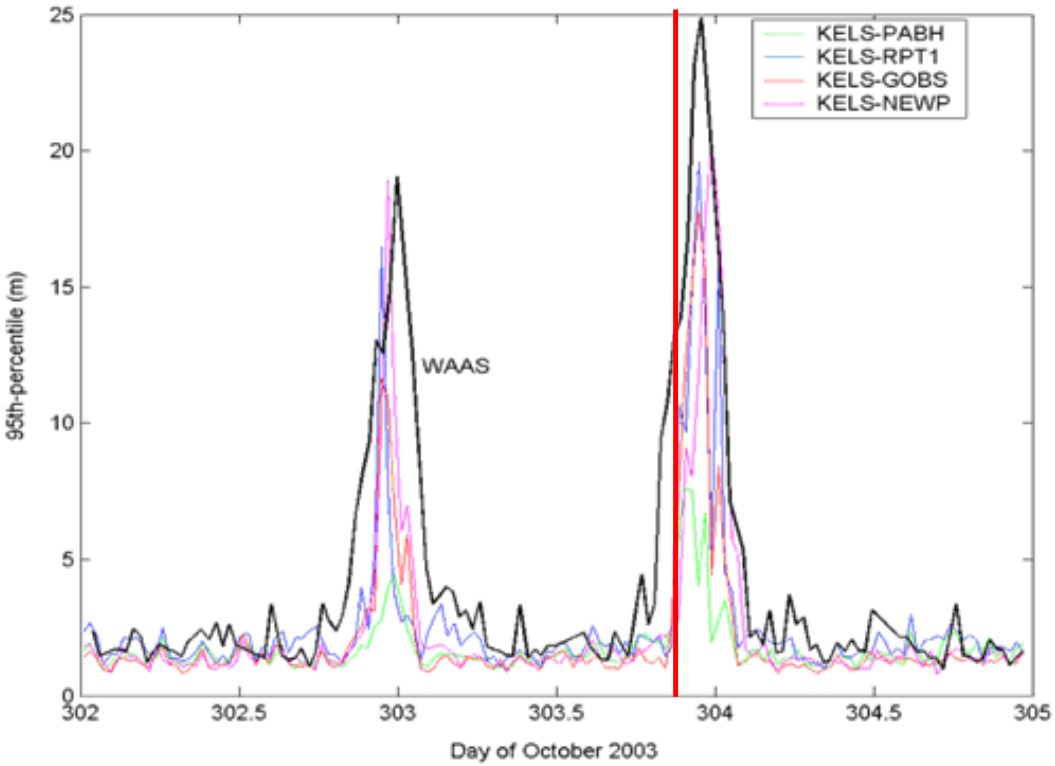
DGPS&WAAS Horizontal Positioning Errors: 29 October 2003

Ionosphere Map: 2130 UT



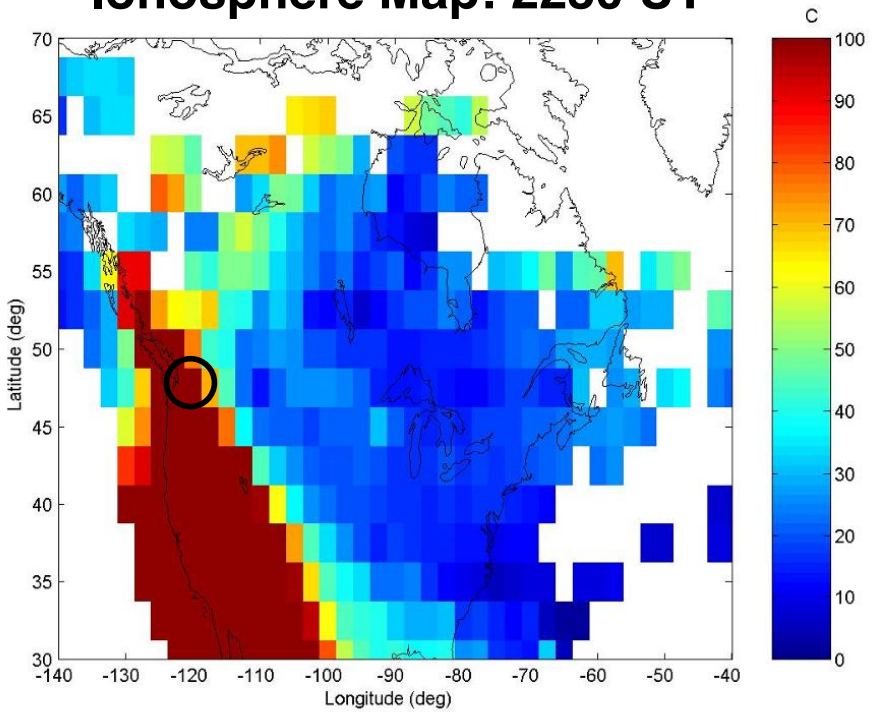
Horizontal Position Errors



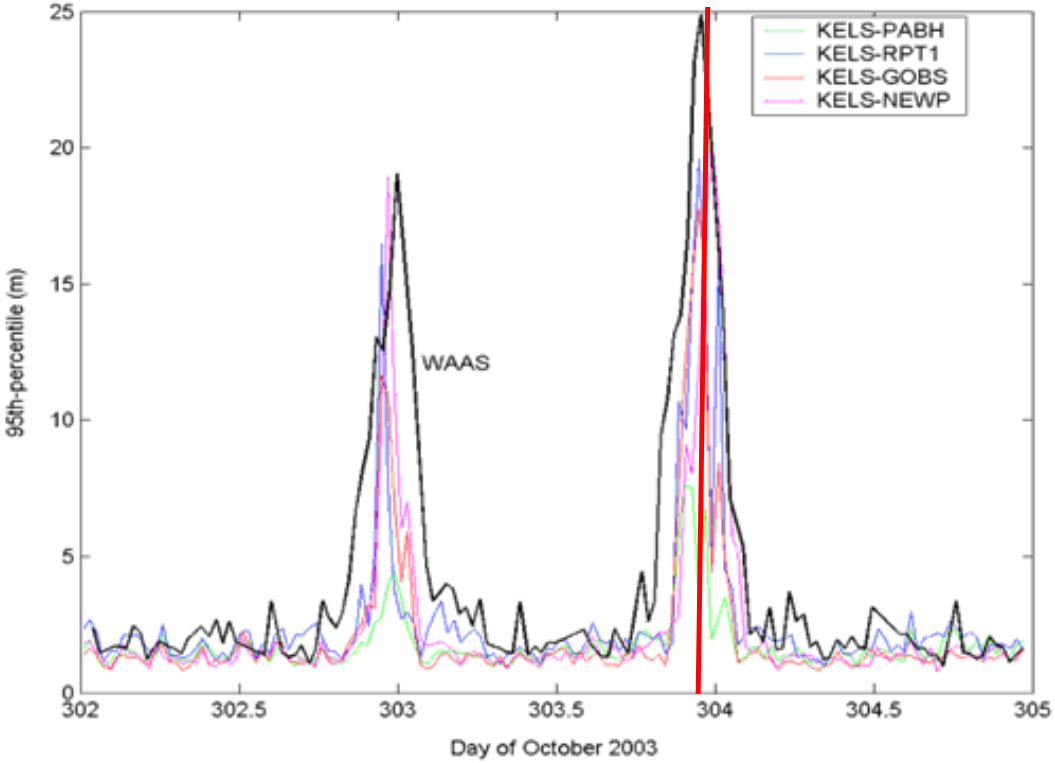
S. Skone/2012

DGPS&WAAS Horizontal Positioning Errors: 29 October 2003

Ionosphere Map: 2230 UT



Horizontal Position Errors



Gradient = 35 ppm

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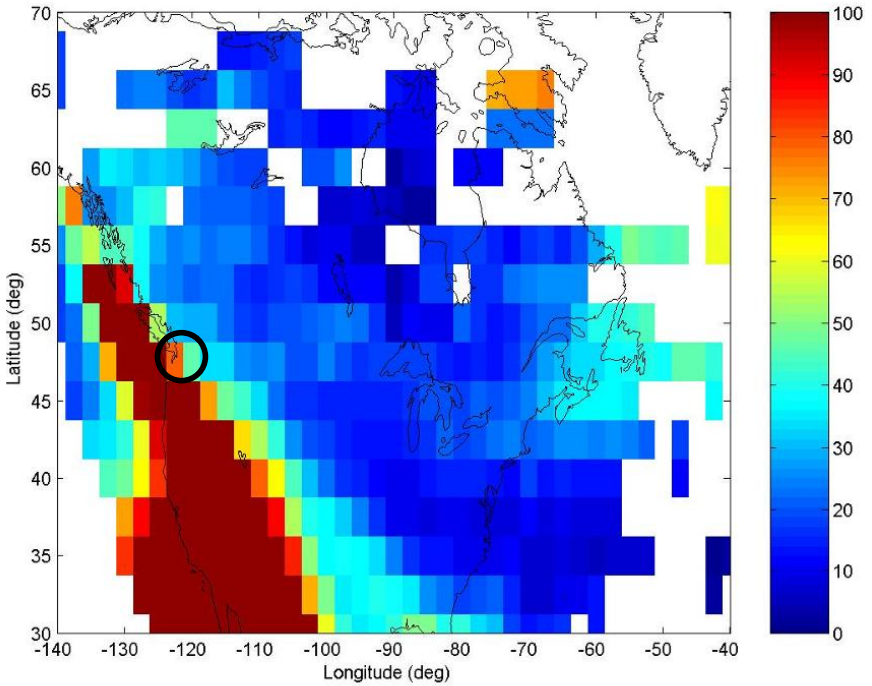
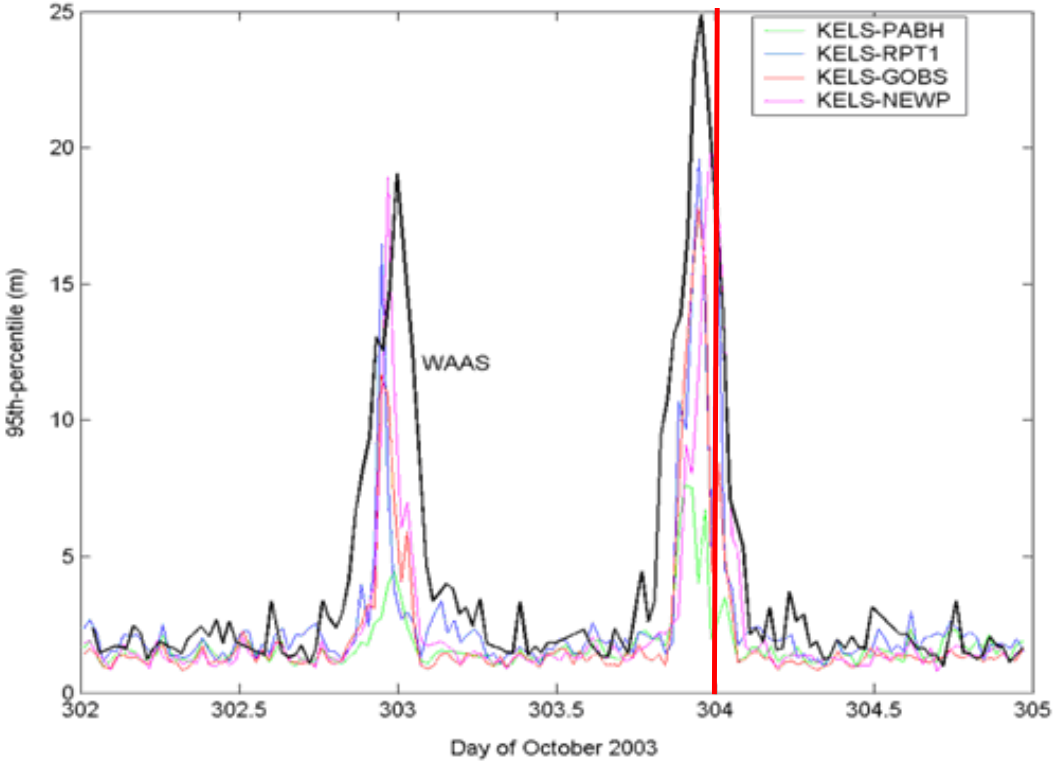
DGPS&WAAS Horizontal Positioning Errors: 29 October 2003

Ionosphere Map: 2330 UT



Horizontal Position Errors



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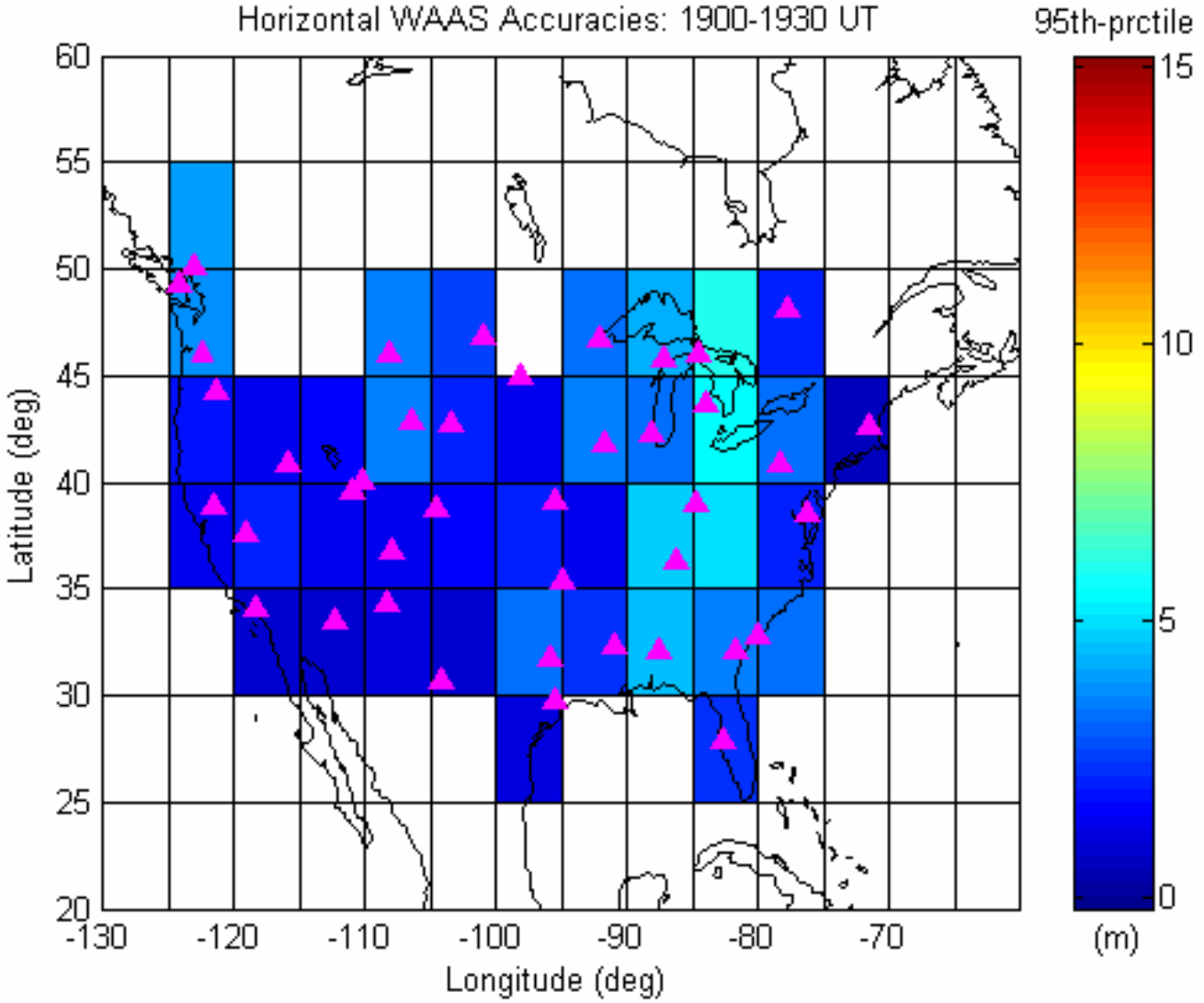
WAAS Analysis



- Positioning accuracies estimated for 40 GPS reference sites
- October 30, 2003

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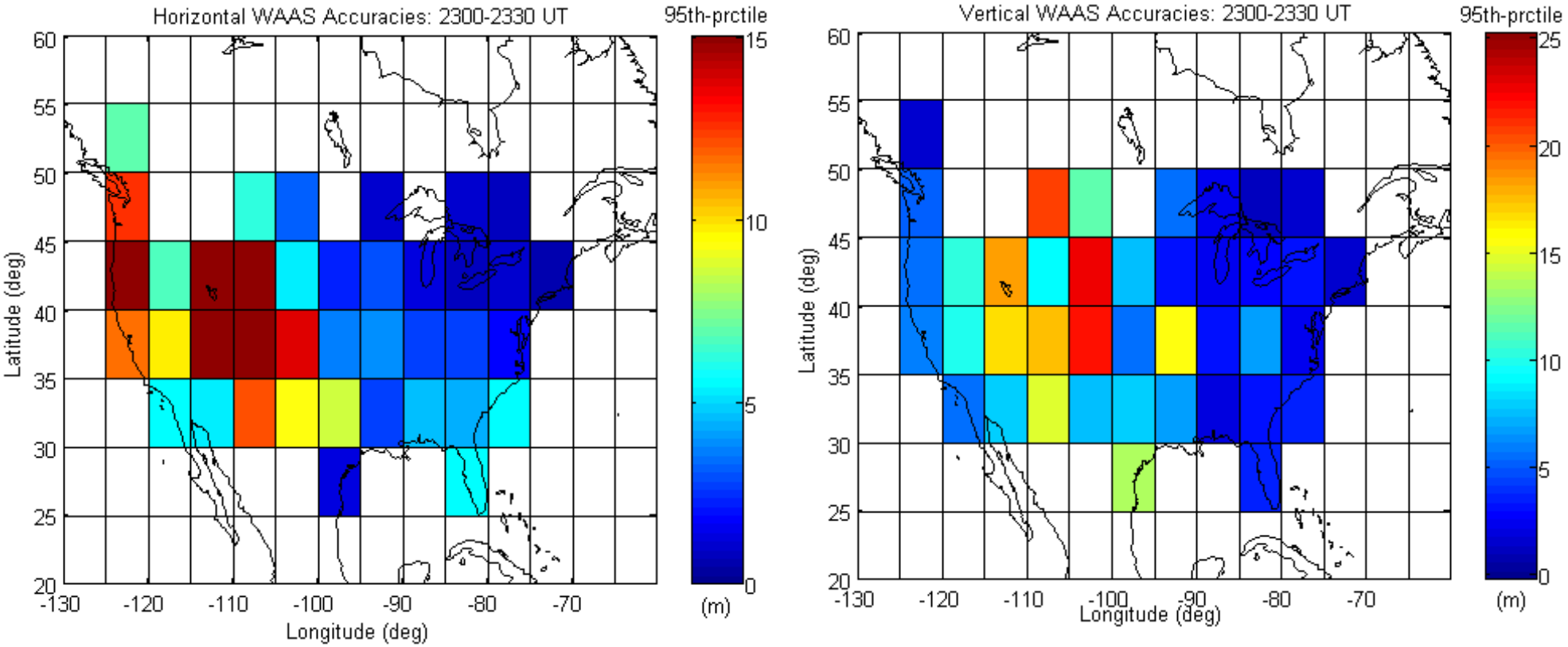
WAAS Positioning Errors



- Errors of >15 m horizontal and 20-25 m vertical

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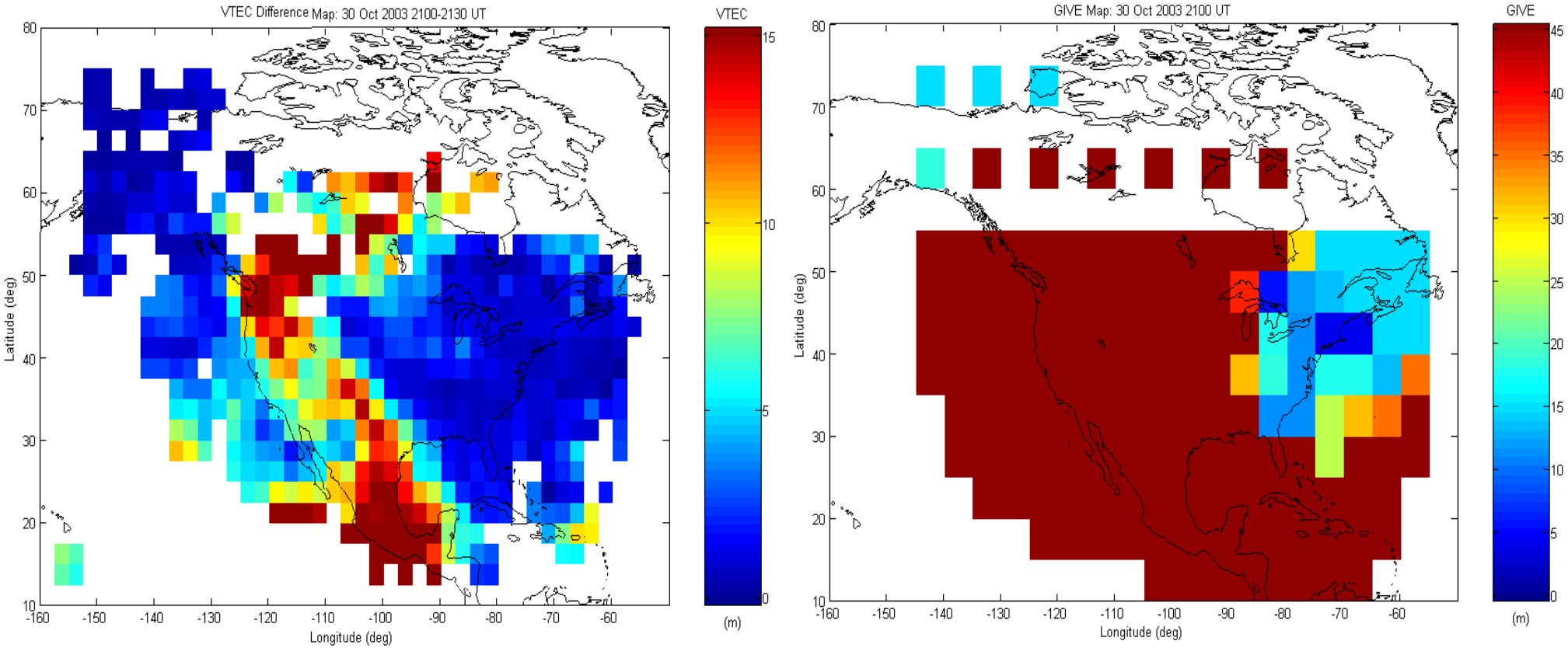
WAAS Iono Model Errors

WAAS Error Oct. 30 **GIVE**



- Errors >15 m in WAAS ionosphere estimates
- Bounded reliably by GIVE values (“do not use”)

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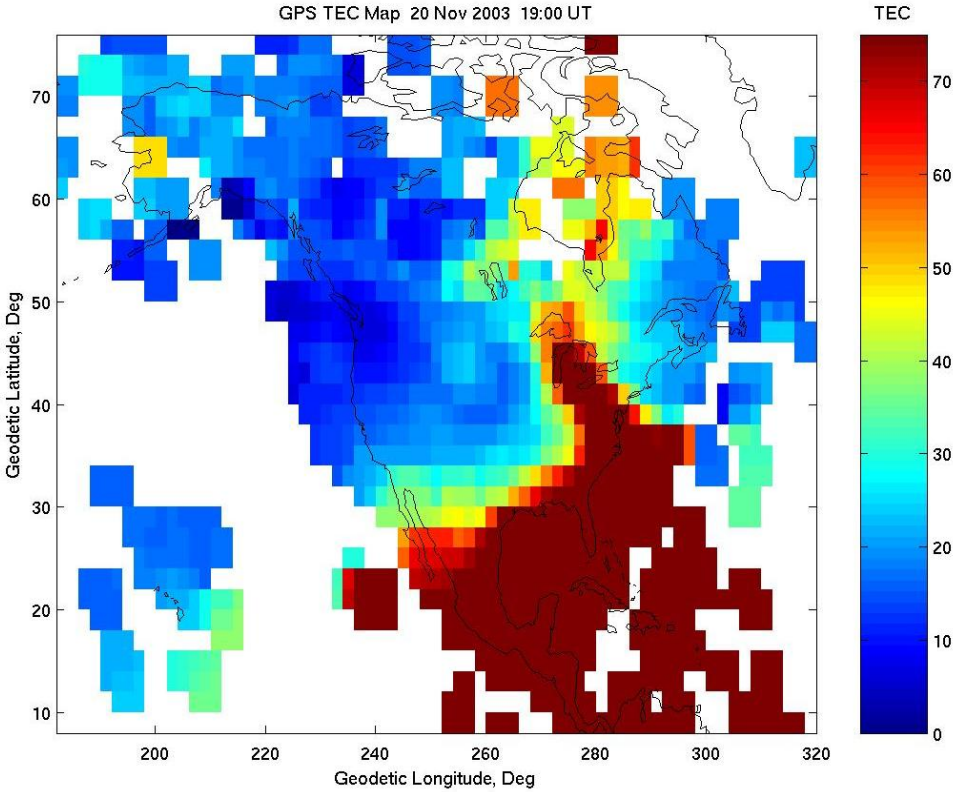
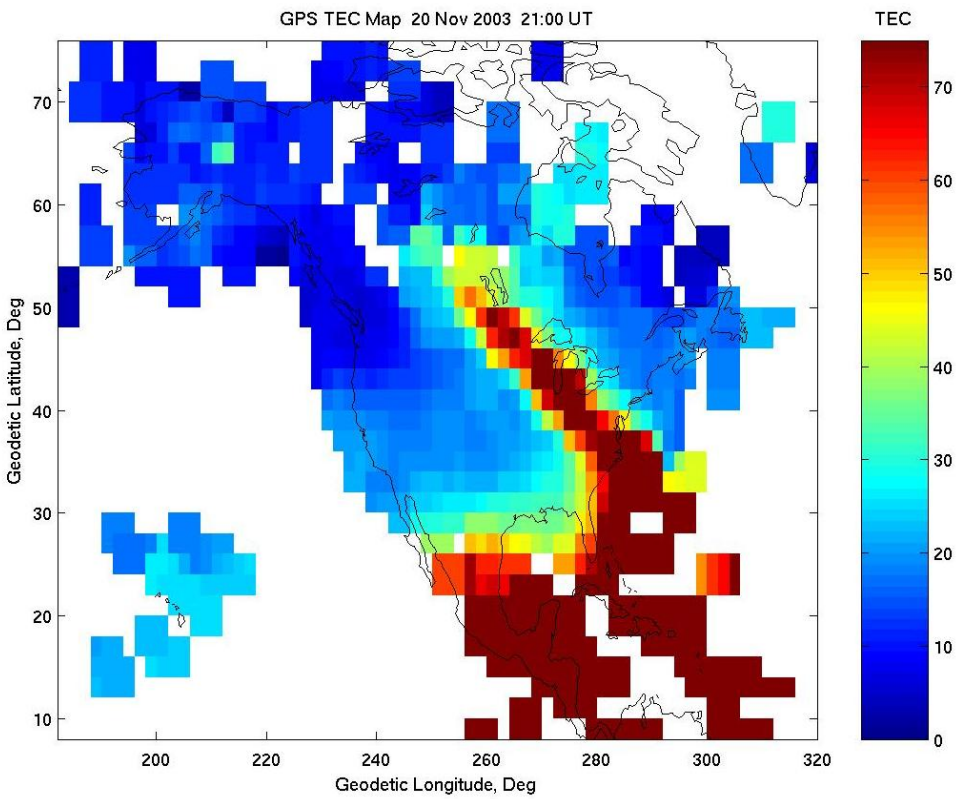
SED Event 20 November 2003

19:00 UT



21:00 UT



- SED develops 18:00 – 22:00 UT
- SED extends north through central Canada
- Impact in eastern and central Canada on DGPS (CCG, USCG, NDGPS) and WAAS

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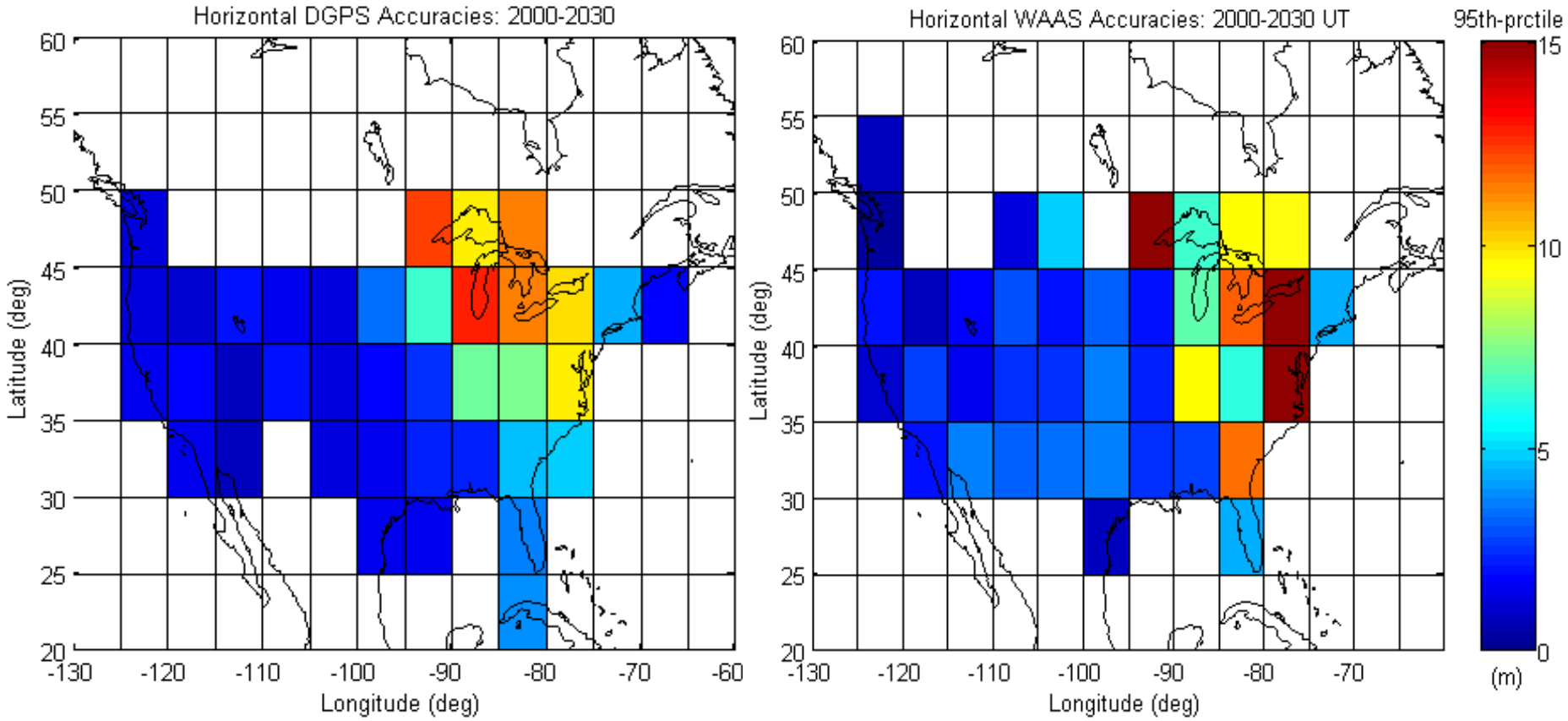
DGPS and WAAS – Horizontal



- DGPS position errors computed for 100-200 km baselines
- Horizontal accuracies of 10-15 m (DGPS) and > 15 m (WAAS) during period 20:00-20:30 UT

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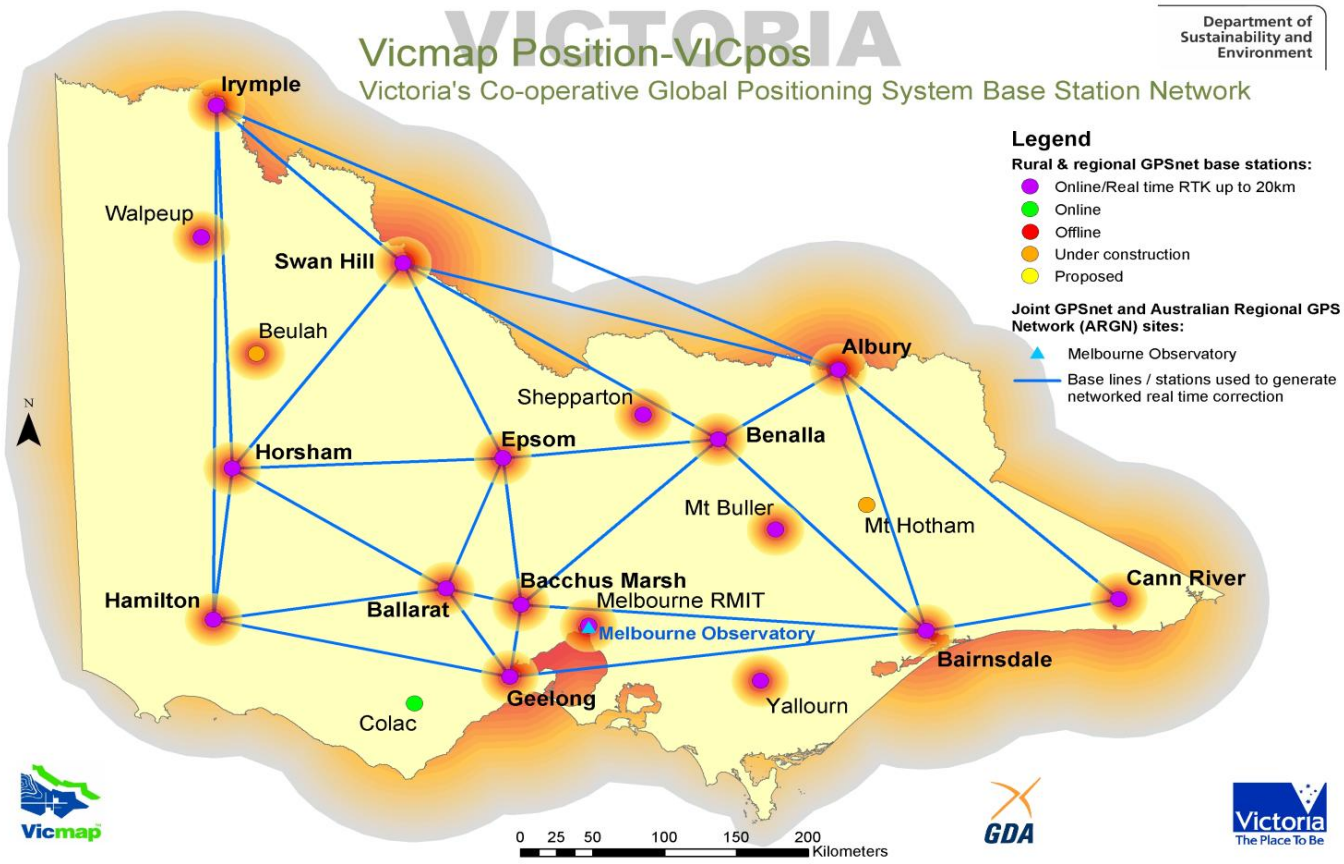
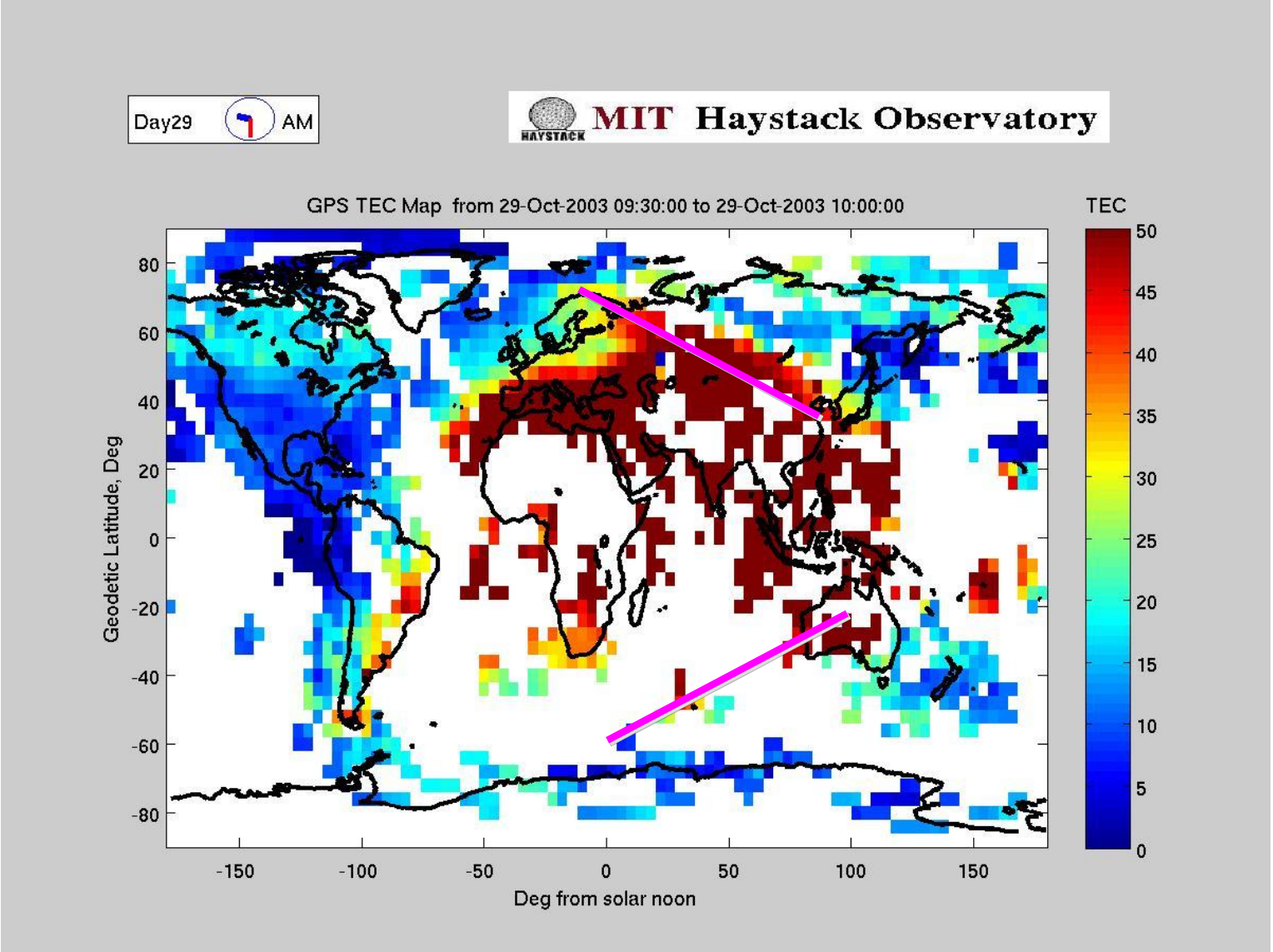
Vicmap Position (Australia) GPS and WAAS – Horizontal

- GPSnet™ operational in 2004 for sub-metre positioning in southeastern Australia
- Reference station spacings of 100-200 km
- Applications in agriculture, GIS, navigation, forestry, surveying, emergency response, mining and transportation



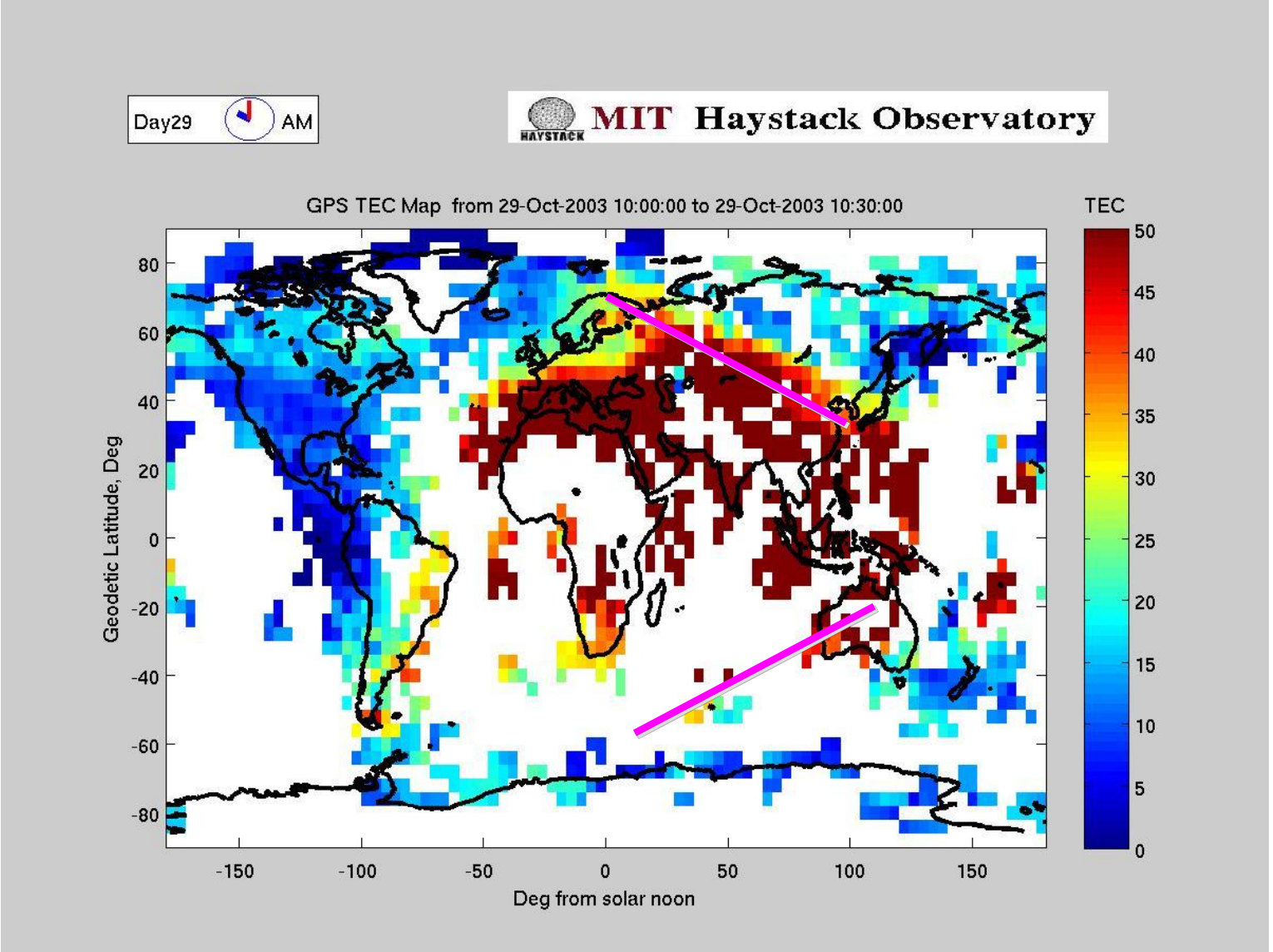
S. Skone/2012

10:00 UT 29 October 2003



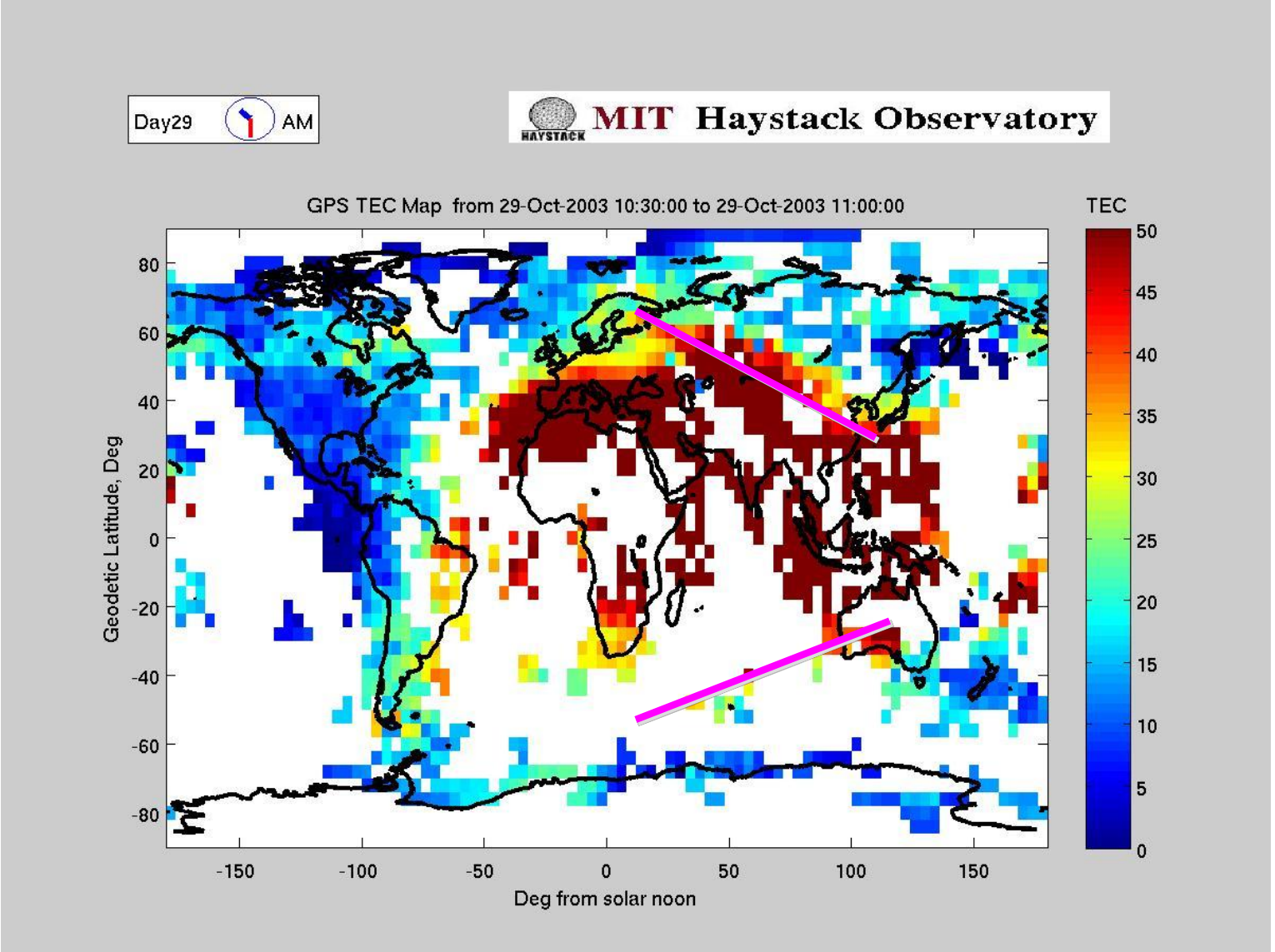
S. Skone/2012

10:30 UT 29 October 2003



S. Skone/2012

11:00 UT 29 October 2003



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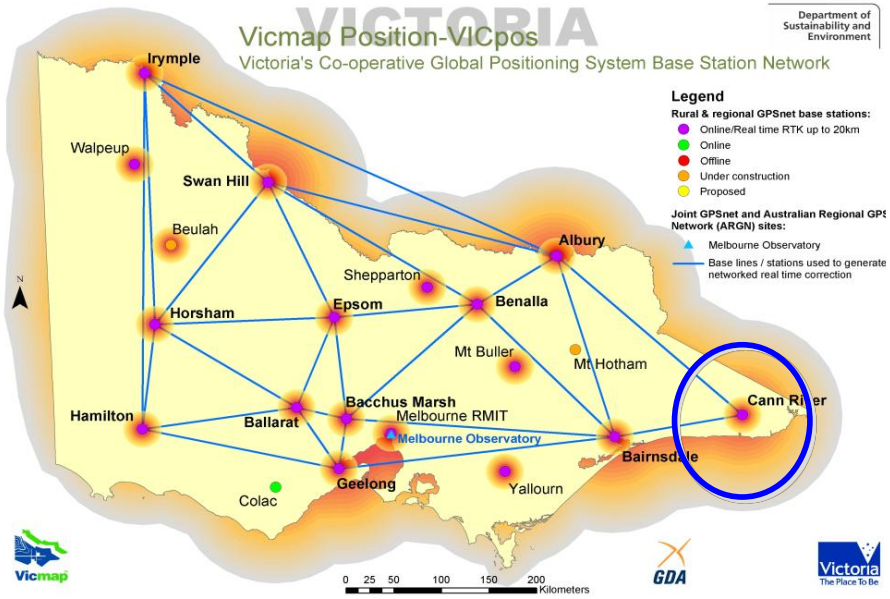
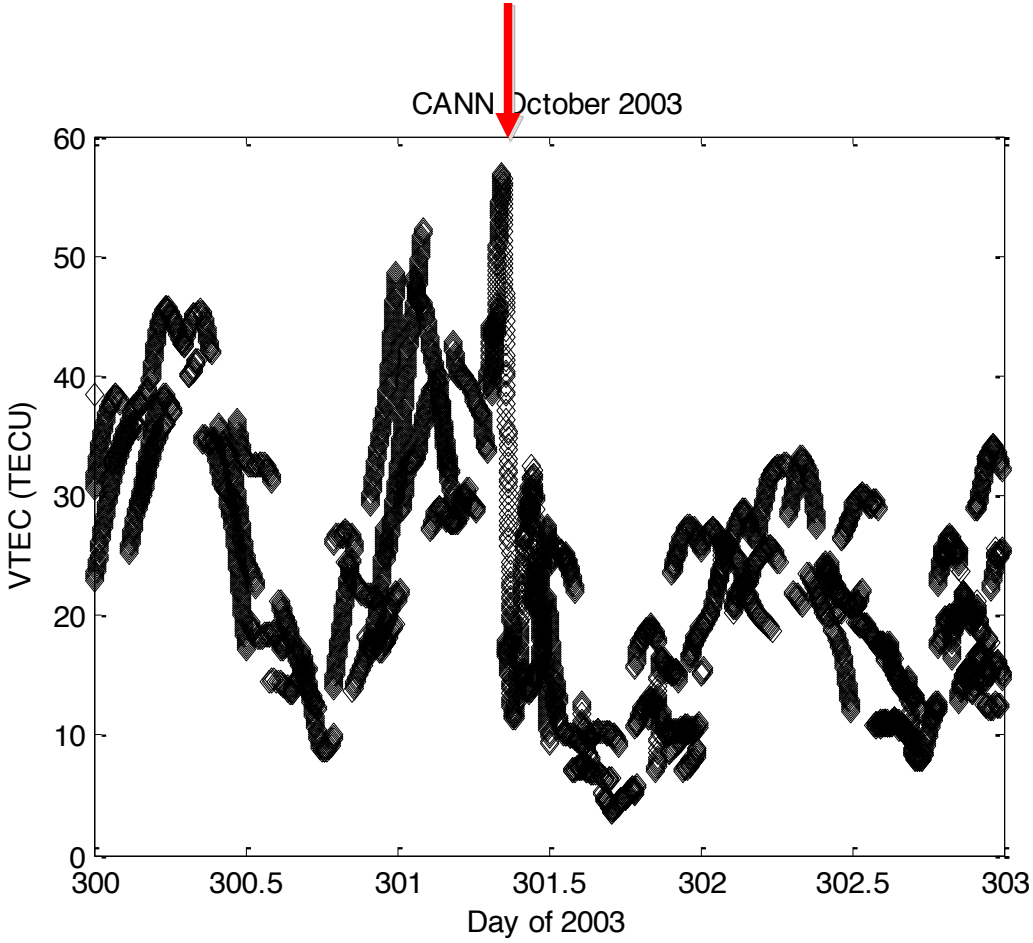
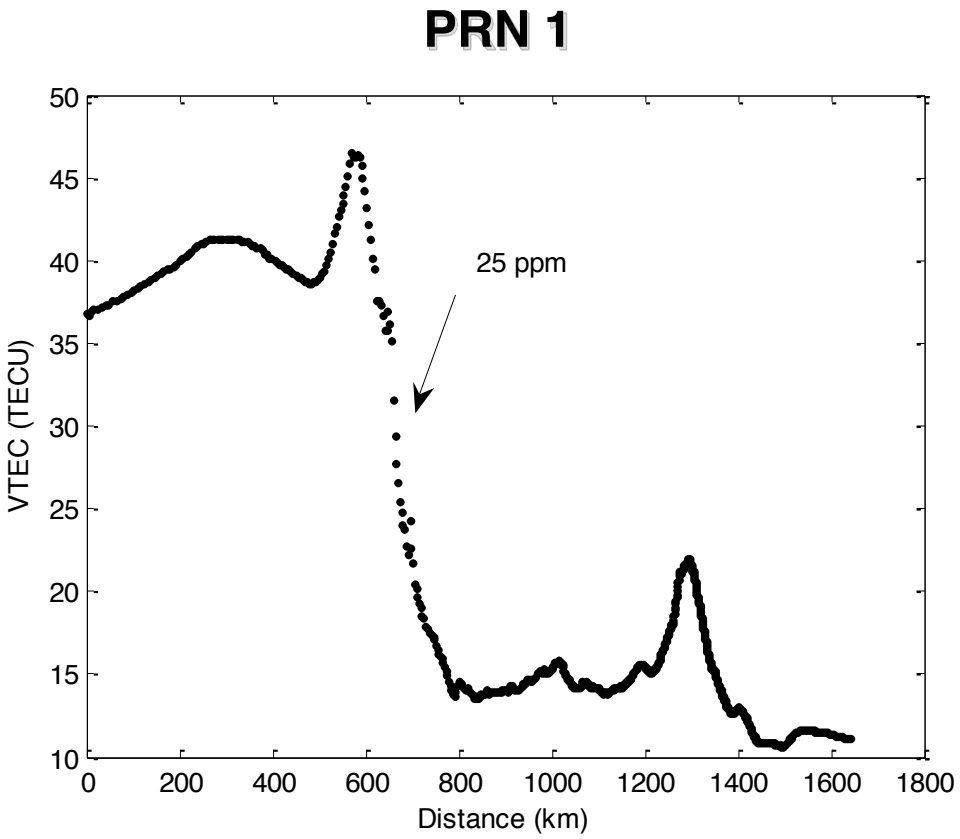
VTEC: Reference Station CANN

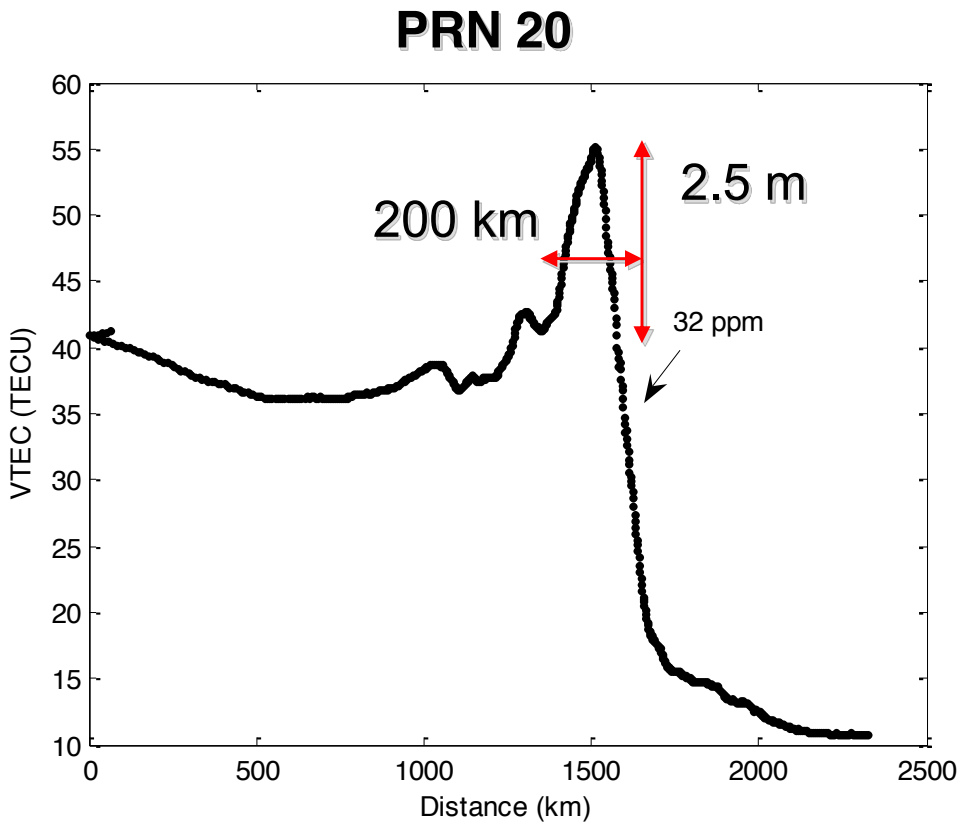




Large TEC variations observed approx. 10:00 UT on October 29 (day 301)

S. Skone/2012





- Gradients of 25-30 ppm over distances of 200 km
- Differential ionosphere range delay of 2 to 3 m for 100 km baseline
- DGPS positioning errors of 6-7 m

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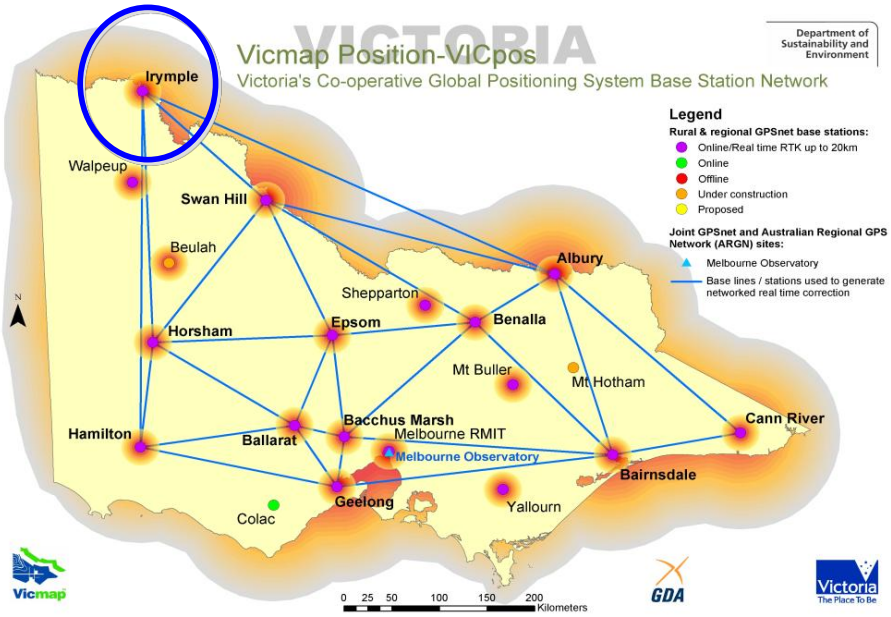
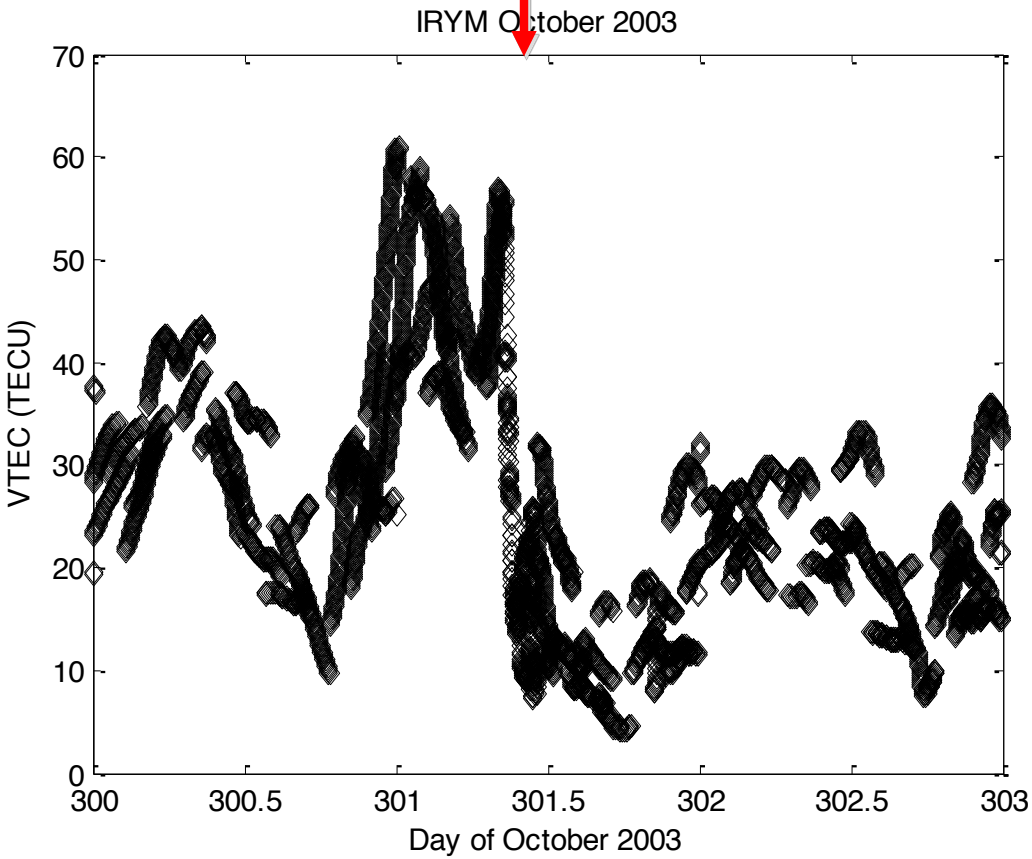
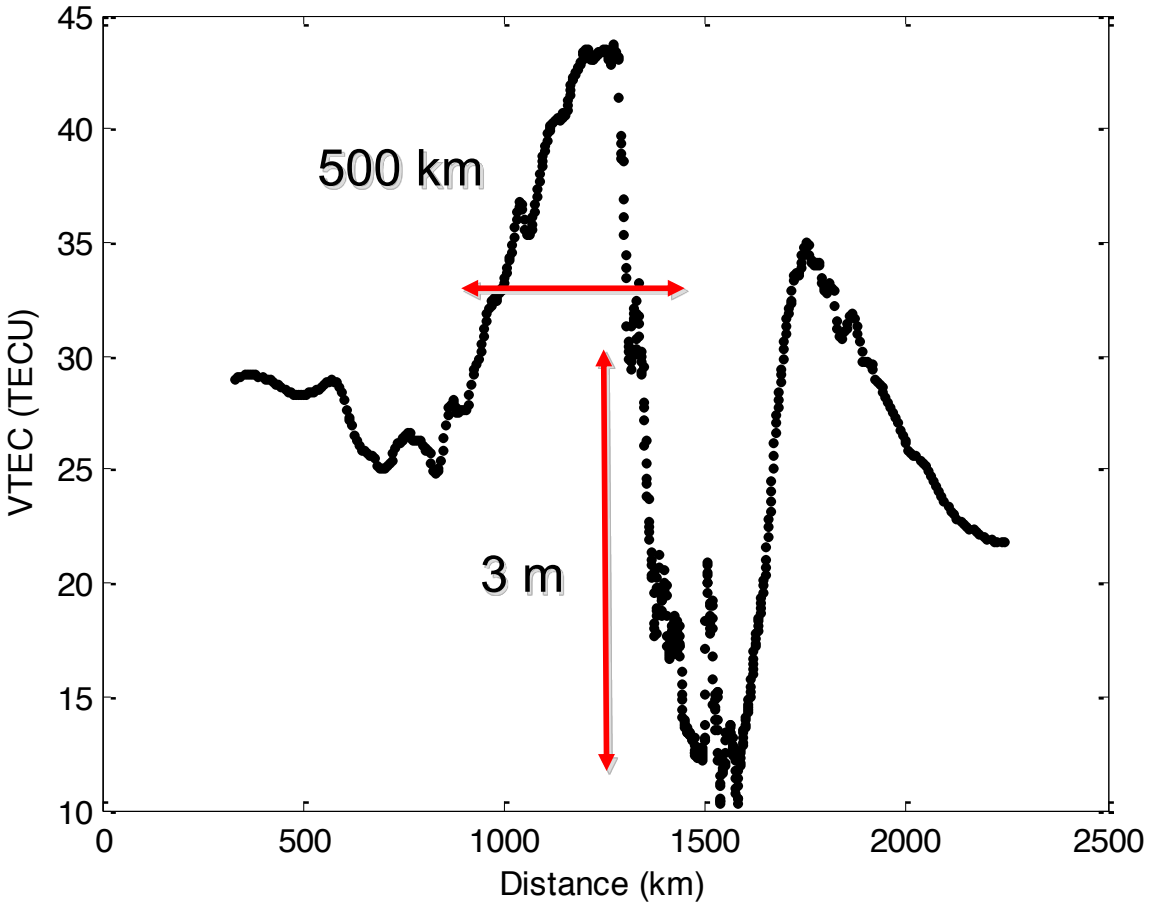
VTEC: Reference Station IRYM





Large TEC variations observed approx. 10:00 UT on October 29 (day 301)

S. Skone/2012



Structure with amplitudes of 2-3 m and scale size of 500 km

S. Skone/2012

Summary

- Large ionospheric gradients observed near equatorial anomaly and near SED
- DGPS positioning errors of 20-30 m (95%) near anomaly
- SBAS such as WAAS with 5 deg by 5 deg grid spacing do not fully resolve gradients
- DGPS positioning errors of 2-10 m (95%) during SED events
- SBAS (WAAS) positioning errors of 8-12 m (95%) during SED events
- Conjugate effects observed in northern/southern hemispheres