Space Weather Impact on Global Navigation Satellite Systems

S. Skone
Department of Geomatics Engineering
Schulich School of Engineering

Solar storm could affect power grids, GPS
The Associated Press
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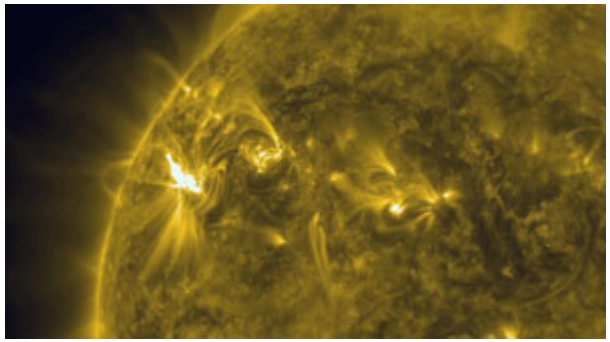

"The largest solar storm in five years is racing toward Earth, threatening to unleash a torrent of charged particles that could disrupt power grids, **GPS** and airplane flights."

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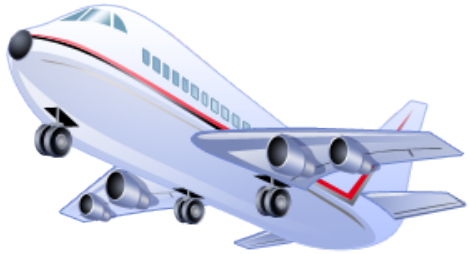
Which GPS/GNSS users are affected?



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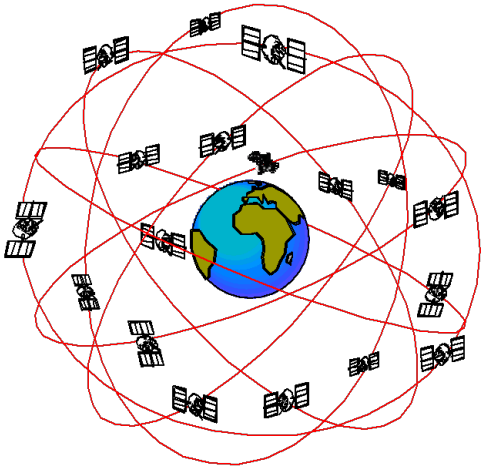
Global Navigation Satellite System: GPS

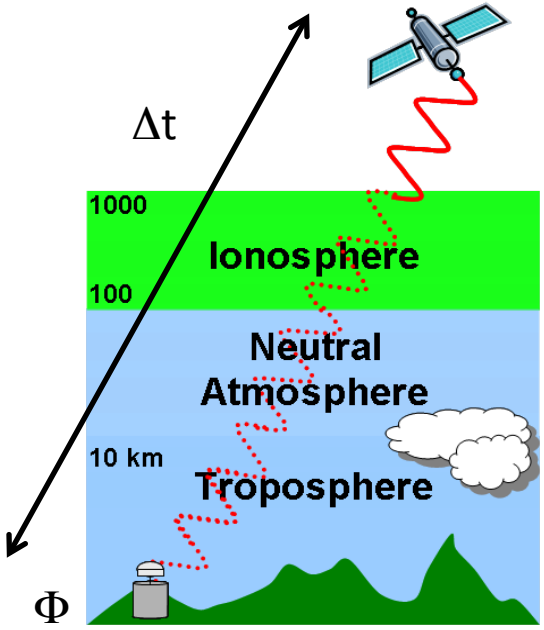
- Nominally 24 satellites orbiting 20,000 km above the Earth
- 6 orbital planes
- Transmits on multiple UHF frequencies
- Passive system
- Coarse positioning and precise positioning applications



Observations

Pseudorange (1-3 m accuracy)

Carrier phase (cm-level accuracy)



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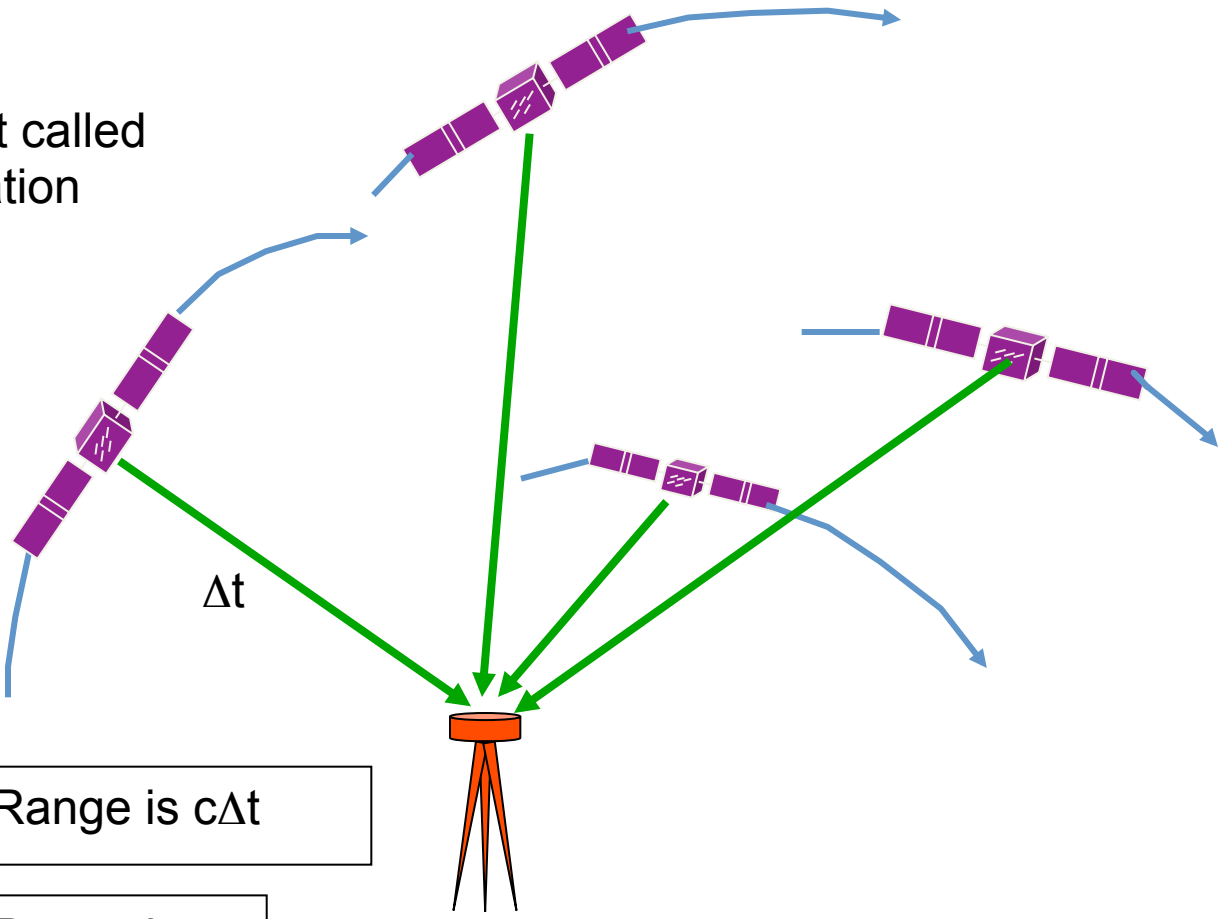
How does GPS work?

Concept called
Trilateration



Range is cΔt

Range is λϕ

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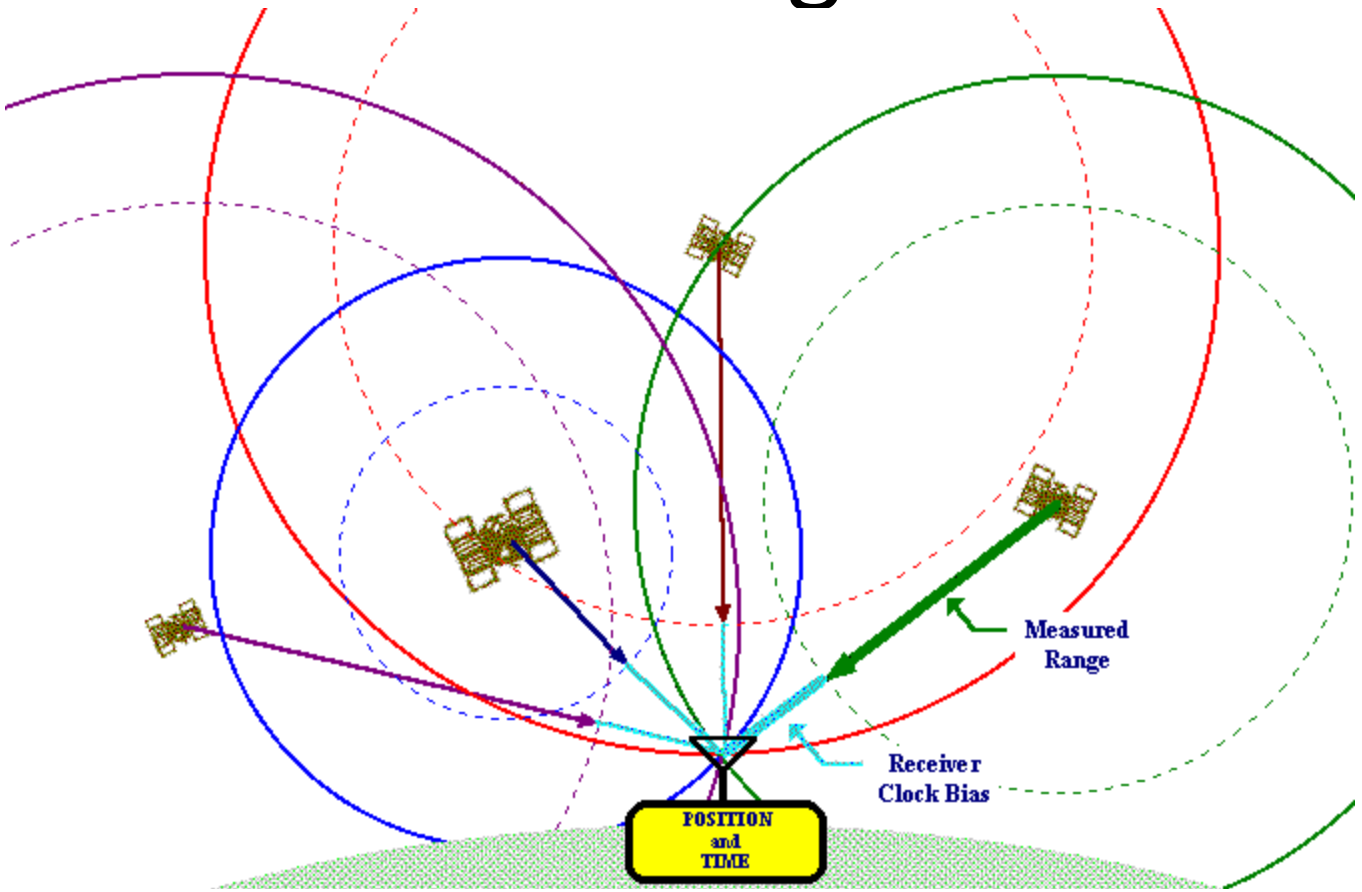
GPS Positioning Solution



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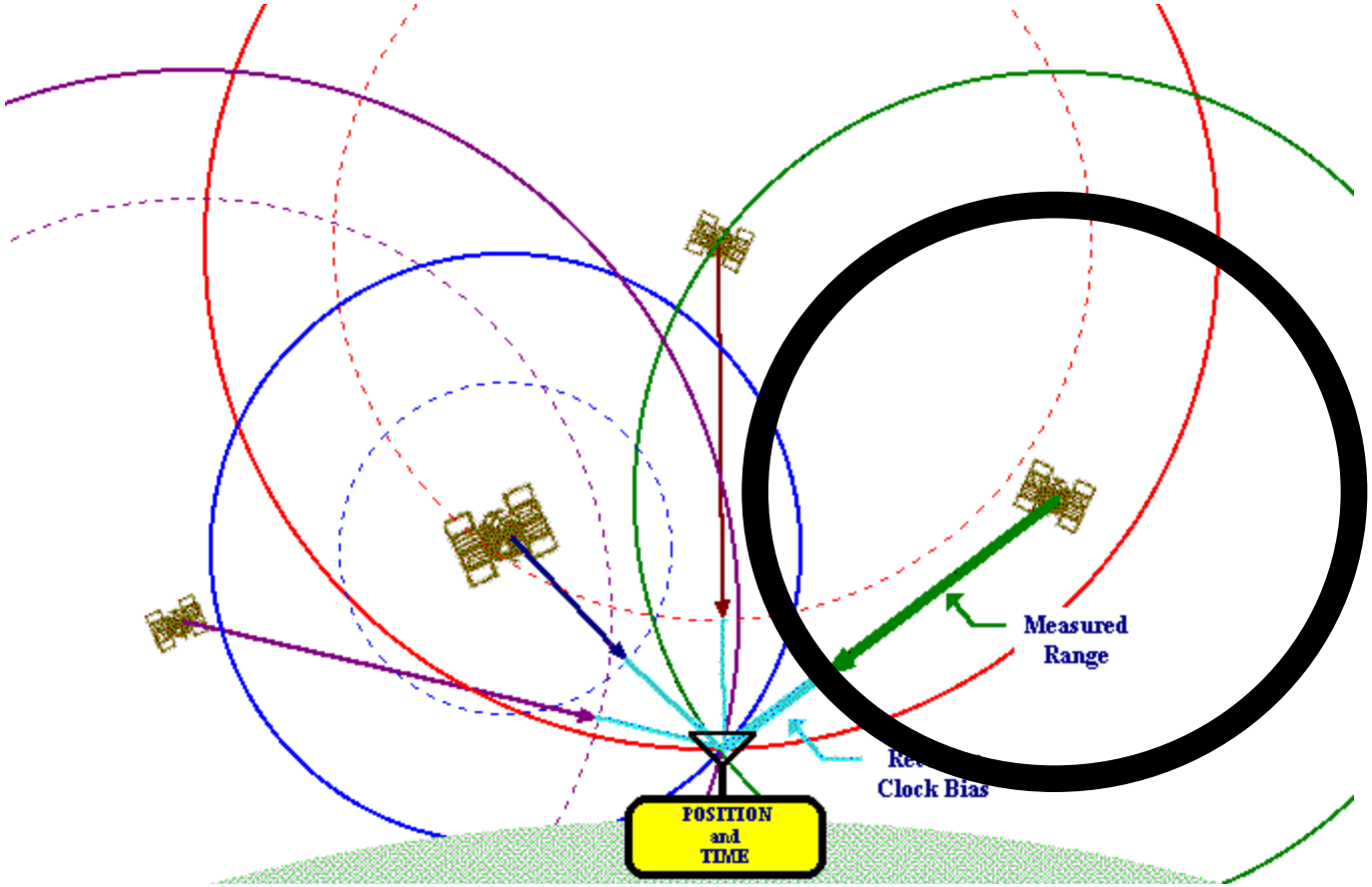

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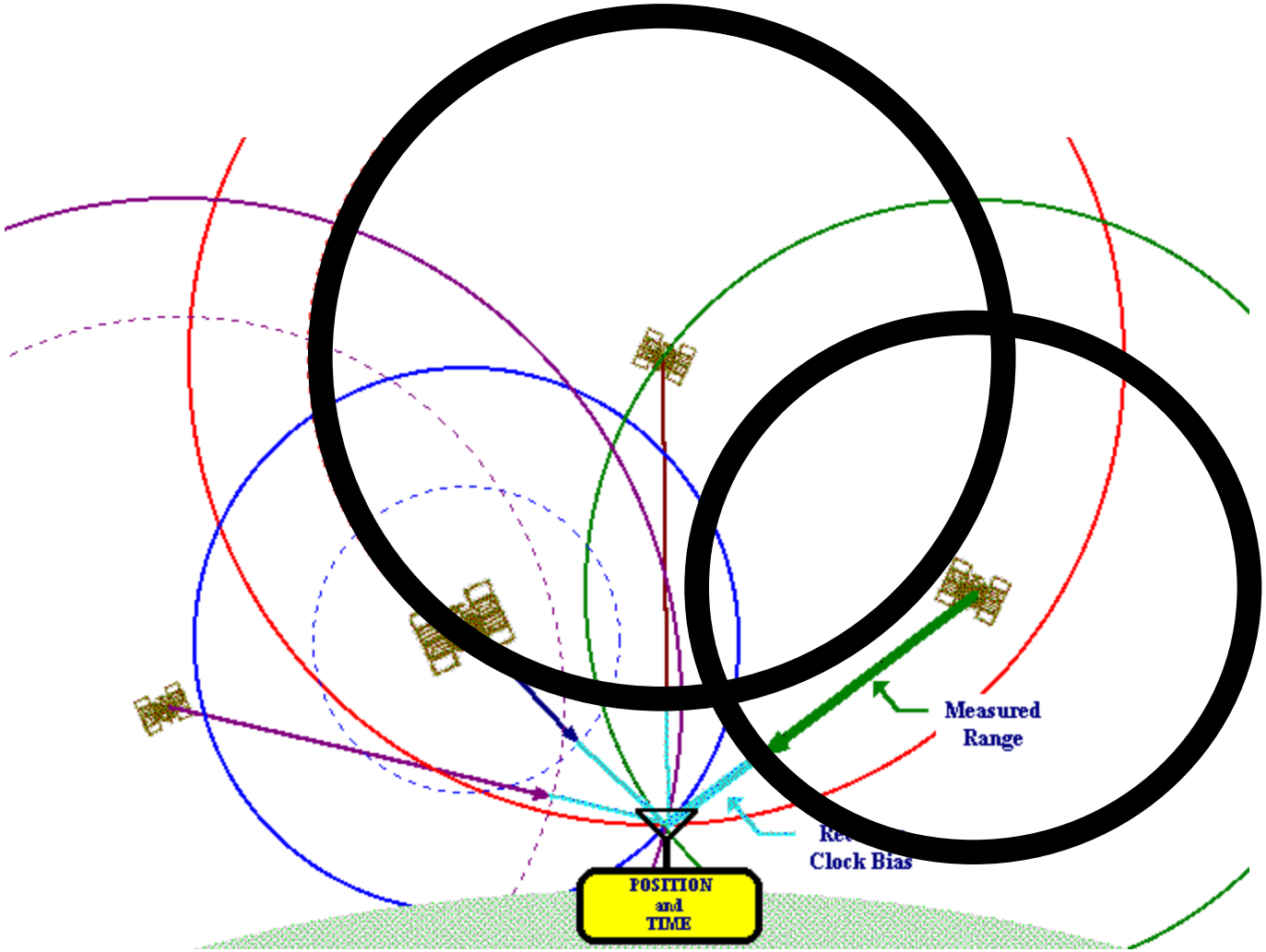

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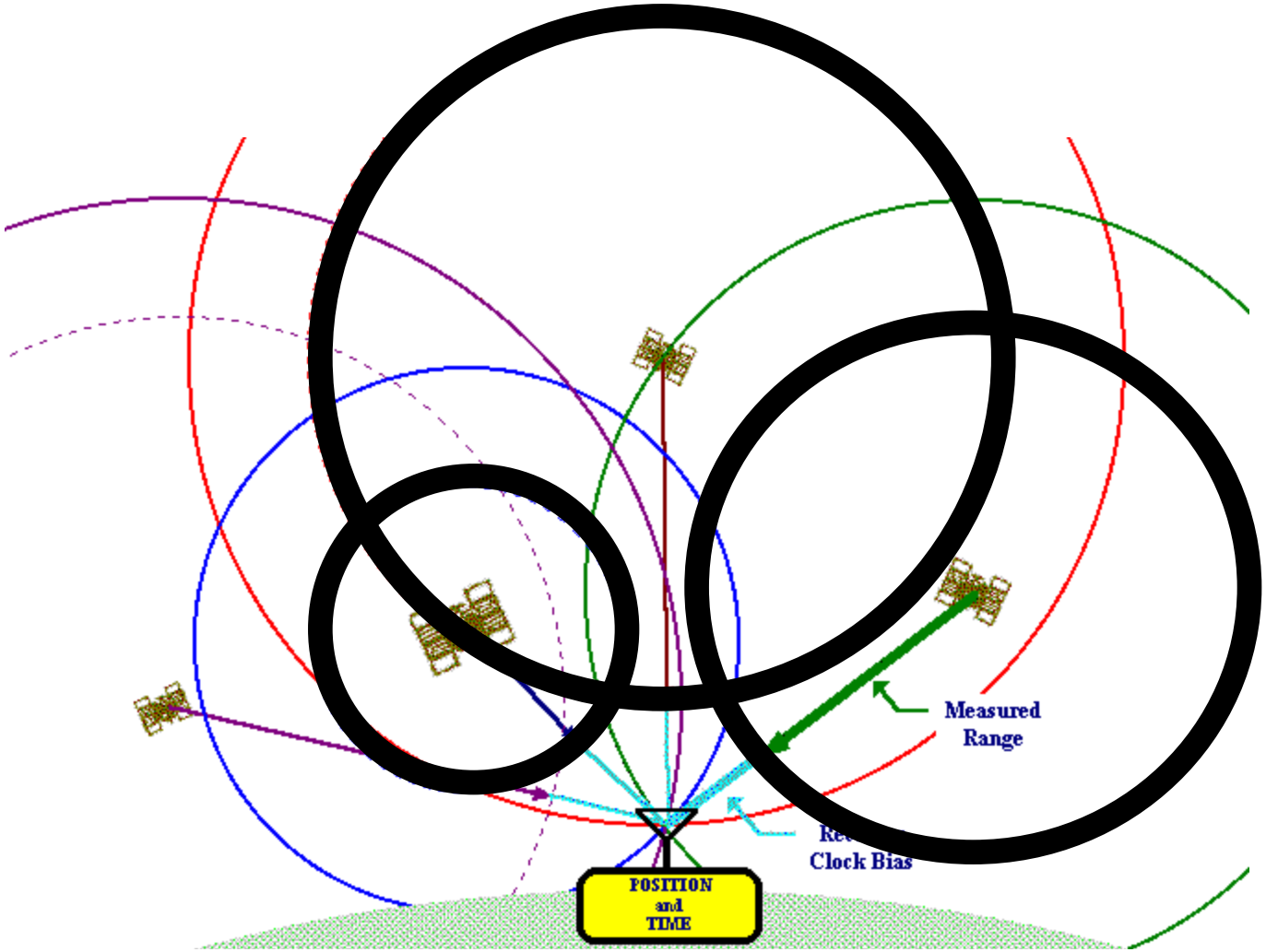

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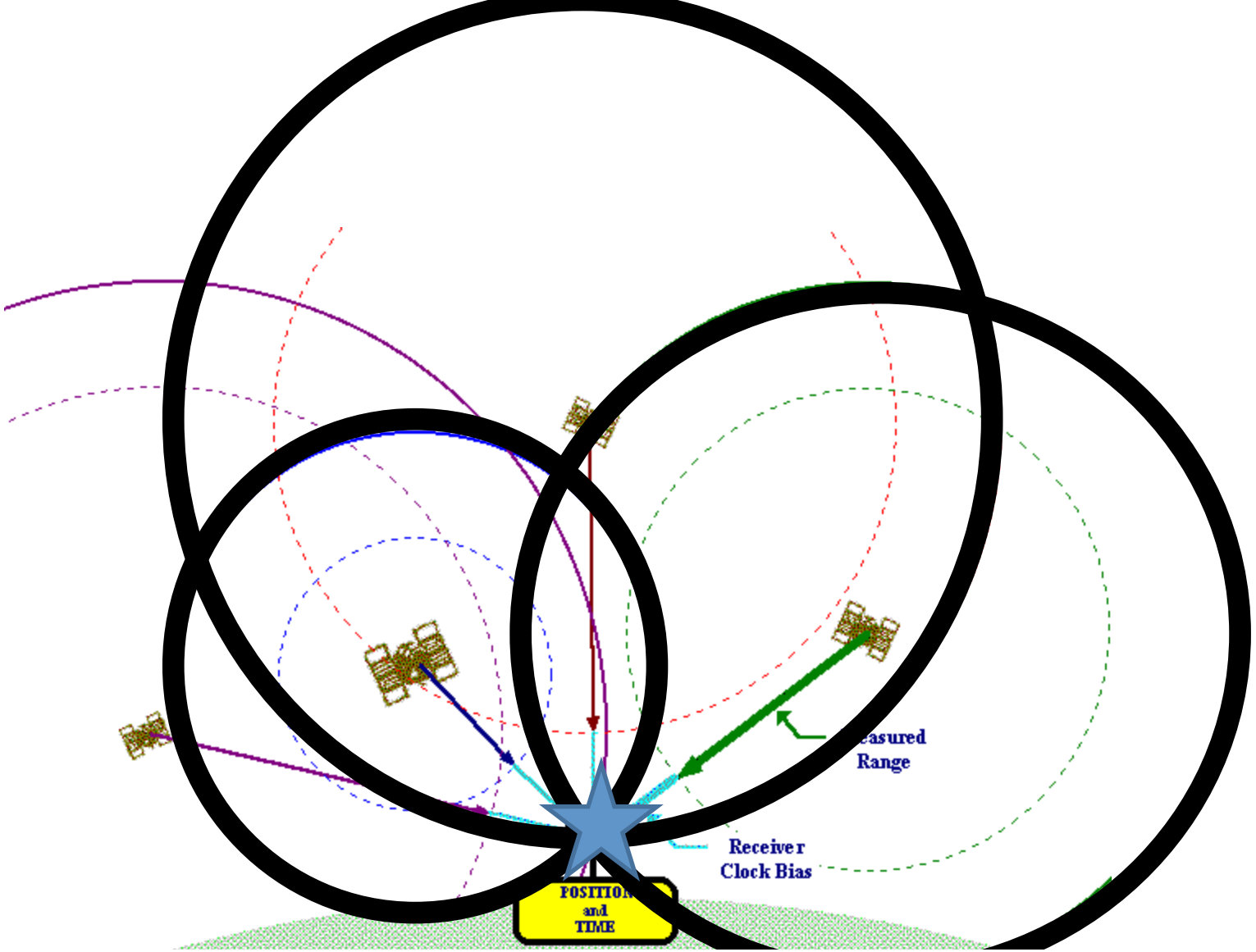

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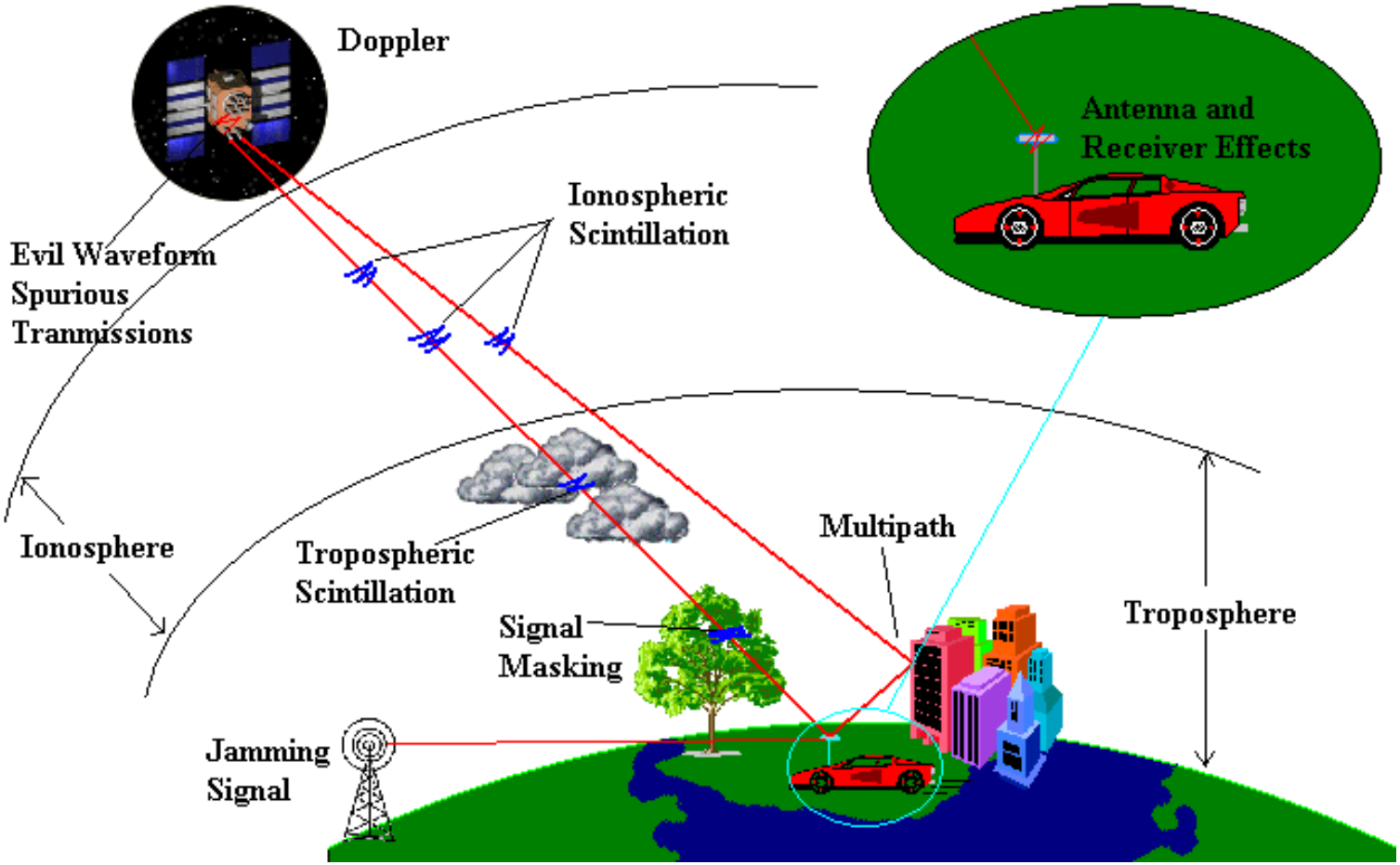
RF Signal Deterioration and Range Error

Orbit Error (Δx, Δy, Δz)



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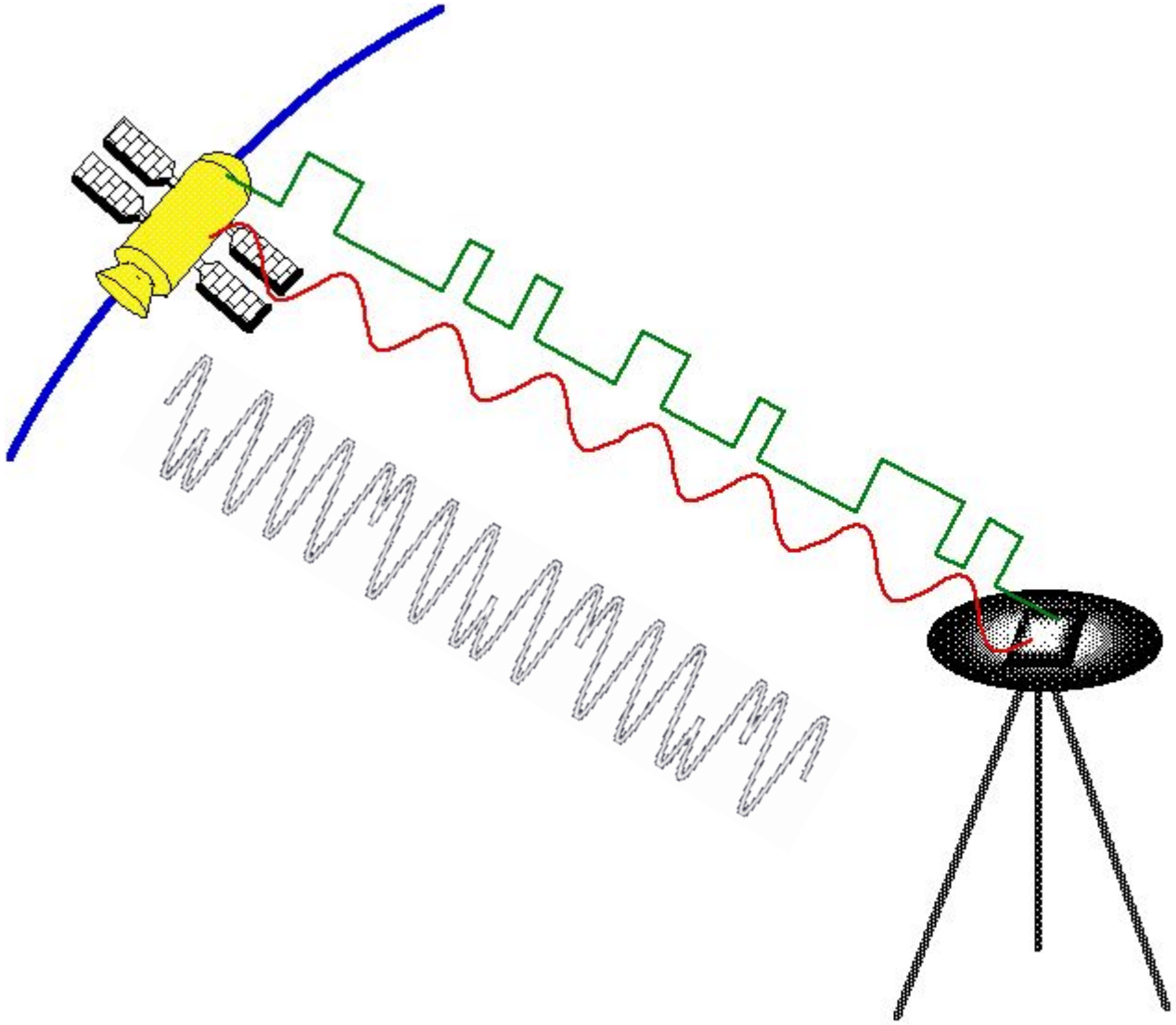
GPS Observations



Receiver Observations

Travel time: Δt

Phase: Φ

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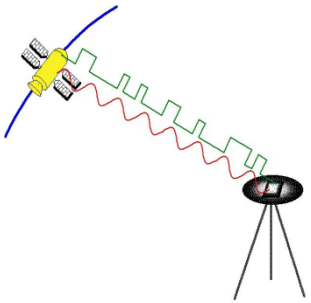
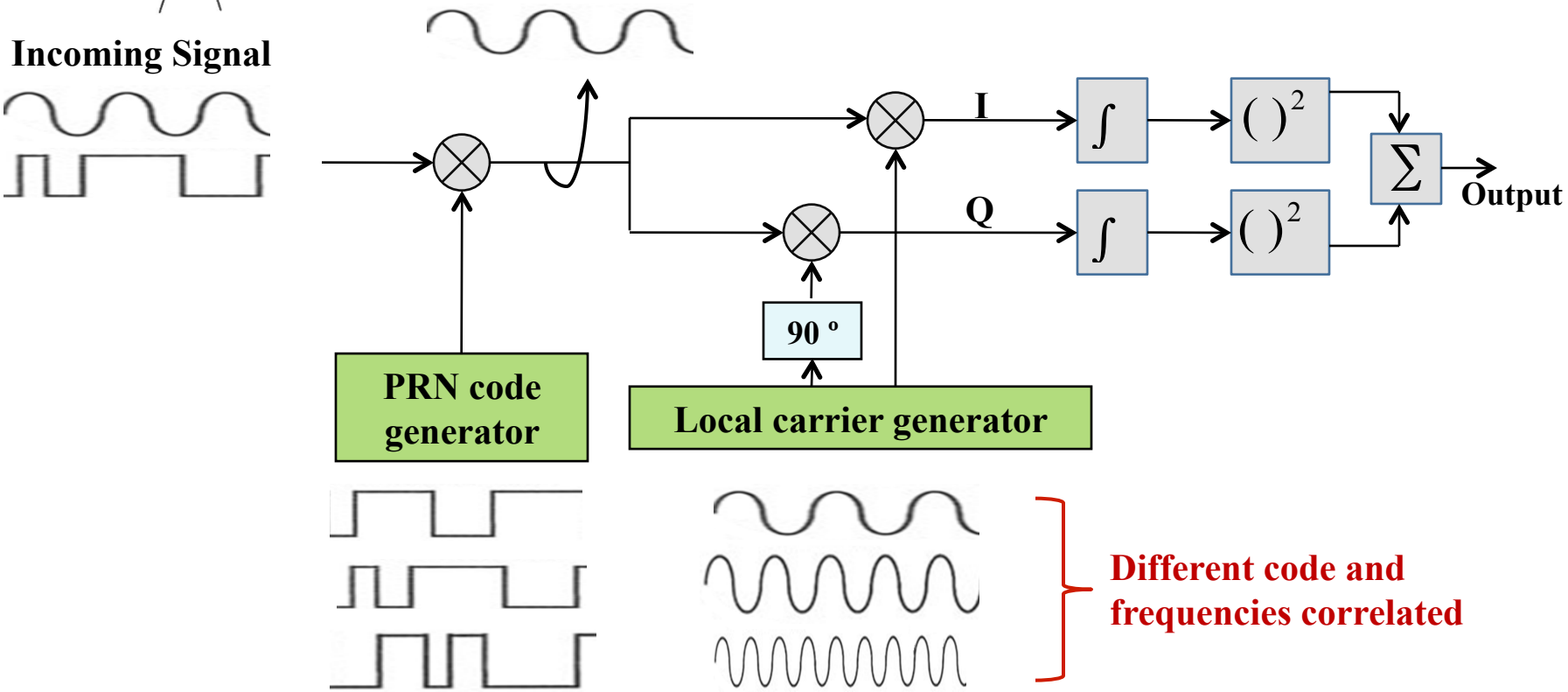
Receiver Acquisition and Tracking



Incoming Signal



GPS Positioning Accuracy

Low

(single frequency,
metre-level accuracy)

High

(multiple frequencies,
centimetre-level accuracy)

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Ionosphere Index of Refraction

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

(Appleton-Hartree formula)

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$$X = \frac{Ne^2}{\varepsilon_0 m\omega^2} = \frac{\omega_p^2}{\omega^2} \longrightarrow \text{Plasma frequency}$$

$$Y_L = \frac{eB_L}{m\omega} = \frac{\omega_L}{\omega} \longrightarrow \text{Gyrofrequency}$$

$$Y_T = \frac{eB_T}{m\omega} = \frac{\omega_T}{\omega} \longrightarrow \text{Gyrofrequency}$$

$$Z = \frac{\nu}{\omega} \longrightarrow \text{Collision frequency}$$

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$$X = \frac{Ne^2}{\varepsilon_0 m\omega^2} = \frac{\omega_p^2}{\omega^2}$$ → Plasma frequency

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$$Y_T = \frac{eB_T}{m\omega} = \frac{\omega_T}{\omega}$$ → Gyrofrequency

$$Z = \frac{\nu}{\omega}$$ → Collision frequency

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Range error?

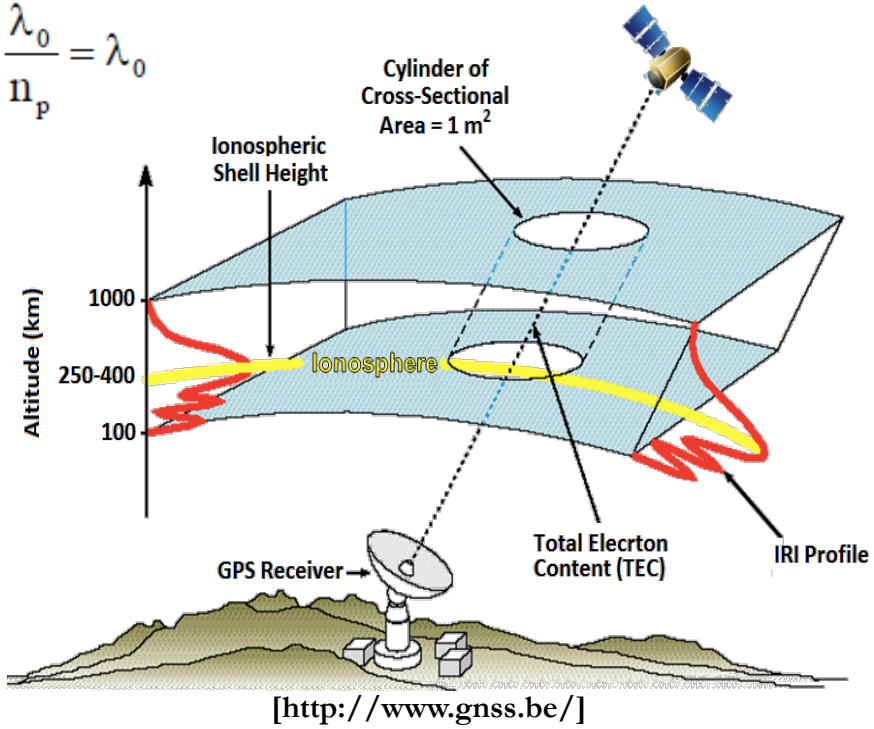
For GPS, we assume $v_g = c,\ v_p = c$ and $\lambda = \frac{\lambda_0}{n_p} = \lambda_0$ to derive range and phase observations

This is not correct $\Rightarrow$ range error

i.e $\left|\Delta v_p\right| = \left|\Delta v_g\right| = \Delta v$

$$\Delta R = \int \Delta v dt = \frac{c}{2\omega^2} \int_{\text{travel time}} \omega_p^2 dt$$

$$\Delta R = \frac{40.3}{f^2} TEC$$



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

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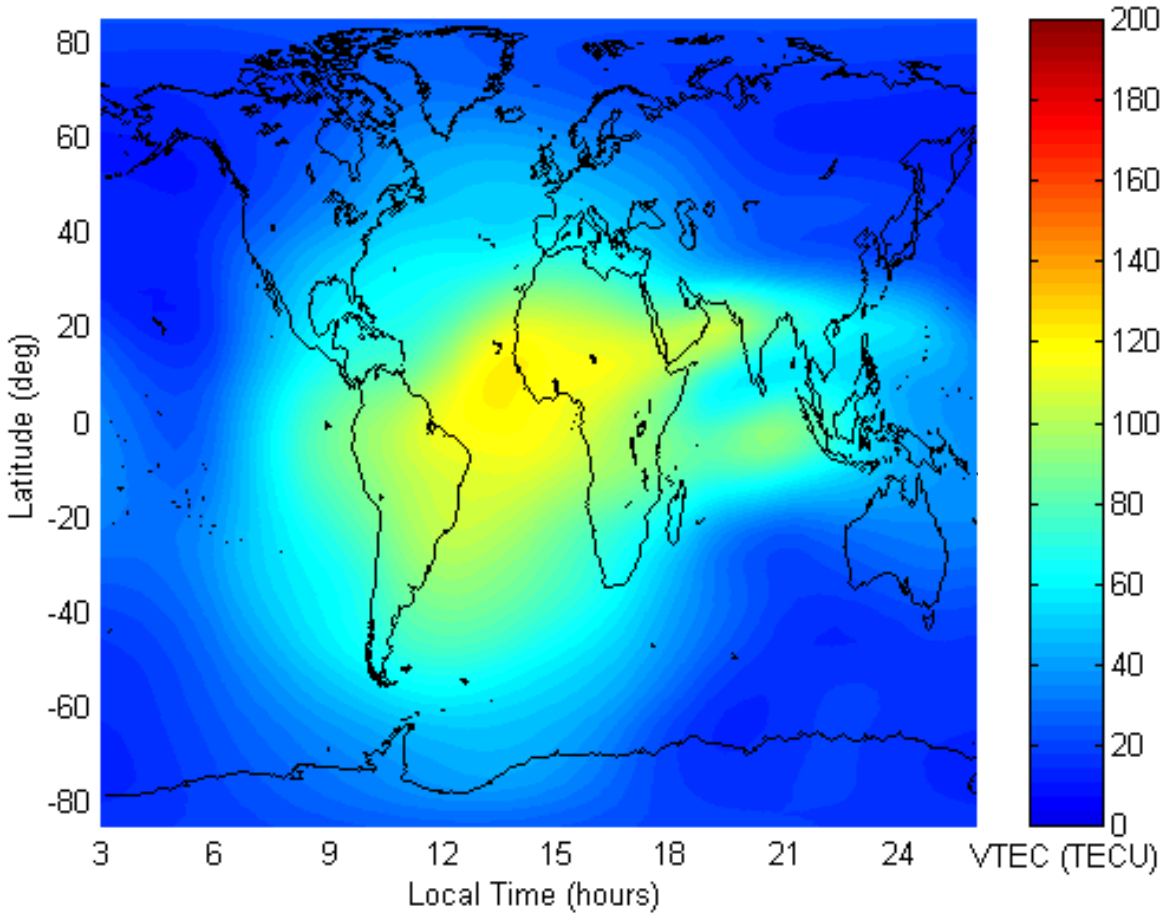
Spatial Distribution of VTEC during Solar Maximum (Equinox)

March 2000



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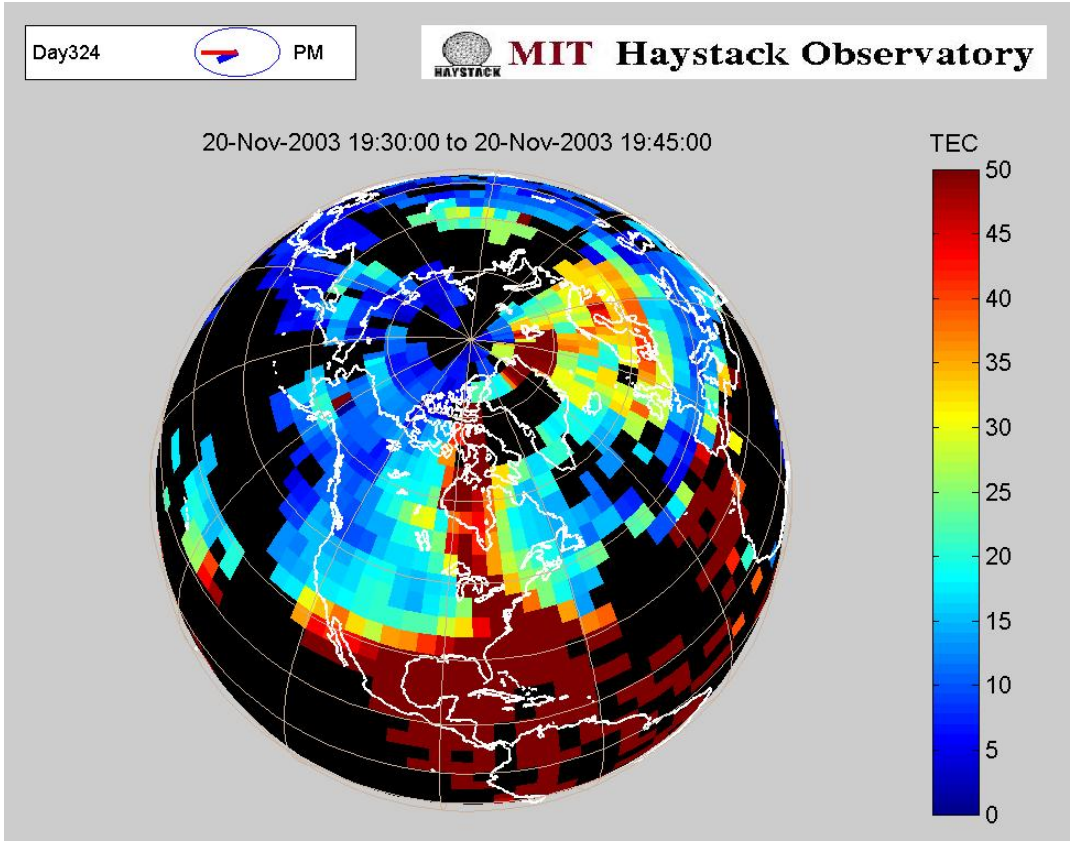
Space Weather Event: Storm Enhanced Density

VTEC



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How would you reduce ionospheric range error for GPS?

Use an Expensive Dual Frequency GPS Receiver

Calculating TEC (Dual Frequency)

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

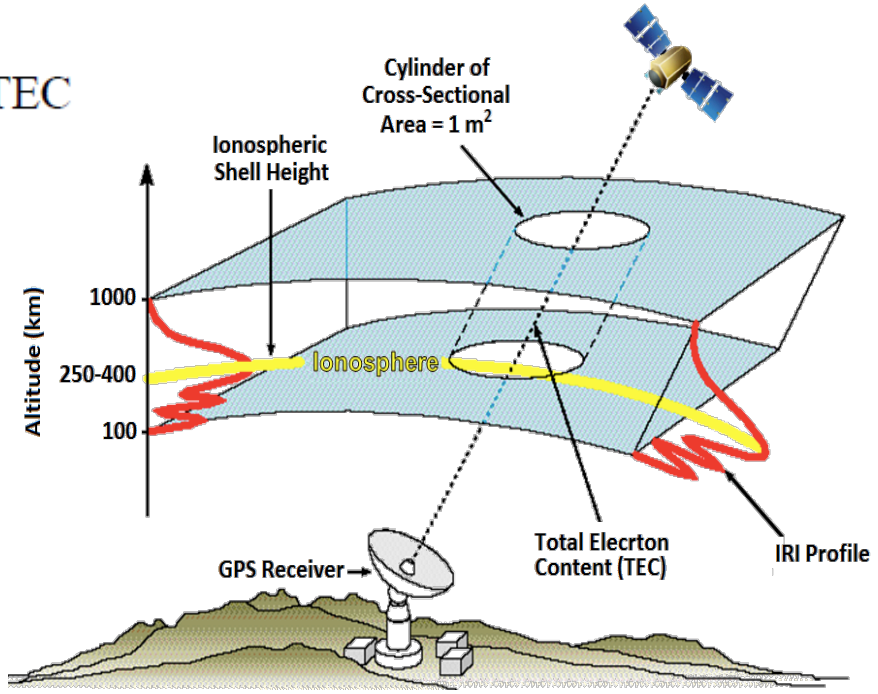
$$\Delta R_1 = \frac{40.3}{f_1^2} TEC \qquad \Delta R_2 = \frac{40.3}{f_2^2} TEC$$

- We can compute TEC:

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

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

L1 = 1.5 GHz
L2 = 1.2 GHz



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

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How would you model ionospheric range error for a low-cost user?

Single frequency only!

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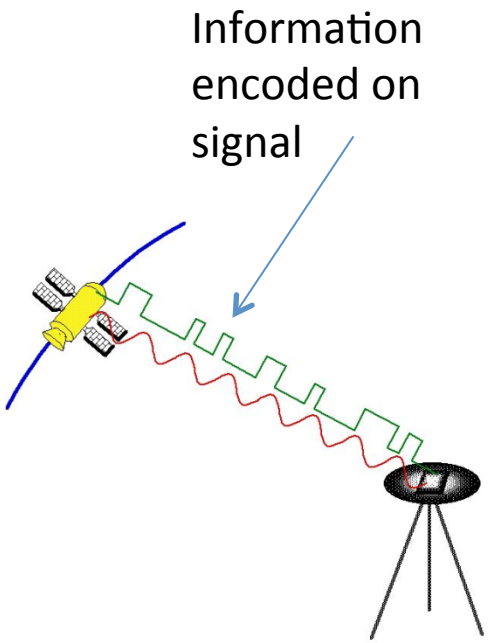
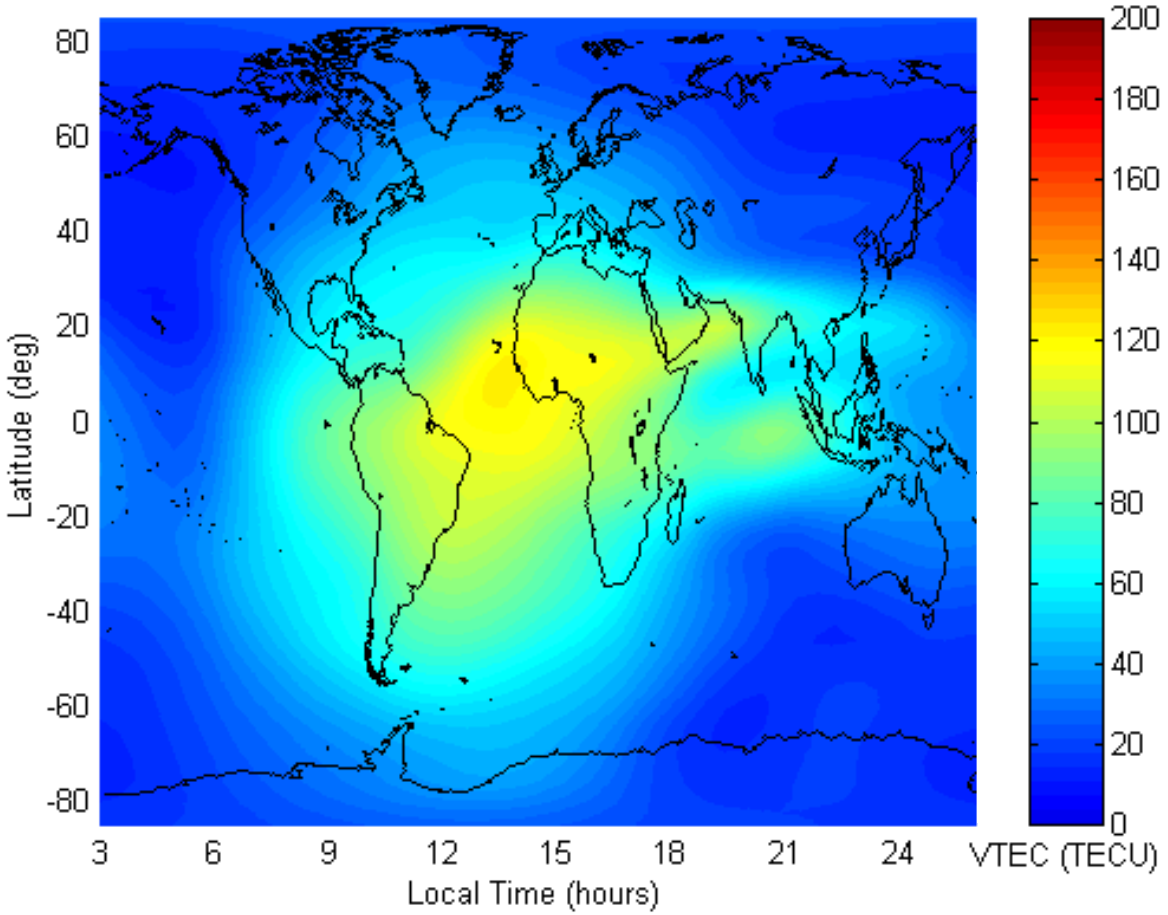
<u>Eight</u> values used to represent the global ionosphere. These values are broadcast to GPS users.





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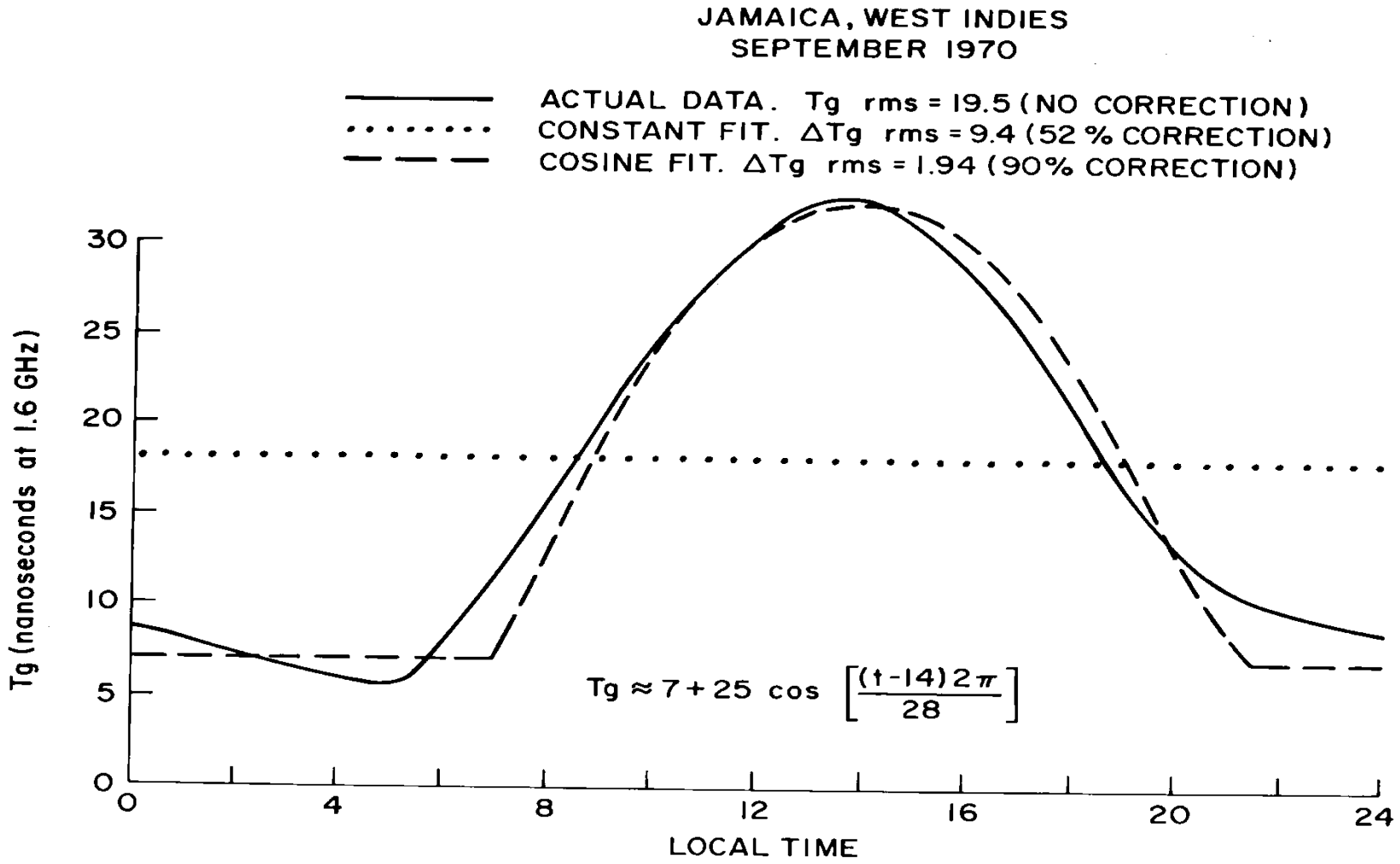
Broadcast (Klobuchar) Ionospheric Correction Algorithm



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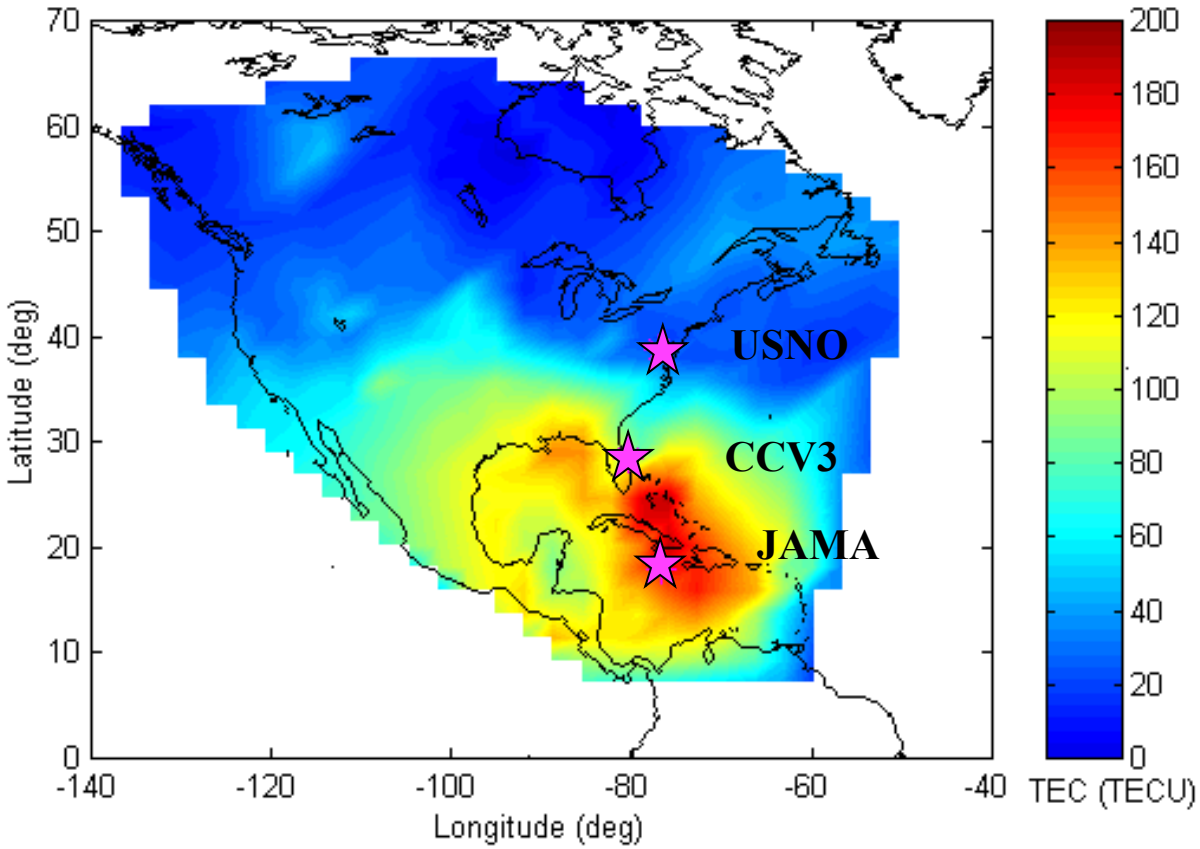
But what happens in this case?!

TEC Map July 15, 2000: 22:25 UT



Severe storm event – not the "normal" cosine trend

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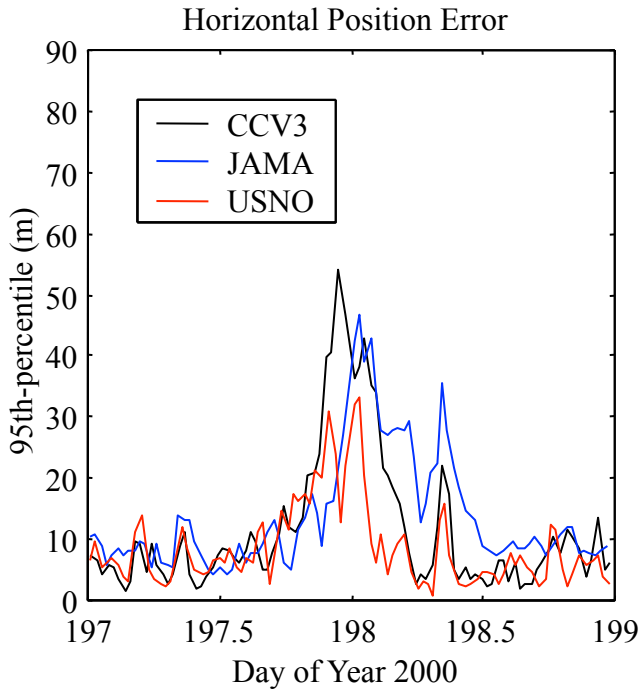
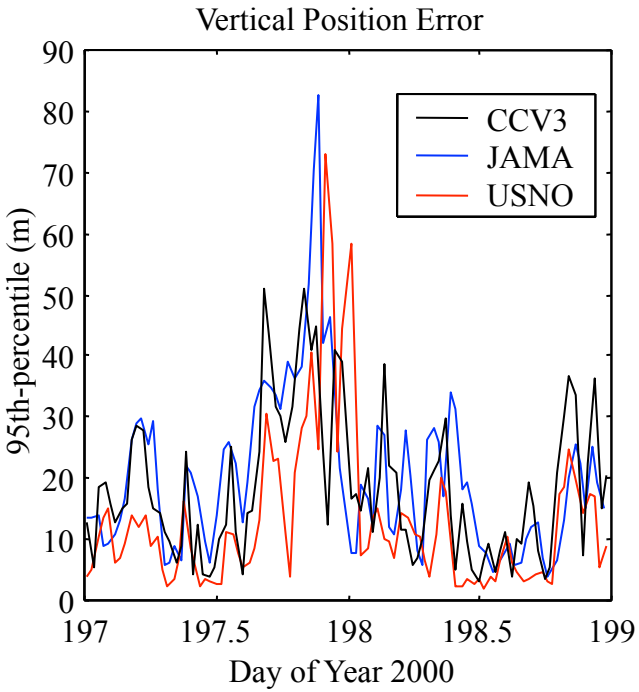
Single Point Positioning Accuracies (Single Frequency)





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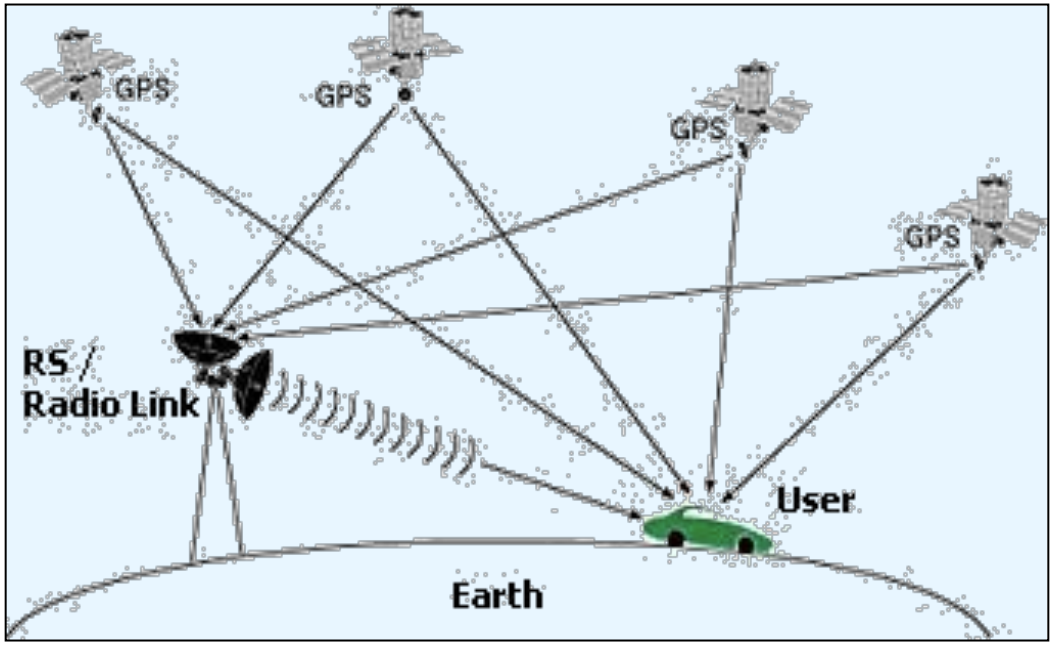
Differential GPS



- 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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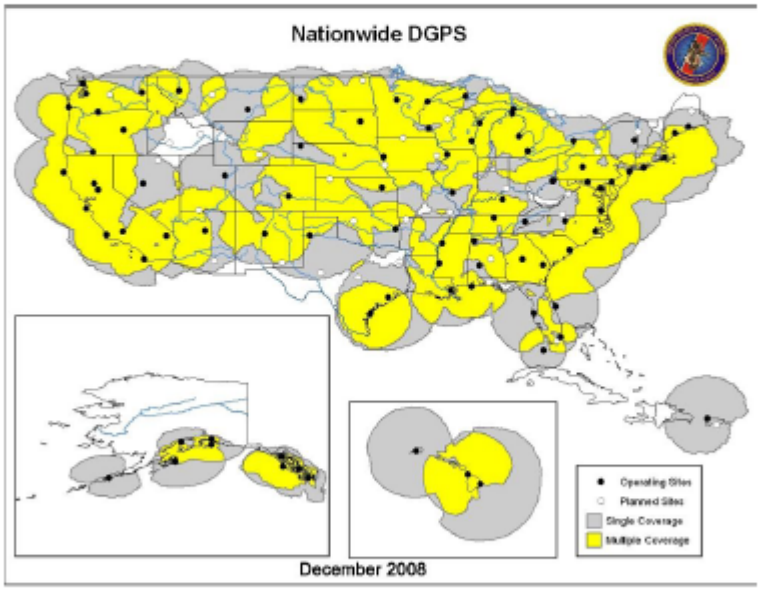
DGPS Services are common in many countries

Canada

- The United States DGPS service is operated by the United States Coast Guard and has many applications in mapping and surveying, natural resource exploration/exploitation, agriculture, GIS, land-based transportation and emergency response.



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

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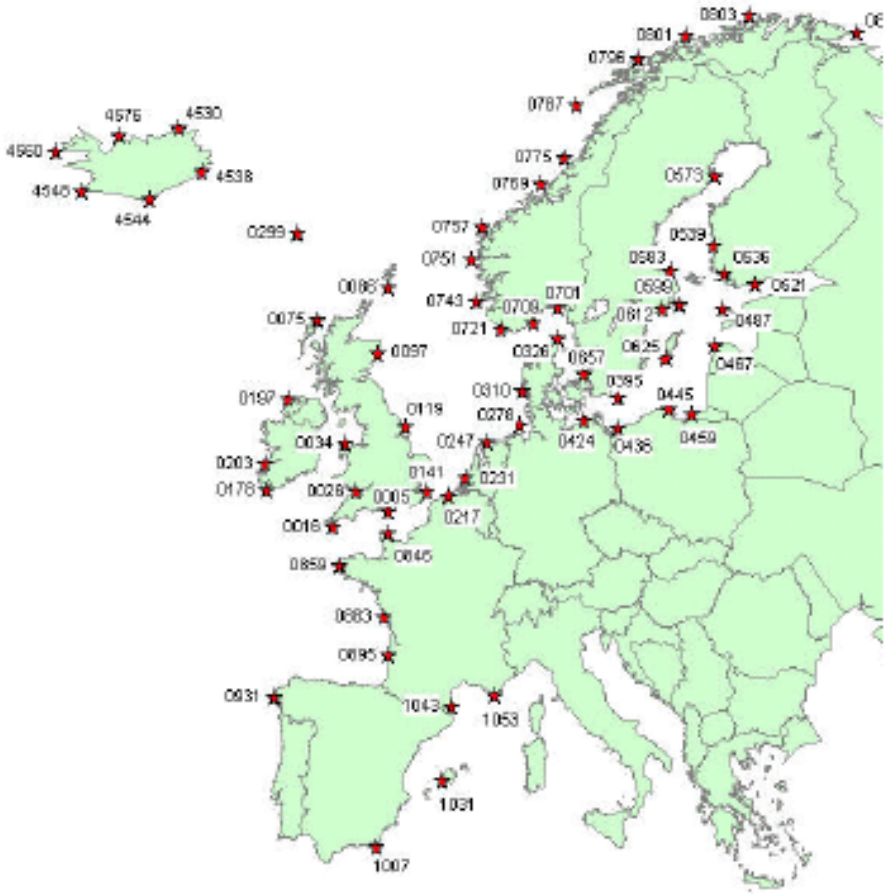

http://www.effective-solutions.co.uk/beacons.html

- A European public system is operated by consortium of countries. Accuracies of 10 m 2DRMS (95%) are guaranteed at ranges of 500 km.

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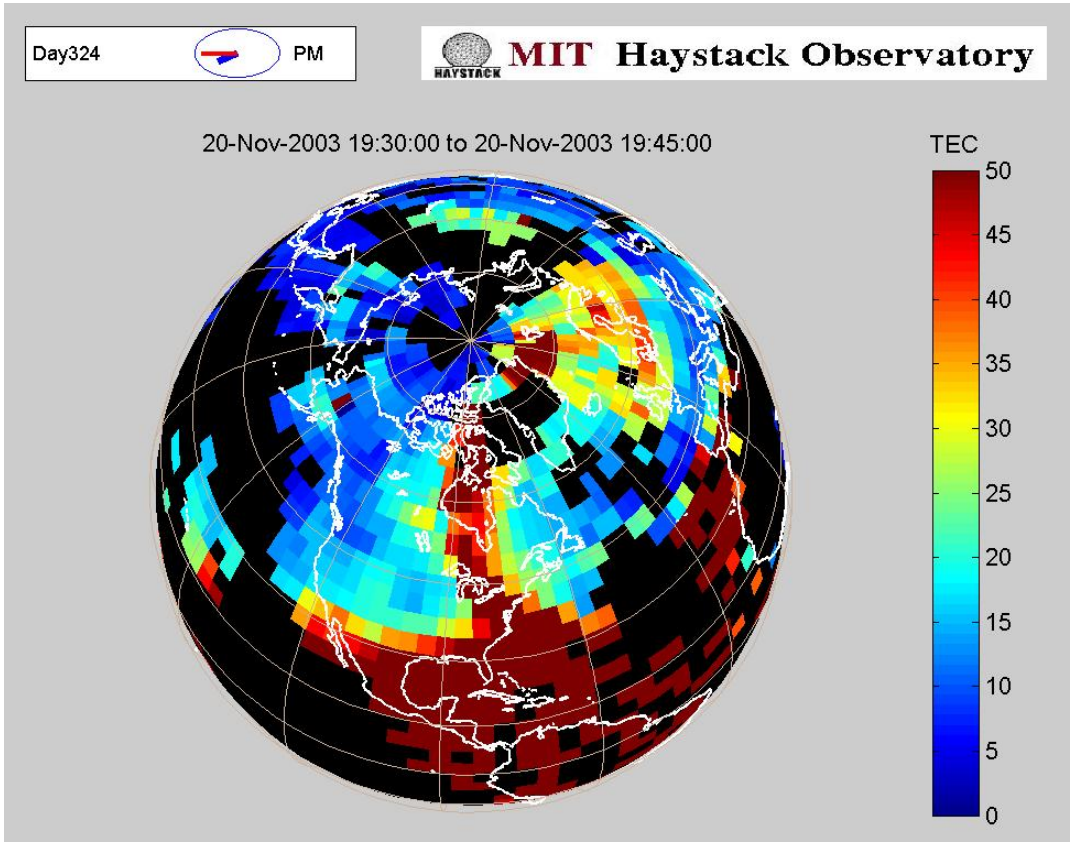
But what happens in this case?!
Storm Enhanced Density



Large ionosphere gradients

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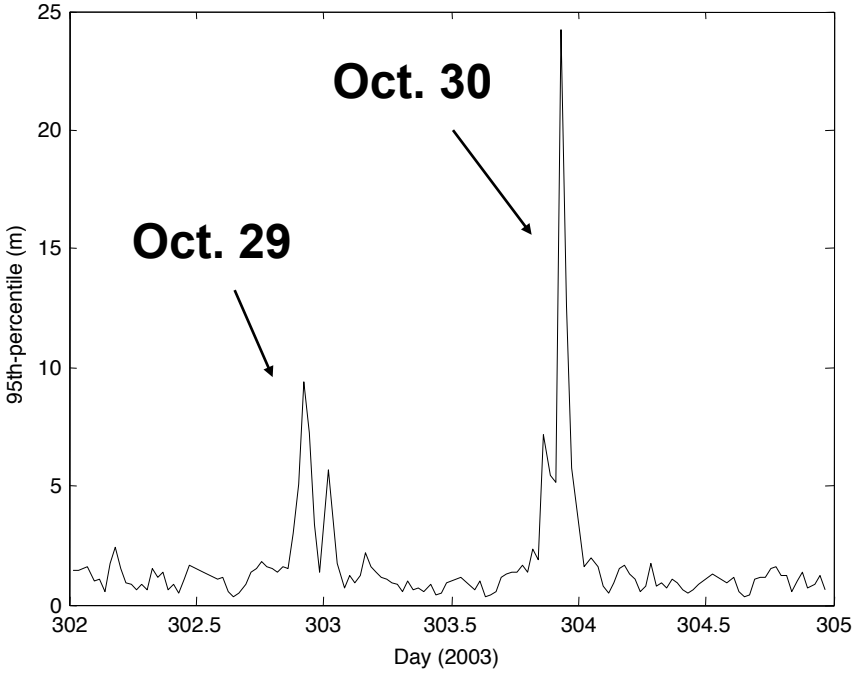
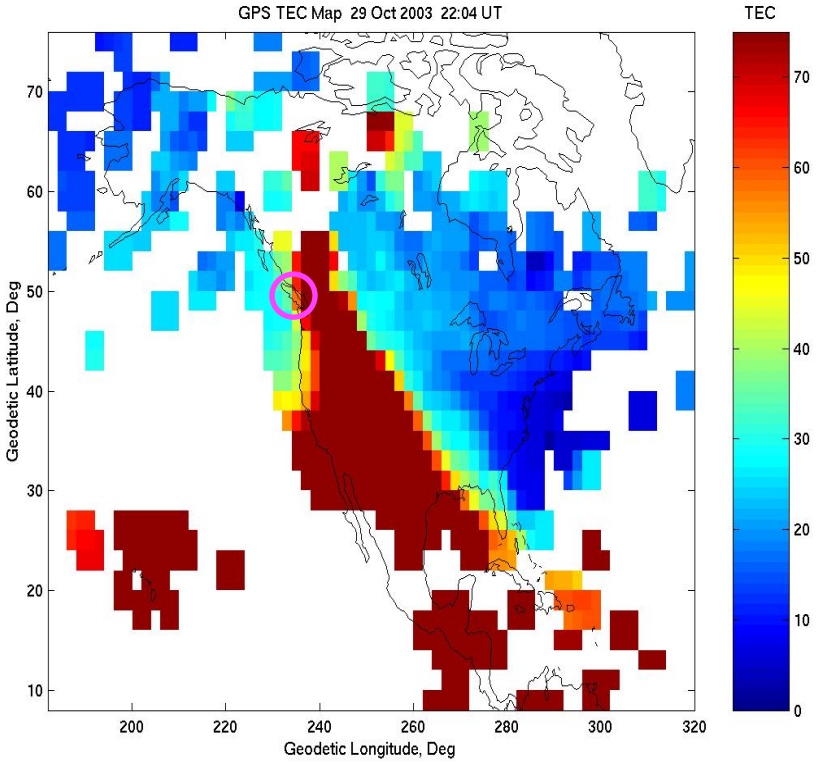
Example SED - October 29-31, 2003

Horizontal DGPS Pos. Accuracies: 125 km Baseline





- **Position accuracies > 10 m (95%) for 90 minutes**

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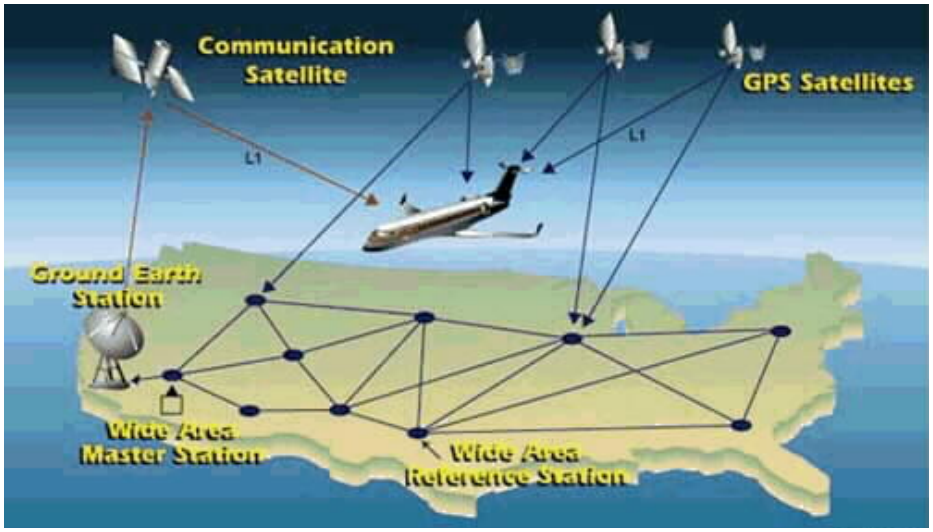
Wide Area Augmentation System



- Designed to provide reliable positioning accuracies better than 8 m (vertically and horizontally) for aircraft navigation
- 38 reference stations and 2 master stations
- WAAS vector corrections: satellite clock & orbit, and ionosphere
- WAAS messages provided by geostationary downlink
- WAAS positioning capabilities in low-cost receivers (marine and land applications)

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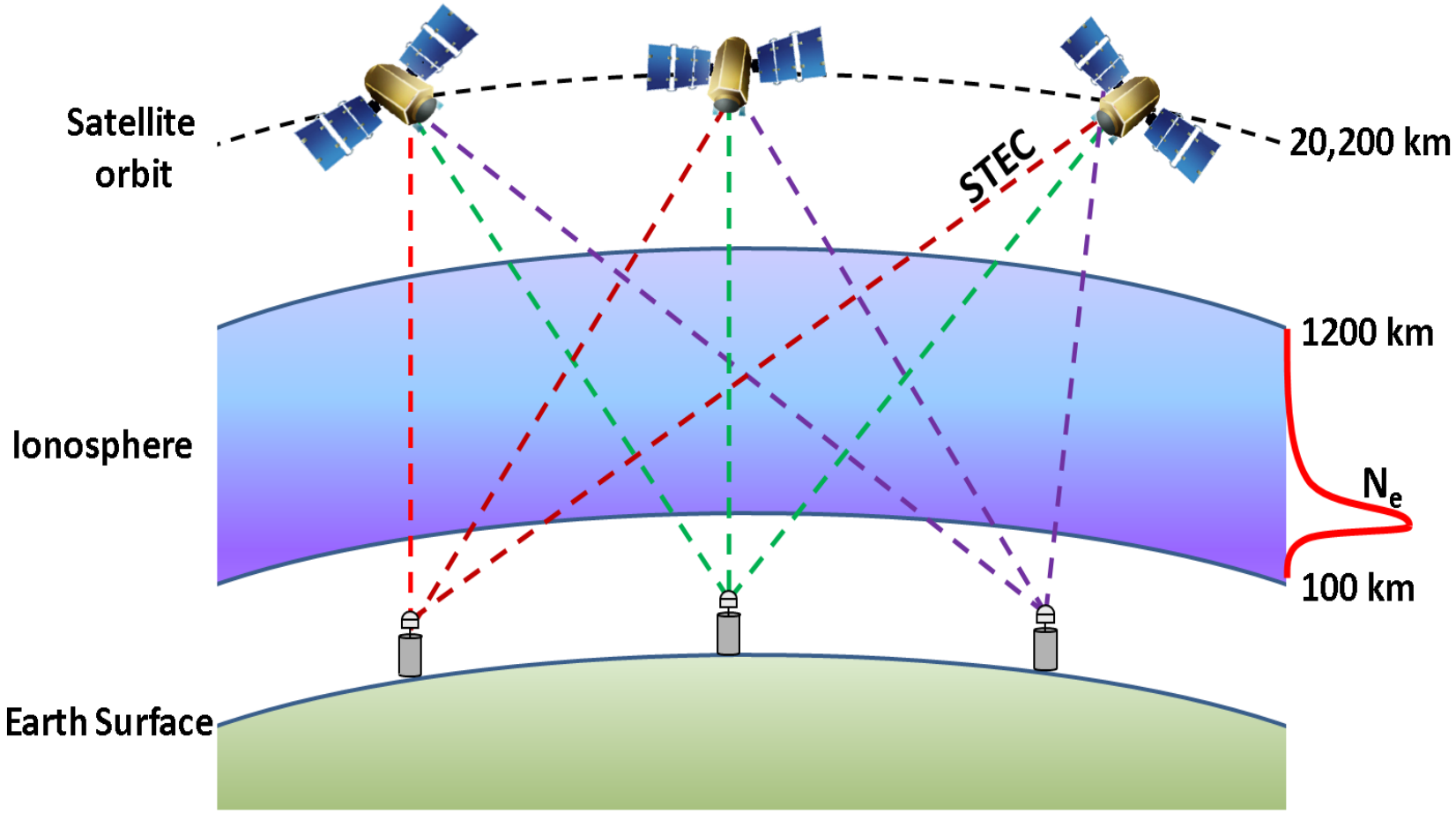
Wide Area Ionosphere Observation



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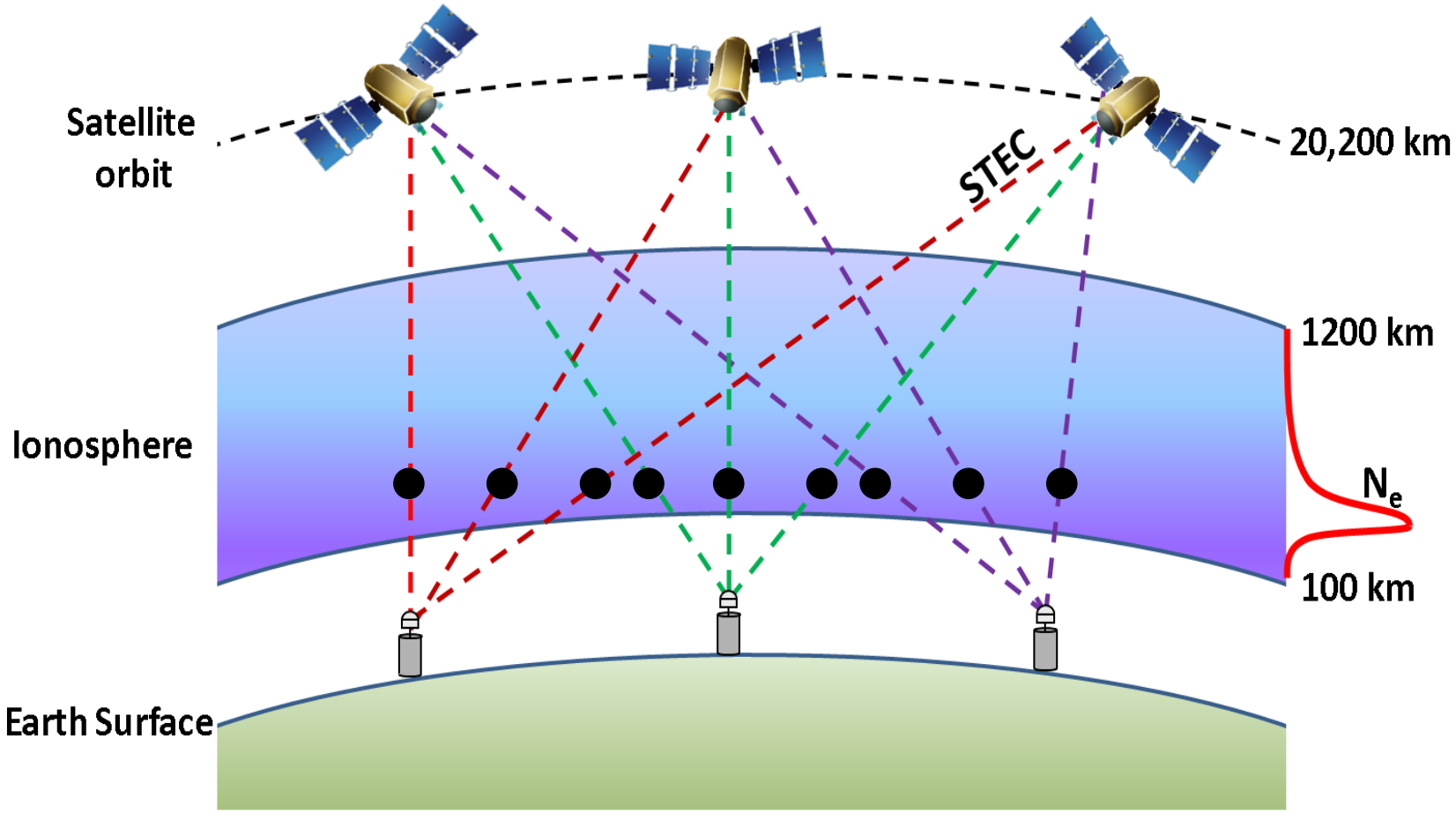
Mapped to Two Dimensions



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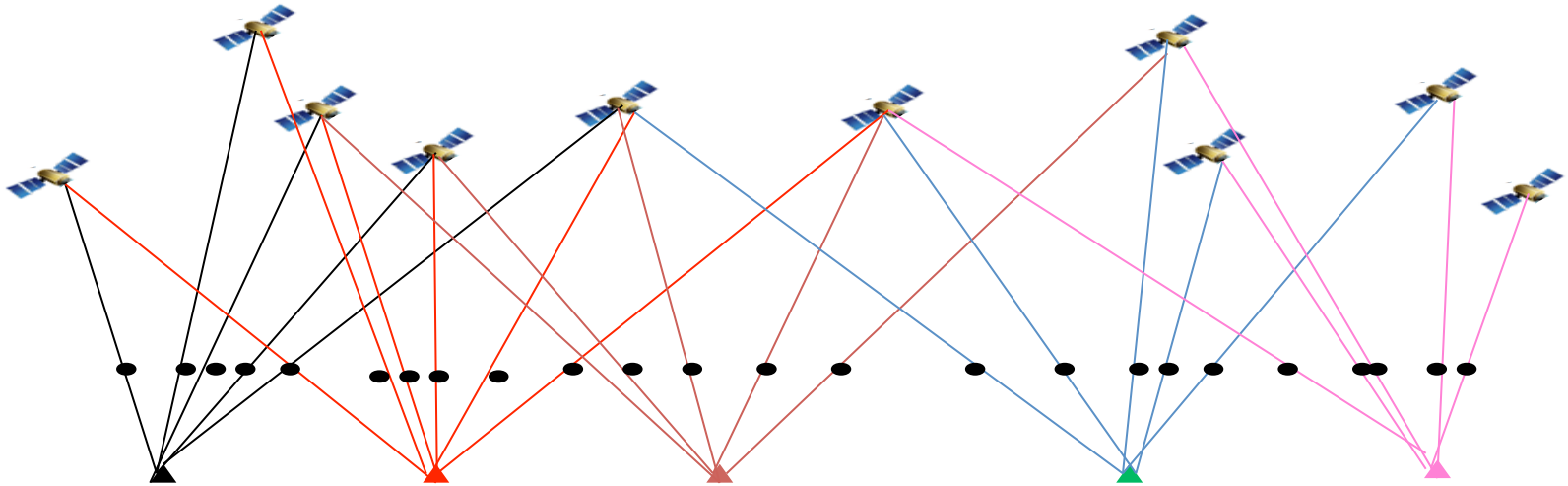
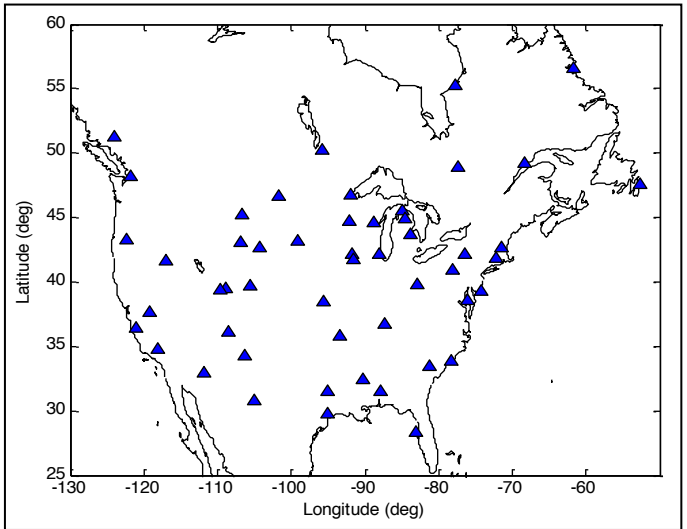
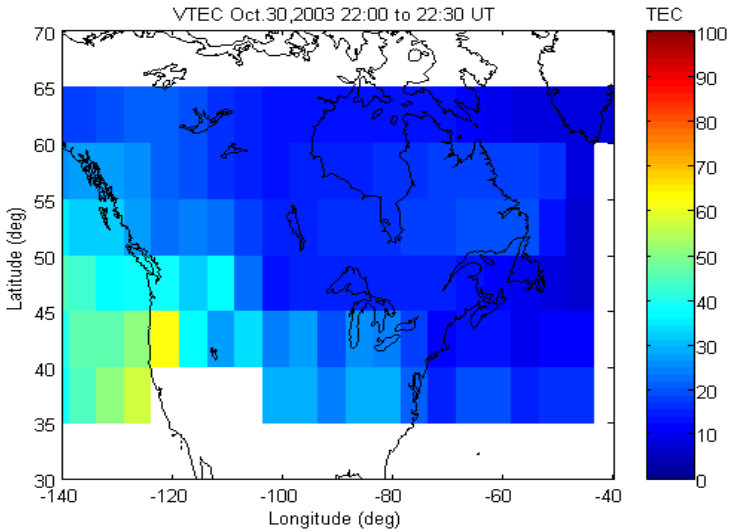
Network Observations and Output

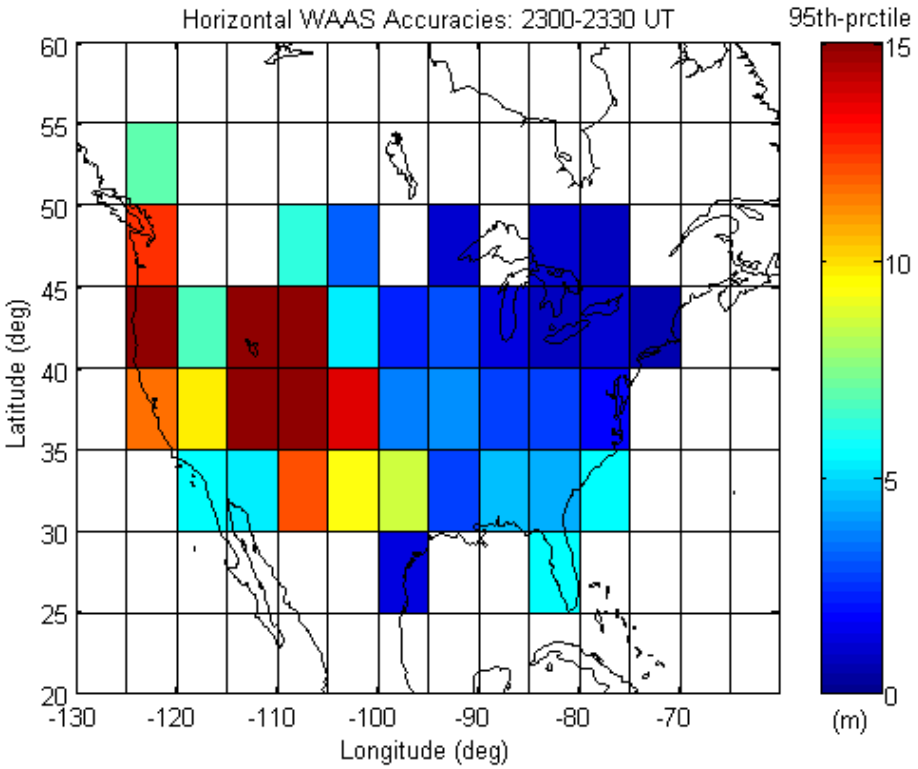


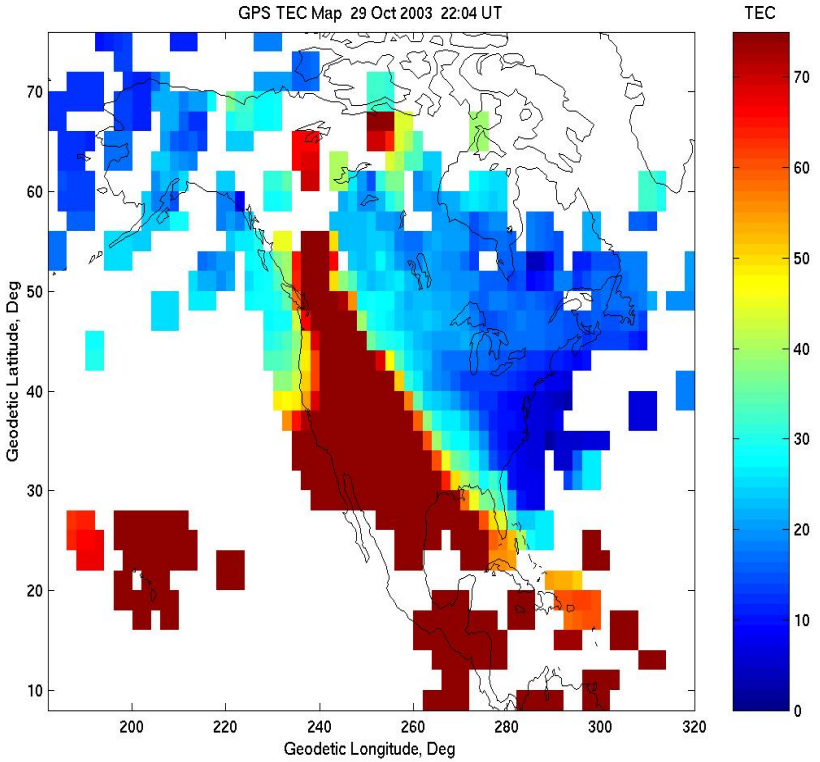
$$F = a_0 + a_1\Delta\lambda + a_2\Delta\phi$$





WAAS Position Error





- Errors of >15 m horizontal

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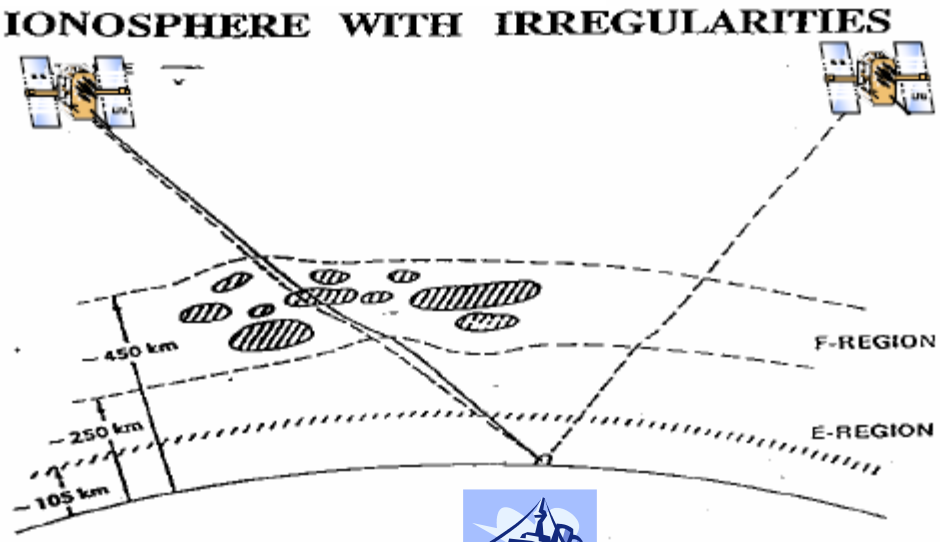
Another Effect

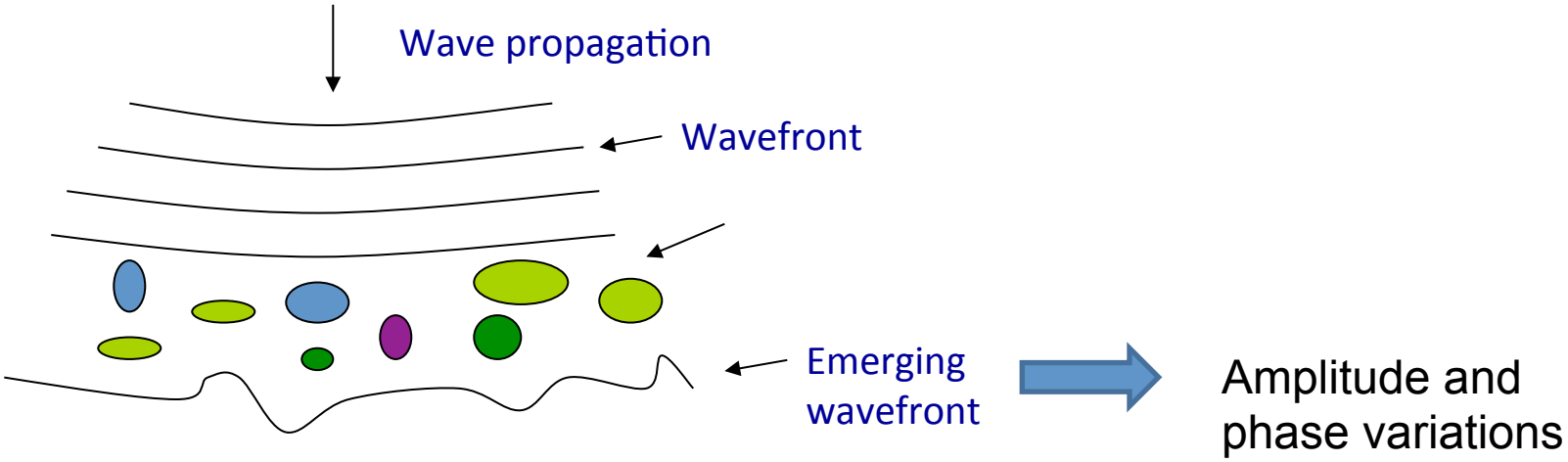
Space Weather Causes Ionospheric Scintillation

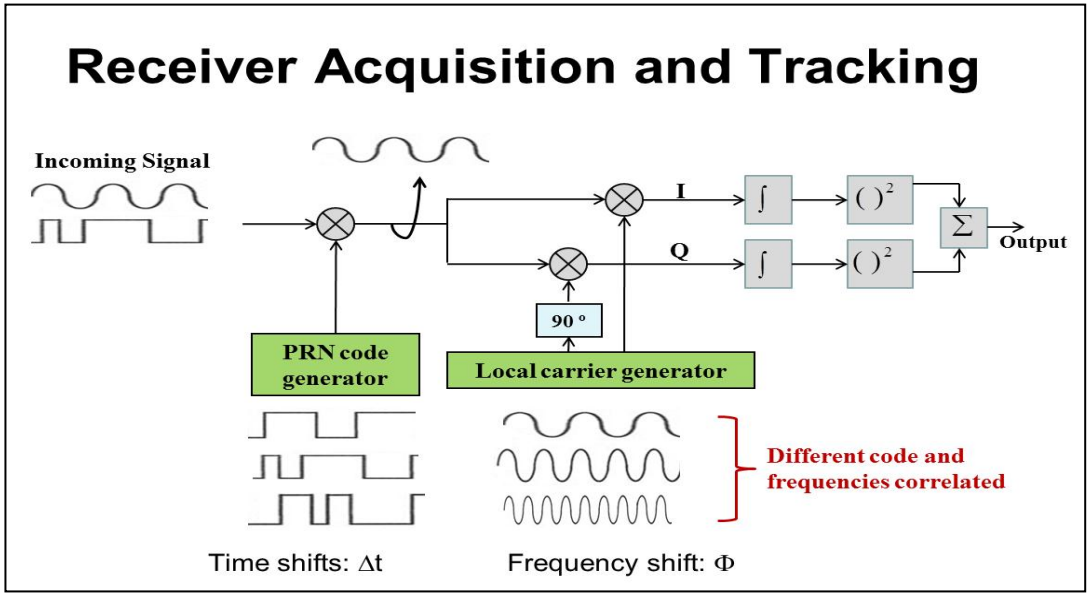
Ionospheric Scintillation

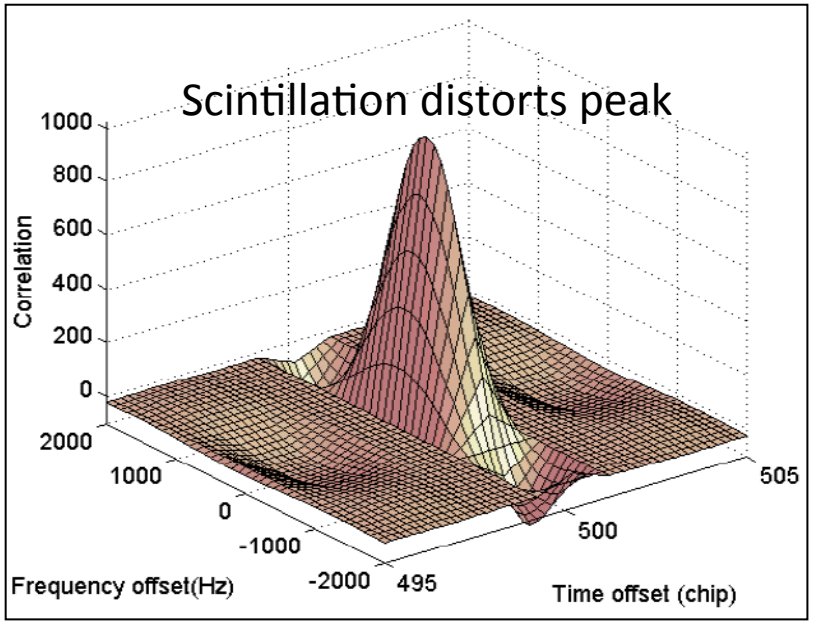
- Random rapid functions of the signal (signal strength, phase, range) about a mean value
- Phase and amplitude scintillations due to "turbulence" or irregularities (m→km in scale size) in electron density along signal path



GPS Receiver Performance







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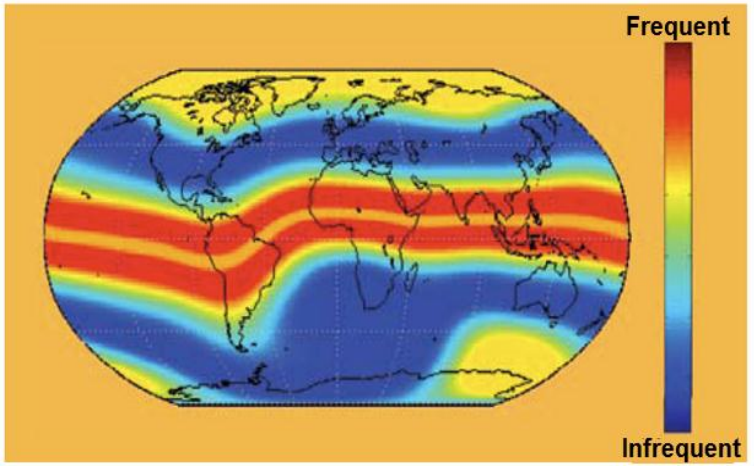
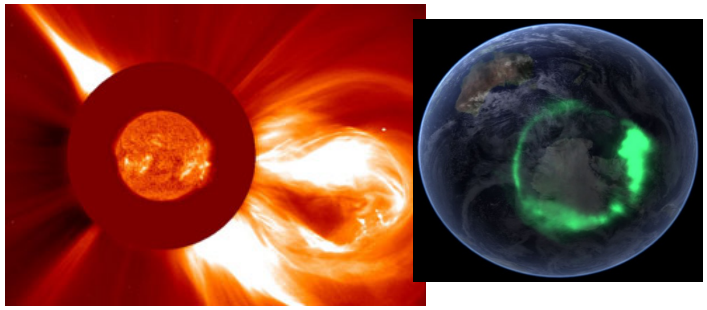
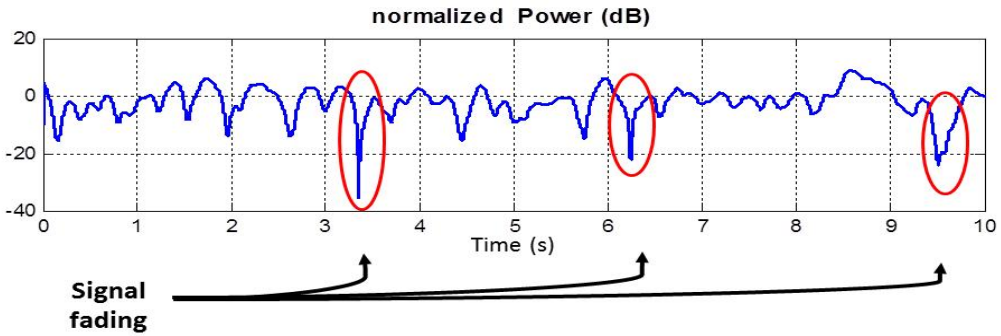
Ionospheric Scintillation Impact







GPS signals weak and GPS receiver loses observations and navigation capabilities

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GPS Positioning Accuracy

Low

(single frequency,
metre-level accuracy)

High

(multiple frequencies,
centimetre-level accuracy)

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GPS Positioning Accuracy

Affected by scintillation

Low

(single frequency,
metre-level accuracy)

High

(multiple frequencies,
centimetre-level accuracy)

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What GNSS Needs

- Alarmist media statements? No
- Space weather predictions? Not really…
- Specification of structures, irregularities and gradients in electron density (ISR)
- Simulation tools for
  - assessing space weather impact on GPS modernization, Galileo and COMPASS
  - designs of future systems and signals

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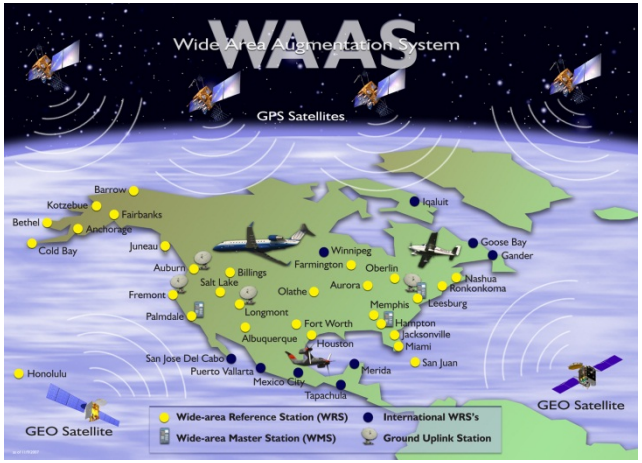
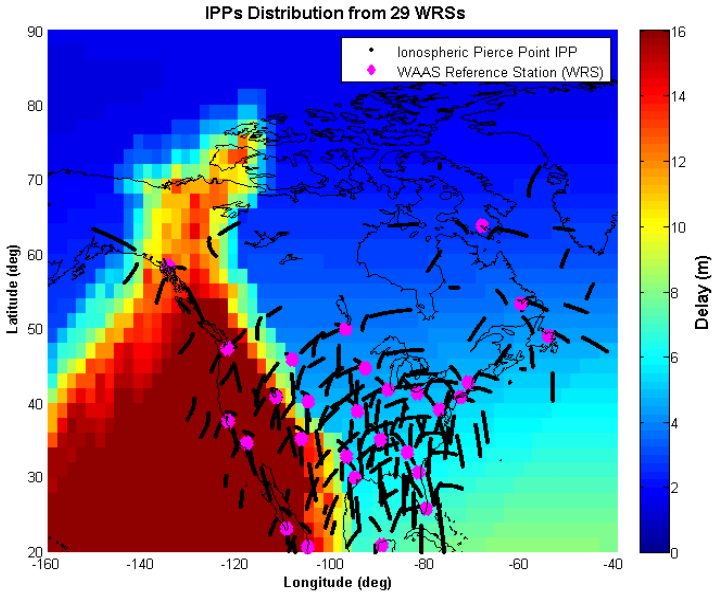
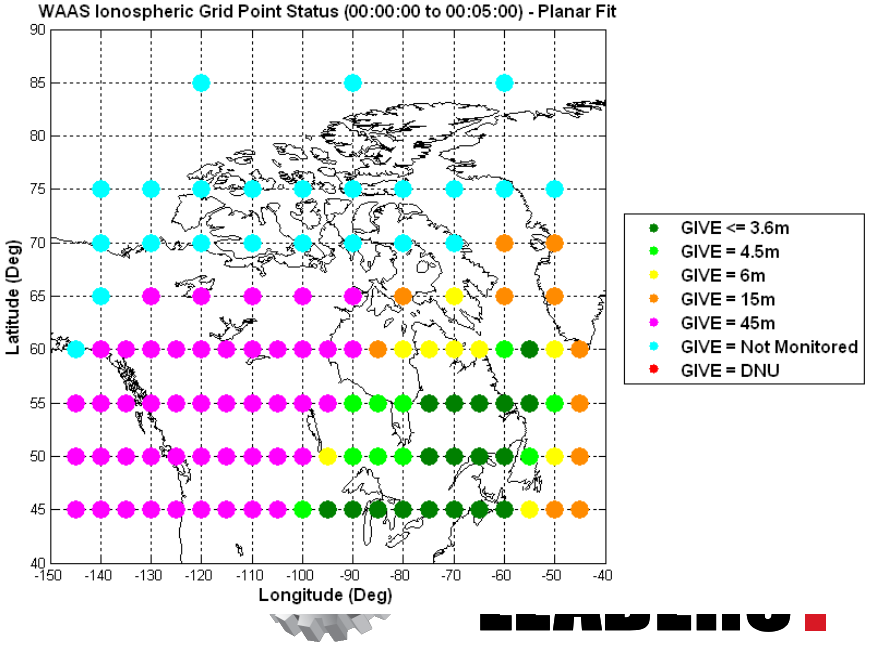
Project: Commercial Aviation

Sponsors/partners:
NAV CANADA, NASA/JPL

Objective:
Detect and reduce space weather effects



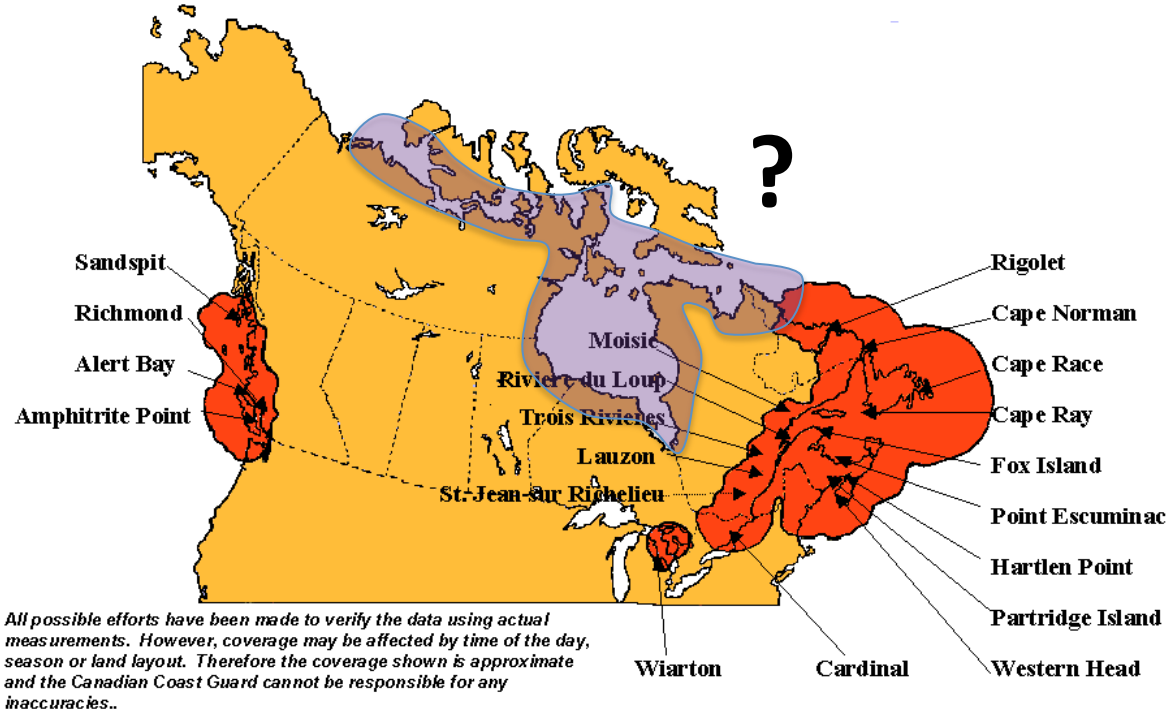




Project: Maritime Navigation

Sponsors/partners:
Canadian Coast Guard

Objective:
Expand marine DGPS services in northern Canada



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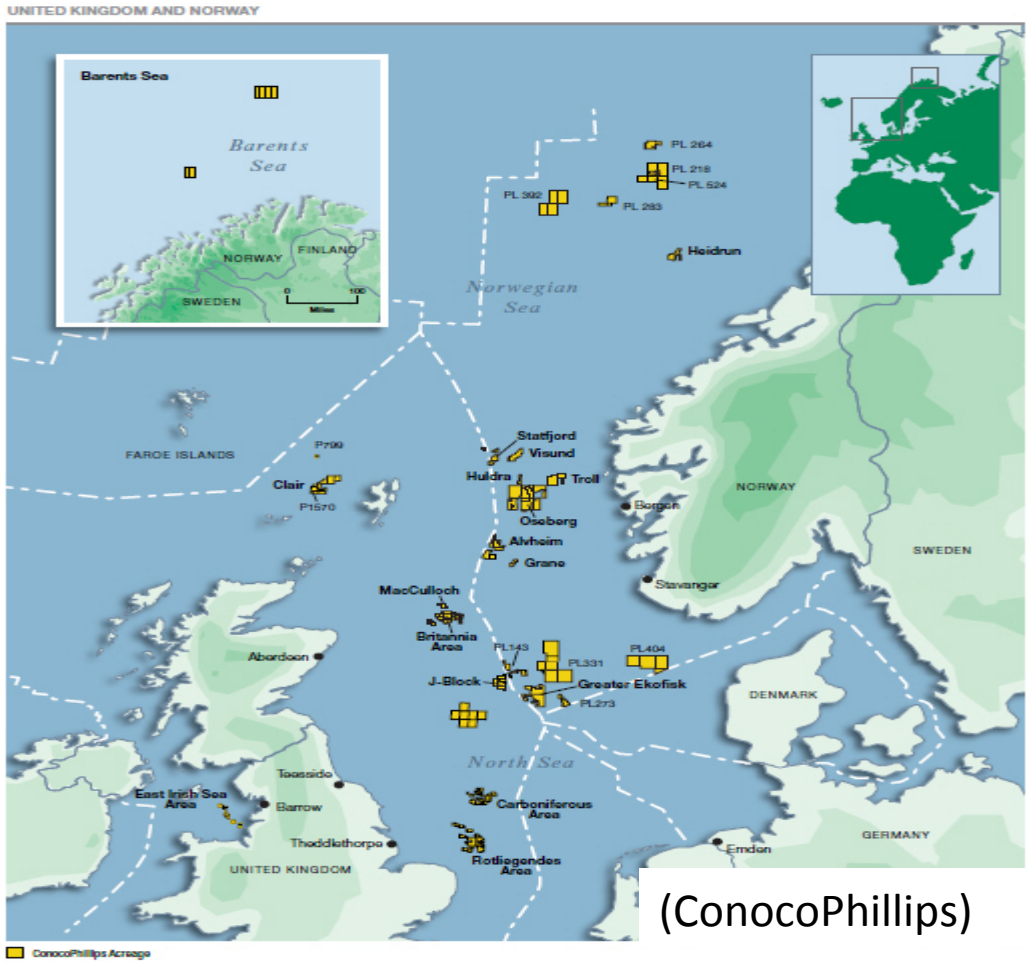
Project: Arctic Testbed

Sponsors/partners:
European Space Agency,
Kongsberg Seatex

Objective:
Determine optimal marine and aviation navigation services in European Arctic region

- Develop better navigation methods
- Develop improved GNSS receivers
- Develop space weather warnings



(ConocoPhillips)

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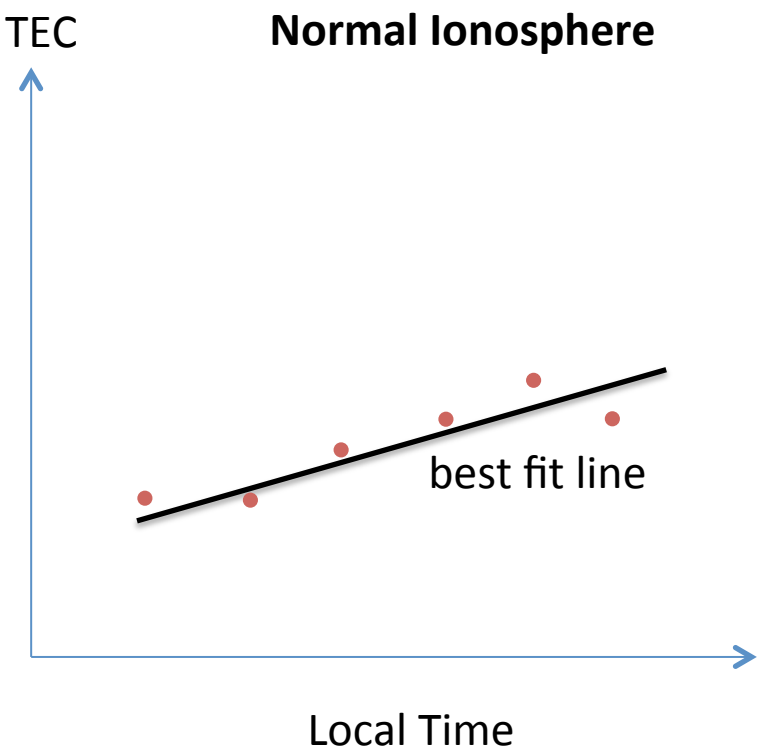
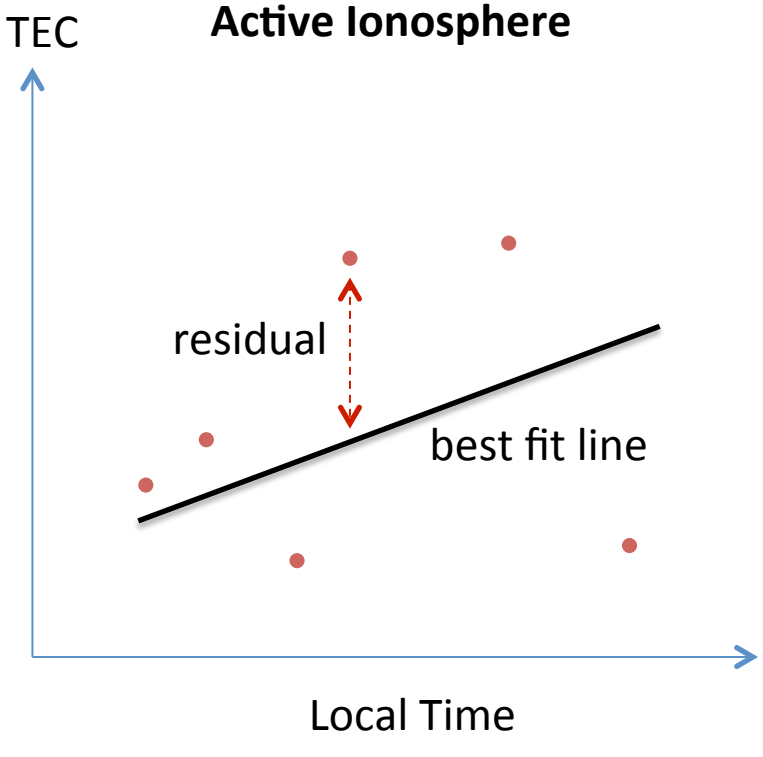
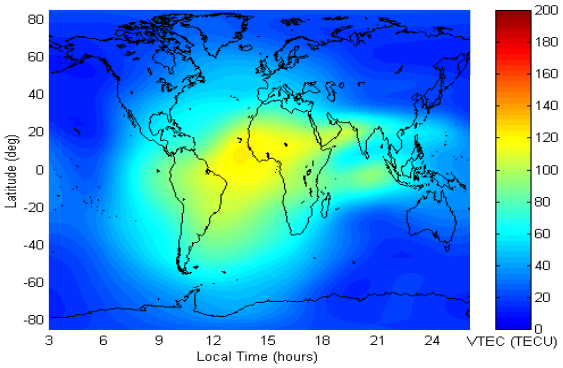
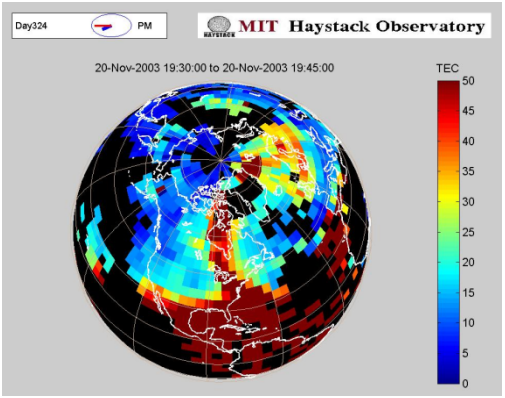
Extra

Error Bounds









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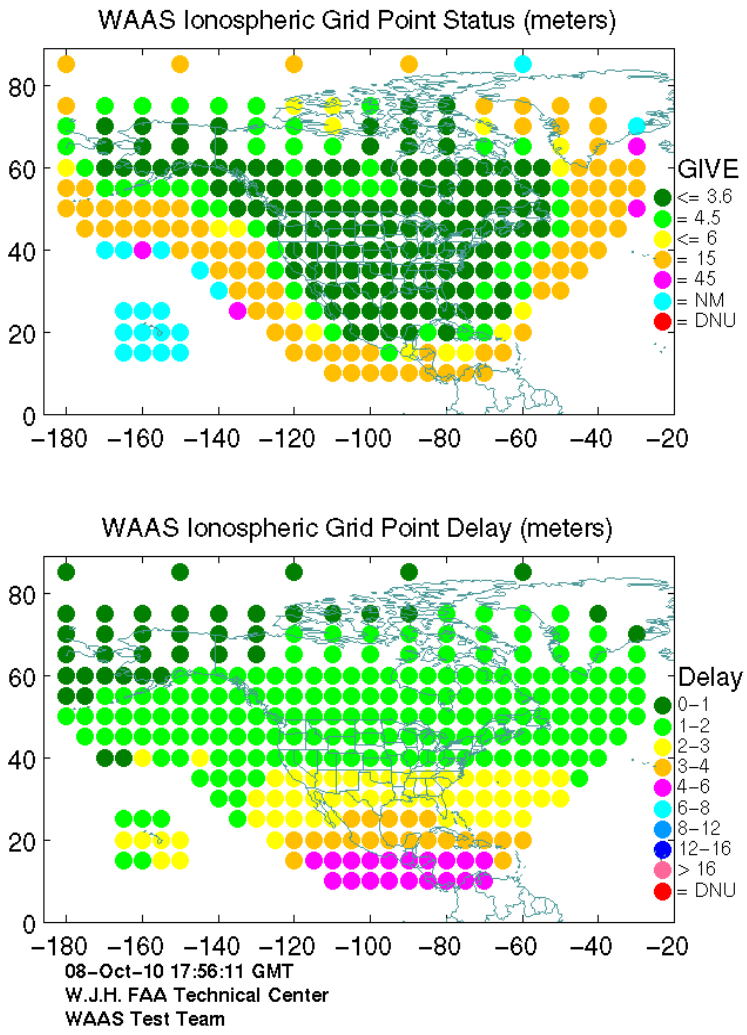
WAAS Error Bounds



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

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