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Ionospheric Effects on Satellite Navigation Systems

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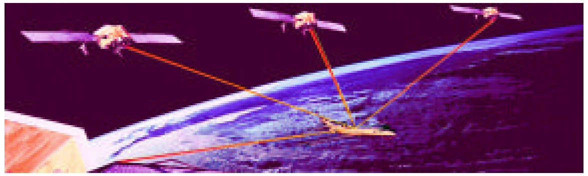
OUTLINE

- Satellite Navigation Systems
  - Overview
  - Applications
  - Main propagation effects
- Ionospheric effects on SatNav Systems
  - Signal delay
  - Scintillations
  - Questions posed by ESA SatNav Projects

Satellite Navigation - Overview



Simplified principle of position determination

- Satellites transmit their position and time
- Receiver measures time (= distance) to sat
- With 4 satellites, receiver resolves for x,y,z,t

Satellite Navigation provides

- Position
  - Latitude, Longitude and Height (datum: WGS84)
    Example: ESTEC Lat: +52° 13' 15.67“ Lon: +4° 25' 25.40“ Alt: 0 m
    Horizontal Accuracy (95%) :
    Consumer grade GPS receivers: SF < 15 m, SBAS: < 3 m, DGPS: 2-5 m ,
    Geodetic DF receivers: CDGPS < 0.25 m, RTK: < 0.1 m Static Survey: < 0.05 m
- Speed
  - By processing the position difference between two recordings and by processing the Doppler shift on each link
    Can be used for measuring movements of tectonic plates (1 mm/yr) and of missiles (4 Mach = 4770 km/h)
- Time
  - Atomic time. GPS time = UTC + 13 s (no leap seconds)
    (GPS Timing receivers have accuracies of 2 – 200 ns)

Sat Nav Applications

Fishery
Car Navigation
Oil drilling
Civil Aviation
Network sync.
Defence
Shipping
Recreation
Forestry
Trucking
Rail
Survey
Precision farming
Science

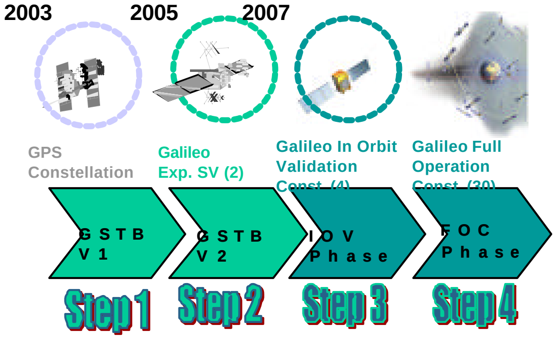
ESA's Satellite Navigation Programme

- **EGNOS** – terrestrial overlay for GPS to provide integrity to aeronautical users (http://www.esa.int/esaNA/egnos.html). Certification in 2005 (see www.essp.be). Currently the extension to Africa is being investigated.
- **GALILEO** – independent civilian satellite navigation system. (http://www.esa.int/esaNA/galileo.html). First 2 satellites (GSTB-V2) being prepared for launch next year, followed by the IOV phase. System fully operational by 2012.

Different SatNav Systems

NAME	Nr Sats	Nr Planes	Inclin [deg]	Orbit [km] Period [h]	Repeat Track [days]	Signal sep.
GPS [US]	21+3	6	55.0	20180 12:00	1	CDMA
GLONASS [RU]	21+3	3	64.8	19100 11:15	8	FDMA
GALILEO [EU]	27+3	3	56.0	29600 18:52	10	CDMA

Galileo Development Sequence



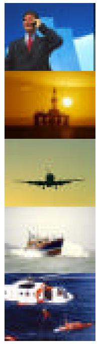
2003
2005
2007

GPS Constellation
Galileo Exp. SV (2)
Galileo In Orbit Validation Const. (4)
Galileo Full Operation Const. (30)

GSTB V1
GSTB V2
IOV Phase
FOC Phase

Step 1
Step 2
Step 3
Step 4

Galileo Services



- **Open Access**
  Free to air; Mass market; Simple positioning
- **Commercial**
  Encrypted; High accuracy; Guaranteed service
- **Safety of Life**
  Unencrypted; Integrity; Authentication of signal
- **Search and Rescue**
  Near real-time; Precise; Return link feasible
- **Public Regulated**
  Encrypted; Integrity; Continuous availability

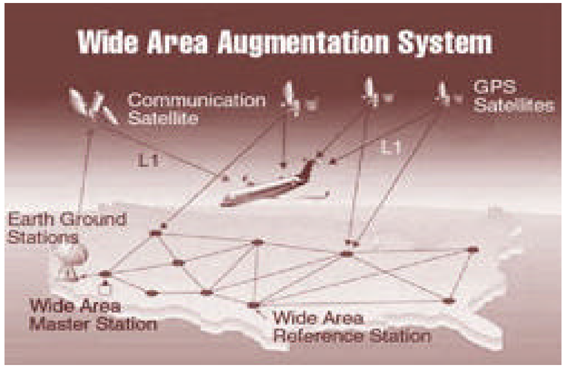
Source: P. MARCHLEWSKI, Galileo Joint Undertaking

SBAS Systems

SBAS = Satellite-Based Augmentation System

A network of ground stations observes the signal in space and transmits ionospheric corrections as well as integrity information to the user receiver. This way, GPS can be used for landing commercial aircraft.

SBAS Concept

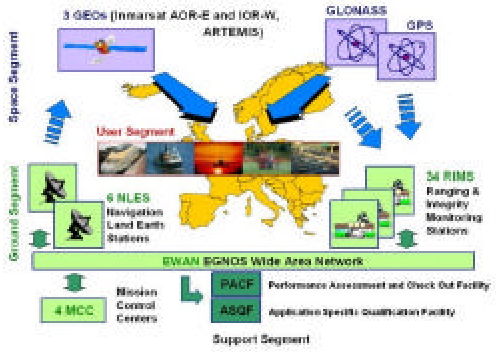


Source: FAA)

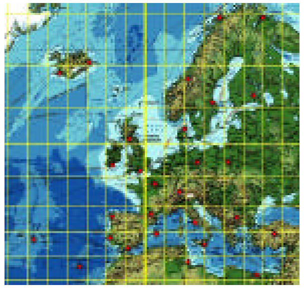
SBAS Terminology

- **GIVD**: **G**rid **I**onospheric **V**ertical **D**elay
  - This is the estimated vertical delay at L1 at the **I**onospheric **G**rid **P**oint (**IGP**; typically a node in a 5 degree by 5 degree raster). The user receiver performs a bilinear interpolation to estimate the vertical delay at the Ionospheric Pierce Point (**IPP**) (interception of path to GPS satellite with 350 km altitude sphere) and uses an obliquity function to estimate the path delay.
- **GIVE**: **G**rid **I**onospheric **V**ertical **E**rror
  - Is transmitted for integrity purposes.

EGNOS Infrastructure



SBAS System

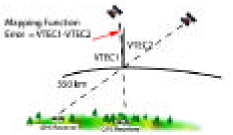


Red dots: EGNOS RIMS (Ranging and Integrity Monitoring Stations)
Yellow grid: 5-degrees lat/lon

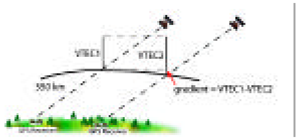
A **S**atellite-**b**ased **A**ugmentation **S**ystem uses a network of reference stations to observe the signals from navigation satellites and one or more geo-stationary satellites to transmit the obtained corrections to the users. It allows to improve the position accuracy (differential corrections) and to create integrity, which is required for Safety-of-Life critical applications.

The ionospheric corrections are transmitted in form of a 5 x 5 degree grid. The user receiver calculates the vertical TEC at the iono pierce points by interpolation between grid points.

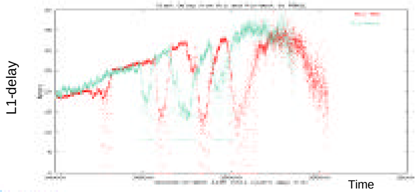
SBAS Ionospheric issues



1. Converting from sTEC to vTEC involves obliquity error.



2. Strong gradients lead to interpolation errors

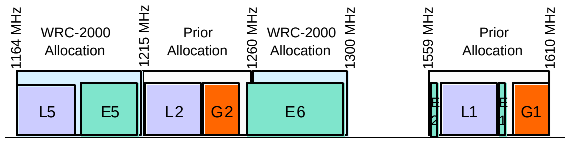


In particular, in equatorial regions ionospheric depletions can cause strong TEC variations over short distances. Left: two concurrent observations, site spacing 95 km (source: T. Dehel, 2002)

Ionospheric Corrections for EGNOS

- CPF Algorithm calculates the GIVDs, GIVEs and GEO slant ionospheric delays.
- Estimate the vertical ionospheric delays at 642 triangular nodes on a sphere, using a Kalman filter implementation of a modified Solar-TRIN algorithm.
- Computes a “basic” GIVE variance.
- GIVDs and GEO ionospheric delays are computed by triangular interpolation
- Final GIVE estimate is computed by checking and inflating the basic GIVE to consider several factors like poor geometry and temporal degradation.

Satellite Navigation Frequency bands



GPS: L1 = 1575.42 MHz (C/A code), L2=1227.6 MHz (P-code), L5

GLONASS: G1, G2

GALILEO: E1, E2, E5, E6.

Note: WRC-2000 refers to allocations granted at the World Radio Conference in Istanbul in Spring 2000

Propagation Effects on SatNav Systems

Ionosphere
- •Delay
- •Scintillations
- •(Faraday Rotation)

Troposphere
- •Delay
- •(Rain attenuation)
- •(Cloud attenuation)
- •(Scintillations)
- •(XPD reduction)

Environment
- •Shadowing
- •Blockage
- •Multipath

Ionospheric delay effects

- Without correction, this can lead to UERE of 50 m

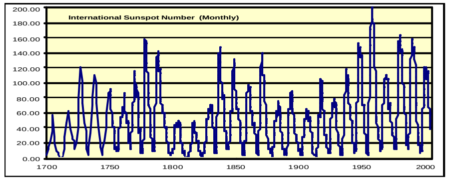
  (User Equivalent Range Error for L1 if vTEC=120 TECu and Elevation angle = 12 deg using simple obliquity function)
- For single frequency receivers a broadcast message is used to correct for this delay (GPS: Klobuchar)
- Multi frequency receivers can correct for the ionospheric delay (because ionosphere is dispersive)

Ionospheric scintillations

Rapid variations of amplitude and phase

- Can lead to cycle slips and loss-of-lock
- If less then 4 visible satellites are left un-affected, the navigation solution is lost.
- For SBAS receivers, if the GEO link is lost due to scintillations, the corrections and integrity information are lost.
- There is a need for understanding the spatial and temporal correlation of scintillations.

Sunspot Numbers -Solar Cycle



The solar cycle is 11 years

$R = k\,(10g+s)$

where

R= Sunspot number

g= # groups

s = # indiv.spots

Questions:

- How do we define a “typical”solar cycle?
- What is the maximum solar flux to be expected in solarmax conditions?
- Can we make any (useful) predictions about the characteristics of future solar cycles?

Real time information: `http://www.nwra-az.com/spawx/ssne24.html`

Indices for Ionospheric Models

R_{12} ... the 12-month running mean sunspot number for month n

$$R_{12} = \frac{1}{12}\left[\sum_{n-5}^{n+5}(R_k) + 0.5(R_{n+6} + R_{n-6})\right]$$

where R_k is the mean value of R for a single month k

{0-160}

Φ_{12} … (also $F_{10.7}$) the 2 800 MHz (10.7 cm) solar radio noise flux [10^{-22} Wm^{-2} Hz^{-1}]

$$\Phi_{12} = 63.7 + 0.728 R_{12} + 8.9\times10^{-4} R_{12}^2$$

{65-200}

foF2…the critical frequency of the F_2 layer (frequency just penetrates F_2) [MHz]

$$foF2 = f_s \cos^n c$$

Where: c = solar zenith angle

$$f_s = f_{s_0} + 0.01(f_{s_{100}} - f_{s_0})R_{12} \qquad f_{s_0} = 4.35 + 0.058\,l - 0.00012\,l^2$$

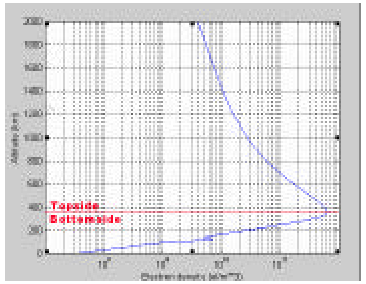
$$f_{s_{100}} = 5.35 + 0.011\,l - 0.00023\,l^2 \qquad n = 0.093 + 0.0461\,l - 0.000054\,l^2 + 0.00031 R_{12}$$

$$l = \left|\arcsin\left[\sin LAT_0 \cdot \sin LAT + \cos LAT_0 \cdot \cos LAT \cdot \cos(LON_0 - LON)\right]\right|$$

LAT_0 = 78.3 deg N, LON_0 = 291 deg E *(coordinates of magnetic North-pole)*

Source: Kenneth Davies, “Ionospheric Radio”, PeterPeregrinus Ltd.

Ionospheric Electron Density Profile



The ionosphere

The peak is between 350 and 400 km height.

1 TECU = 10^{16} el / m^2

For calculating ionospheric delay, the Electron Density along the propagation path has to be integrated (giving Total Electron Content)

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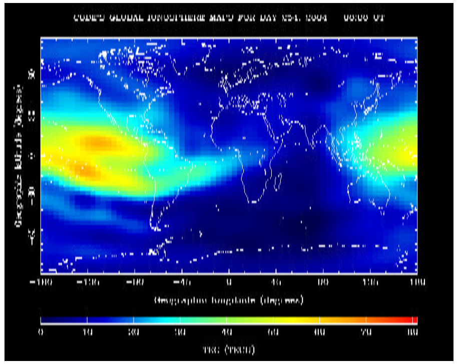
vTEC – nominal day

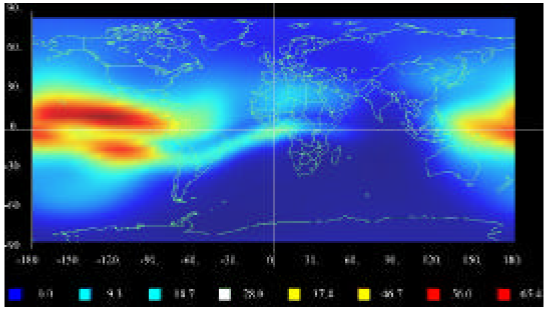


2004-09-04 (Day 254) was a “normal” day without unusual solar activity. Note the maximum of the vTEC –scale being 80 TECu

Data and animation courtesy of CODE team at U Berne. Input data from IGS Network (350 stations)

`http://www.cx.unibe.ch/aiub/ionosphere.html`

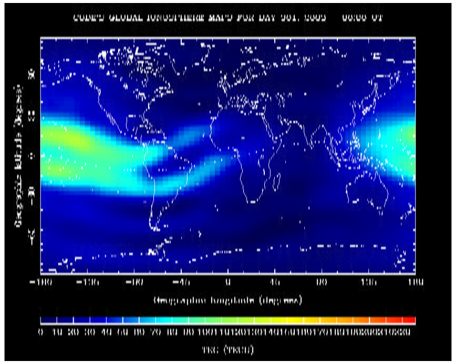
Global Map of Vertical TEC



Vertical TEC plotted in TECU (calculated using NeQuick)
F10.7 = 150, 1999-07-15, 23:00 UTC

Source: Y. Beniguel, "Improved version of GIM"

vTEC – storm day



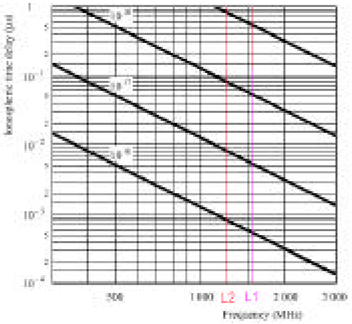
2003-10-29 (Day 302) was a "storm" day following a strong solar flare (actually, there were two in succession). Note the maximum of the vTEC –scale being 220 TECu

Data and animation courtesy of CODE team at U Berne. Input data from IGS Network (350 stations)

`http://www.cx.unibe.ch/aiub/ionosphere.html`

Trans-ionospheric delay

Group delay: $\Delta t = 1.343\, N_T / f^2 \times 10^{-7}$ [s]



Source: ITU-R Rec P.531-5

Where:

Δt: delay time [s] with reference to propagation in a vacuum

f: frequency of propagation [Hz]

N_T: total electron content along the slant propagation path.

Ranging error: (s = c.t)

$\Delta s = 40.3\, TEC / f^2$ [m]

TEC in TECU (1 TECU=10^{16} el/m^2)

at L1, 1 TECU means 0.16 m

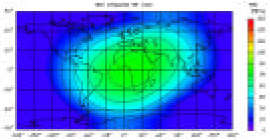
1 µs delay means 300 m range error

Trans-ionospheric delay correction

Dual frequency receiver: use differential delay $(\Delta t_2 - \Delta t_1)$

$TEC = (\Delta t_2 - \Delta t_1)\, f_1^2\ f_2^2\ 10^{-4} / (f_1^2 - f_2^2)$

$\Delta s_1 = 40.3 \times TEC / f_1^2$



Single frequency receiver: use parameters in navigation message.
For GPS, the Klobuchar model is used:

$\Delta t_1 = A_1 + A_2 \cos [2\pi (t - A_3) / A_4]$

where

$A_1 = 5 \times 10^{-9}$ s

$A_2 = \alpha_1 + \alpha_2\ \varphi_{IP} + \alpha_3 \varphi_{IP}^2 + \alpha_4\ \varphi_{IP}^3$

$A_3 = 14{:}00^{h}$ local time

$A_4 = \beta_1 + \beta_2\ \varphi_{IP} + \beta_3 \varphi_{IP}^2 + \beta_4\ \varphi_{IP}^3$

all α_i and β_i are transmitted

$t = t_{UT} + \lambda_{IP} / 15$

t_{UT} is UTC, IP is Iono Point

λ_{IP} is longitude of IP

φ_{IP} is the spherical distance of IP from geomagnetic pole

Sources: 1. Hoffmann-Wellenhof et. al.. "GPS Theoryu & Practise, Spinger Verlag
2. http://home-2.worldonline.nl/~samsvl/pseucorr.htm

Galileo Single Freq. Iono algorithm

SENSOR STATION

Observe slant TEC in Galileo Sensor Stations for 24 hours

Optimise effective ionisation parameter for NeQuick to match observations

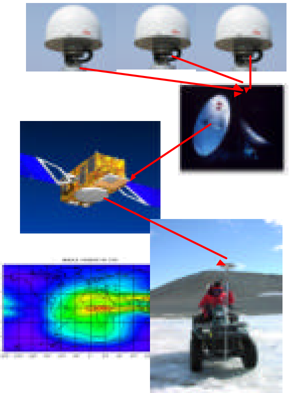
SATELLITE

Transmit effective ionisation parameter in Galileo Navigation message

$$Az = a_0 + a_1 \cdot m + a_2 \cdot m^2$$

USER RECEIVER

Calculate slant TEC using NeQuick with broadcast ionisation parameter. Correct for Ionospheric delay at frequency in question.

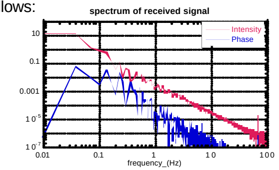


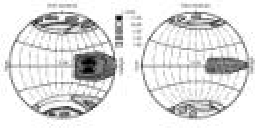
Scintillations

One of the most severe disruptions along a trans-ionospheric propagation path for Navigation signals is caused by ionospheric scintillations. Small-scale irregular structures are causing rapid variations in amplitude, phase and apparent direction of arrival. The scintillation index S_4 is defined as follows:

$$S_4 = \left(\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2} \right)^{1/2}$$

where I is the intensity of the signal and $\langle\ \rangle$ denotes averaging.





There are two intense zones of scintillation, one at high latitudes and the other centred within ± 20° of the magnetic equator *[Basu]*

Scintillations are a threat to continuity and availability of navigation signals since they can cause cycle slips and loss-of-lock in the receivers

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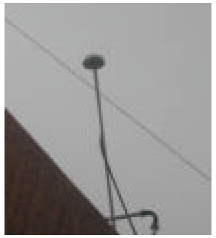
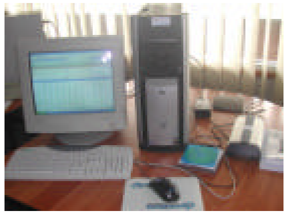
Scintillation Measurements in Douala

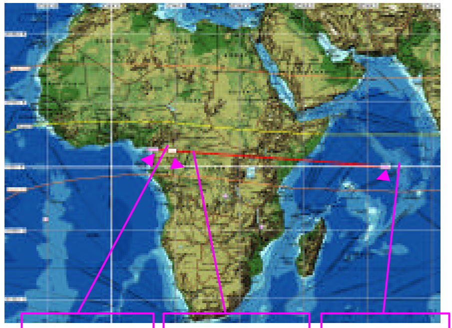


GPS 503 antenna on mast at Douala Airport
Lat: +4° 0' 49.5756"
Lon: +9° 42' 55.4544"
Alt: 48.3 m (WGS84)

GSV 4004 Ionospheric Scintillation Monitor and data logging computer at Douala Airport ASECNA office



Douala Scintillation Experiment



Ground station Douala

Iono Pierce Point (h=400 km)

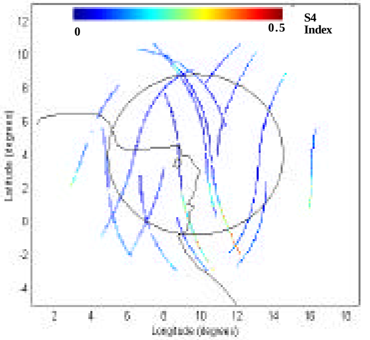
Satellite IOR-R at 64 deg E

The red line depicts the satellite to ground link.
AZ= 92.88 deg
EL = 27.97 deg

The white lines are a 15 deg LAT/LON grid.

The orange curves are the +/- 30 degrees magnetic latitude lines and the yellow line is the magnetic equator.

GPS observed scintillation index

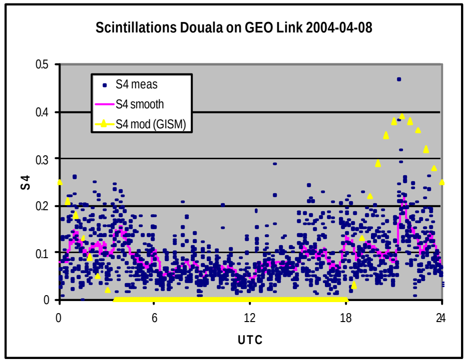


S4 for 2004-05-20 from 18:00 to 24:00 UT.

The black lines are the African coastline and the 30 degree elevation contour.

The colored dots are the projection of the iono-pierce-point (of the GPS-links) to the ground, with the color showing S4.

S4 measured and predicted



The blue dots are measured S4, the purple line is the 30-minute averaged S4. The yellow triangles are the model values predicted by GISM using F10.7 = 100.

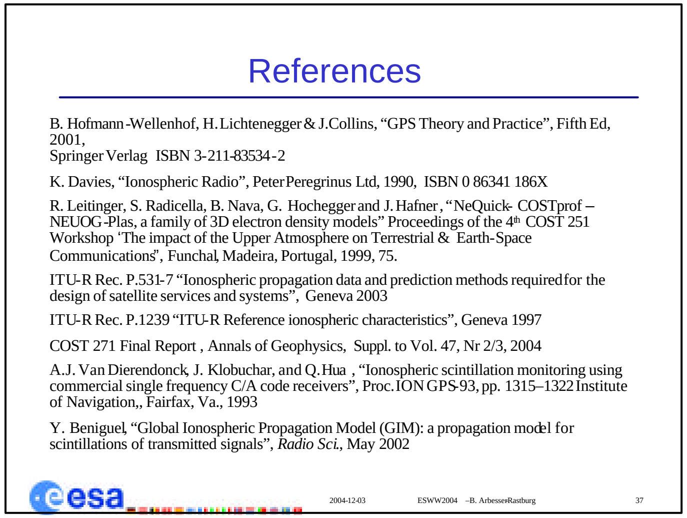
CONCLUSIONS

- Trans-ionospheric propagation effects are critical for Satellite Navigation systems
- They impact on position accuracy, continuity and availability and can challenge integrity
- Sat-Nav signals, in return, offer excellent opportunities for exploratory research of the ionosphere

Areas of work for the Ionospheric Research Community

- What is the best algorithm for the iono- free solution for three or more frequencies?
- Can a model that captures the ionospheric features during storm conditions be developed?
- What is the best strategy to combat the effects of ionospheric scintillations?
  - Can the temporal and spatial correlations of scintillations be modelled?
  - What is the best prediction model for auroral region scintillations
- How can equatorial depletions be modelled?
- How can TIDs be modelled?
- Can we improve the modelling of auroral effects?

WE NEED MORE WELL CALIBRATED LONG TERM OBSERVATIONS!



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