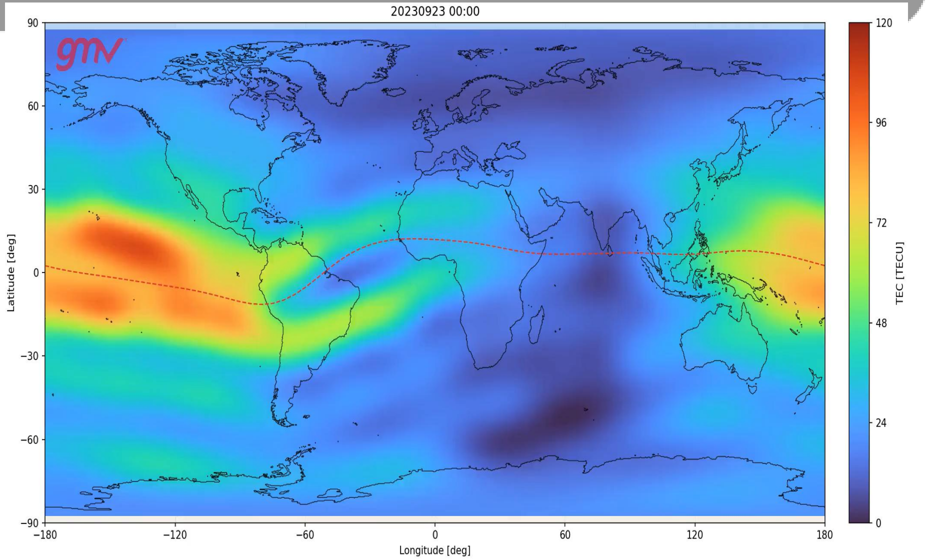
Space Weather and GNSS Navigation

From Solar Activity to System Design



Space Weather Days for Spain
ESAC, Villanueva de la Cañada, June 8-9, 2026

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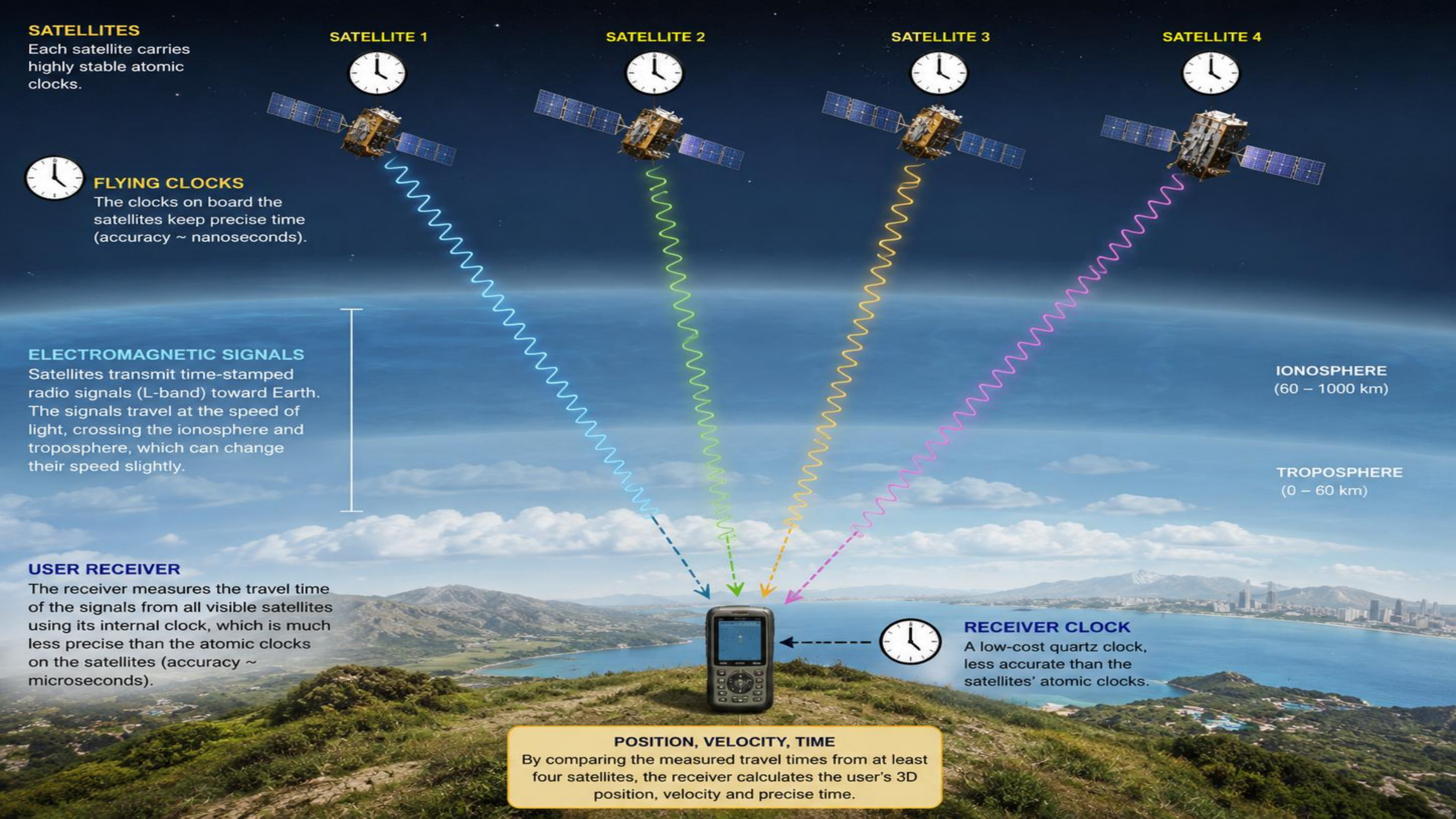
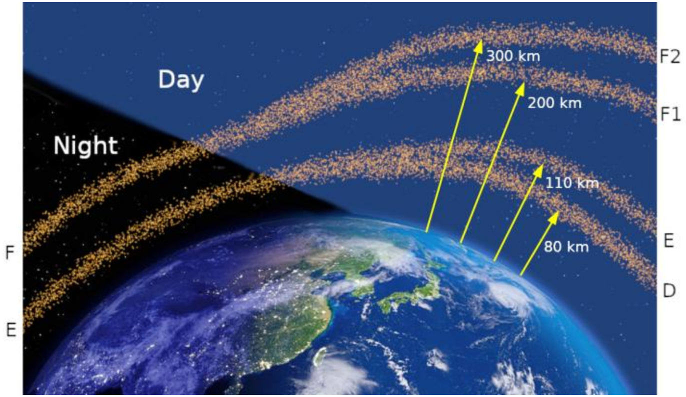
INNOVATING SOLUTIONS


SATELLITES
Each satellite carries highly stable atomic clocks.
SATELLITE 1
SATELLITE 2
SATELLITE 3
SATELLITE 4
FLYING CLOCKS
The clocks on board the satellites keep precise time (accuracy ~ nanoseconds).
ELECTROMAGNETIC SIGNALS
Satellites transmit time-stamped radio signals (L-band) toward Earth. The signals travel at the speed of light, crossing the ionosphere and troposphere, which can change their speed slightly.
IONOSPHERE
(60 – 1000 km)
TROPOSPHERE
(0 – 60 km)
USER RECEIVER
The receiver measures the travel time of the signals from all visible satellites using its internal clock, which is much less precise than the atomic clocks on the satellites (accuracy ~ microseconds).
RECEIVER CLOCK
A low-cost quartz clock, less accurate than the satellites' atomic clocks.
POSITION, VELOCITY, TIME
By comparing the measured travel times from at least four satellites, the receiver calculates the user's 3D position, velocity and precise time.

Ionosphere: a significant error source for single-frequency GNSS



Ionosphere: region of the Earth's upper atmosphere

- solar radiation ionizes gases creating free electrons
- from approx. 60 km to 1,000 km in altitude

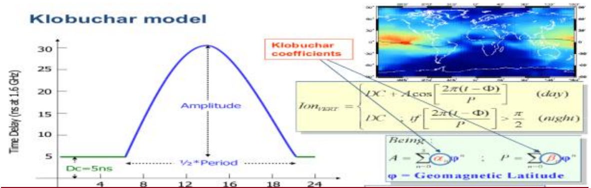
GNSS signals are affected by the ionosphere

- Code Delay $\propto$ STEC (electron content along the signal path)
- Code Delay $\propto 1/f^2$ (frequency-dependent)

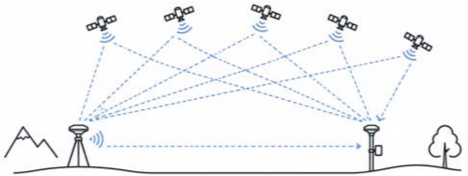
Typical values

- 1 TECU = 10^{16} electron/m^2 $\rightarrow$ ~0.16 m delay at GPS L1 (f=1575.42 MHz)
- Quiet mid-latitude day: ~1 – 10 m at L1
- Equatorial peak / storm: even over 50 m at L1
- Larger impact for slant paths: up to 3 times the vertical path delay

Coping with the ionosphere in GNSS (1)



$$P_{\mathrm{IF}} = \frac{f_1^2 P_1 - f_2^2 P_2}{f_1^2 - f_2^2}$$



Single-frequency Broadcast Models

GPS Klobuchar model
Galileo NeQuick-G

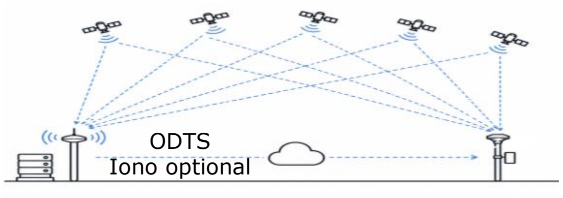
Dual-frequency Iono-free Combination

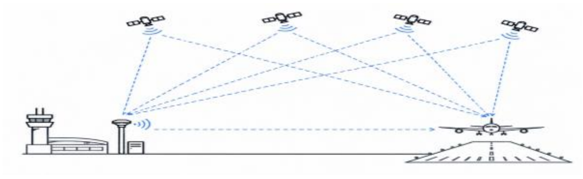
Removed first order or iono delay

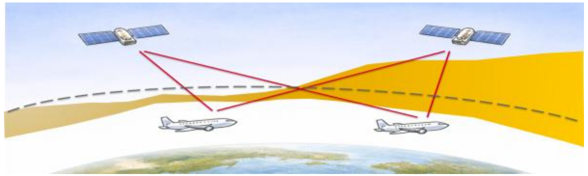
Differential GNSS and RTK

Reference station to correct the pseudoranges
Decorrelates ~ 100 km

Coping with the ionosphere in GNSS (2)







PPP
Precise Point Positioning

Works without iono corrections.
Iono corrections improve convergence time.

GBAS – Ground Based Augmentation Systems

As D-GNSS but for Civil Aviation at a single airport.
Limitations when and where the ionosphere is very active

SBAS – Satellite Based Augmentation Systems

Used for civil aviation in a region.
Iono corrections broadcast in a thin-shell model at fixed height every 5 minutes.

Ionospheric Variability Drivers

Solar Activity (F10.7)

11-year solar cycle modulates global TEC by ~3× - 5×.

Geomagnetic Latitude

Three distinct regimes:

- Equatorial (±20°): anomaly (EIA), plasma bubbles (EPB), strong TEC gradients.
- Mid-lat (20–60°): moderate, predictable.
- Polar/auroral (>60°): particle precipitation, polar cap patches.

Local Time (LT)

- Pre-dawn (~04:00 LT): minimum TEC.
- Afternoon peak (~14–16 LT): maximum TEC.
- Post-sunset equatorial: secondary EIA peak, plasma bubble (EPB) activity

Season

Higher TEC at equinoxes
Lower TEC at solstices

Longitude

Geomagnetic field geometry and thermospheric winds create longitudinal asymmetries

Space Weather Events

- Solar flares can rapidly increase ionization and TEC.
- Coronal Mass Ejections (CMEs) are the main drivers of severe geomagnetic storms.

Space Weather and Ionospheric Key Indices

F10.7 index

- Solar radio flux at 10.7 cm [sfu]
- Correlated with ionospheric activity

ROTI and TEC gradients

- ROTI (Rate of TEC Index) measures temporal variability of TEC.
- TEC gradient characterize spatial TEC variability.

Kp / ap indices

- Kp: global geomagnetic disturbance (3h)
- ap:daily linearized geomagnetic activity

Along Arch TEC Rate

$$AATR = \frac{1}{M(\varepsilon)^2}\frac{\Delta STEC}{\Delta t}$$

- Adopted as a key indicator of ionospheric disturbances affecting GNSS and SBAS.

NOAA G-scale

- Standardized geomagnetic storm scale.
- From G1 (Minor) to G5 (Extreme).

S_4 and σ_ϕ

- S_4 quantifies amplitude scintillation
- σ_ϕ quantifies phase scintillation

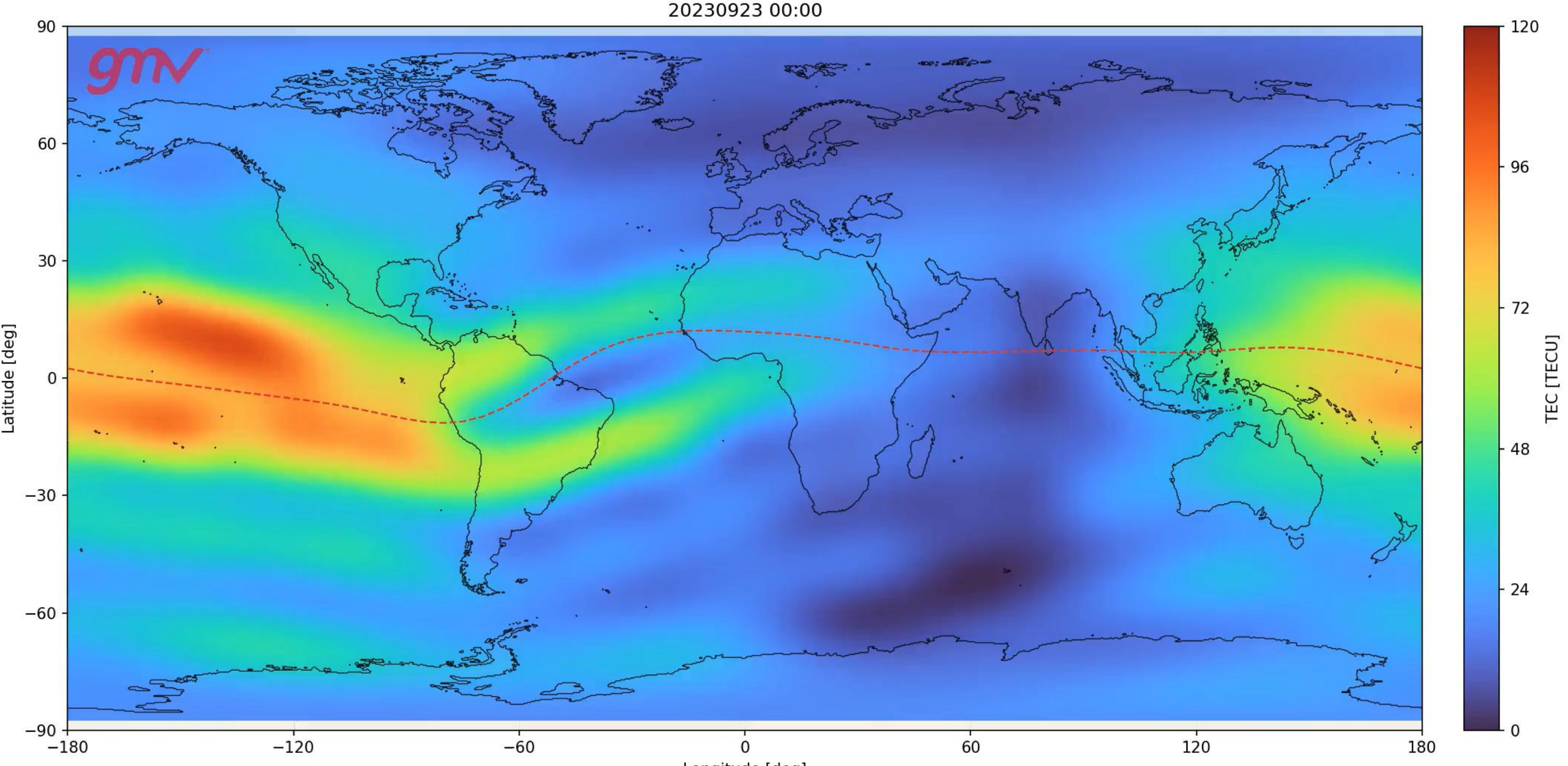
Satellite-Based Augmentation Systems: Flexible GNSS Vertical Guidance for Civil Aviation

SBAS offer vertical guidance: safety cylinders enclose the true aircraft position with extremely high probability. Key to reduce accidents.

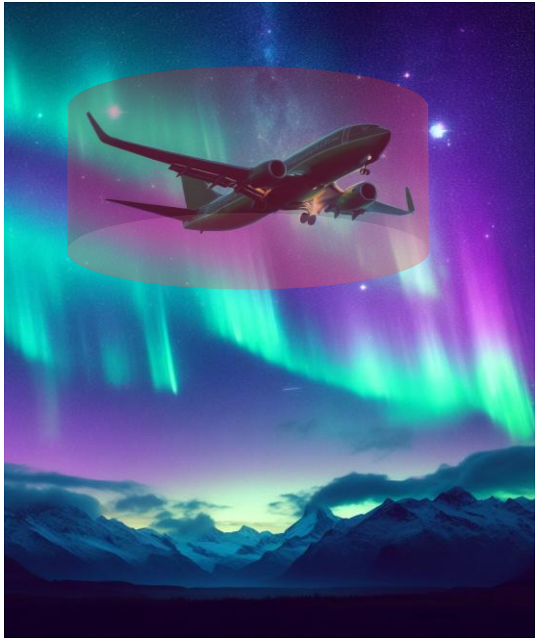
Current standard (L1-SBAS) is single-frequency, very sensitive to ionospheric corrections. Dual freq. std. (DFMC SBAS) will solve this in a few years.

Initially designed for mid-lat regions, there is high appetite to use it in in equatorial regions as well.

Example: Active ionosphere (Sep 23-24 2023)



Why eq. iono challenges SBAS



L1 SBAS assumes a **thin-shell** ionospheric model

- **fixed height and grid points**
- **bilinear interpolation**
- **broadcast every few hundreds of seconds**.

Visibility is limited by the location of the reference stations and the lines-of-view with the satellites

In equatorial regions:

- The **real ionosphere deviates significantly from the thin-layer** assumption
- **Gradients** can exceed model capabilities
- **Reduced correlation** between reference stations and users
- **Scintillations** reduce observability

Residual iono errors can become large and difficult to bound safely.

Impact on SBAS System and Users

L1-SBAS only

L1-SBAS and DFMC-SBAS

Threat	System Effect	User Impact	Overall Impact
Large spatial **gradients**, **temporal** variability, **density** profile variability	**Mismodelling**, required **bigger bounds** to cover uncertainty	**Position error** increases	**Accuracy Availability Continuity Integrity risk** if not properly bounded.
Depletions and local effects	Lack of **visibility**, required **denser network** of reference stations		
Ionospheric **storms**	Rapid model decorrelation, mismodelling, **storm detectors** increasing bounding		
Scintillations	Reference station signal tracking degradation and **loss**, reduced information for estimation	**Signal loss** (GNSS and/or GEO)	**Accuracy Availability Continuity.**

SBAS certification considerations

Certification Data Package requires:

- A validated ionospheric threat model
- Demonstration that mitigation barriers are effective
- Compliance with Hazardously Misleading Information (HMI) probability requirements

The certification authority must accept:

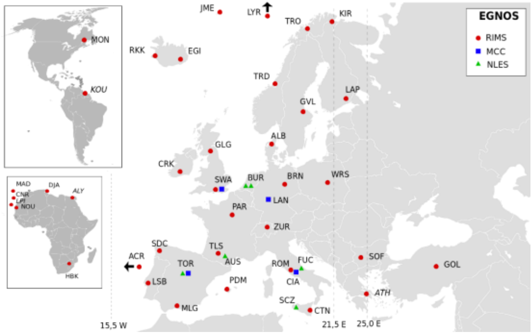
- The representativeness of the threat model
- The robustness of the system response under worst-case conditions

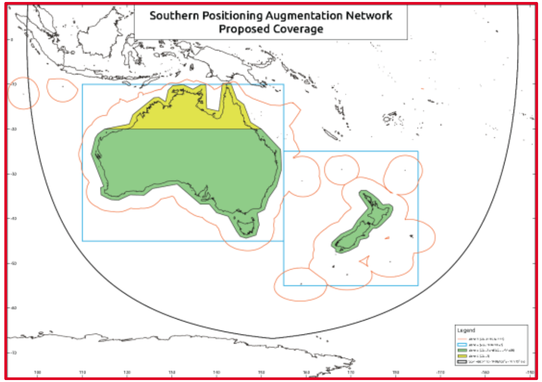
This process is a key driver in system design decisions!!!
Studies conducted without the explicit approval of the certification authority might not be accepted later during system formalization, wasting years of effort and putting the whole program at risk or increasing costs and generating delays!!!

GMV Solutions for Space Weather in Navigation

GMV products generate ionospheric corrections for different systems:

- Galileo, with navigation messages produced by GMV's Galileo Orbitography and Synchronisation Processing Facility (OSPF)
- EGNOS V2, the European SBAS system, with Central Processing Facility – Processing Set (CPFPS) producing the navigation messages
- SouthPAN, the Australian SBAS system, through the Correction Processing Facility
- magicGNSS, high-accuracy reliable PPP with ionospheric corrections





Key messages

- In satellite navigation, the main impact of Space Weather is through the ionosphere
- The ionosphere is a key error source for single-frequency GNSS, PPP convergence and Satellite Based Augmentation Systems (SBAS)
  - The equatorial region is particularly challenging
- The main Space Weather drivers affecting GNSS performance are:
  - Solar cycle
  - Solar flares
  - Coronal Mass Ejections (CMEs)
- For L1-SBAS systems, understanding and characterizing the ionosphere over the service area is both a performance driver and a certification requirement
- GMV contributes to operational GNSS resilience through ionospheric correction generation for systems including Galileo, EGNOS and SouthPAN

Thank you

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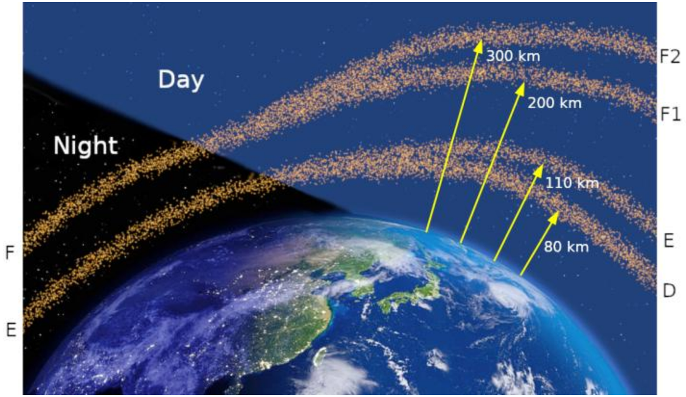
Backup Slides

Ionosphere: a significant error source for single-frequency GNSS



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GNSS signals are affected by the ionosphere

- Code Delay ∝ STEC (electron content along the signal path)
- Code Delay ∝ $1/f^2$ (frequency-dependent)

Ionospheric code delay (first order)

$$I = \frac{40.3 \times 10^{16} \times STEC}{f^2}$$

I: ionospheric code delay [meters]
STEC: Slant Total Electron Content in the signal path [TECU]
f: signal carrier frequency [Hz]

Typical values

- 1 TECU = 10^{16} electron/m^2 → ~0.16 m delay at GPS L1 (f=1575.42 MHz)
- Quiet mid-latitude day: ~1 – 10 m at L1
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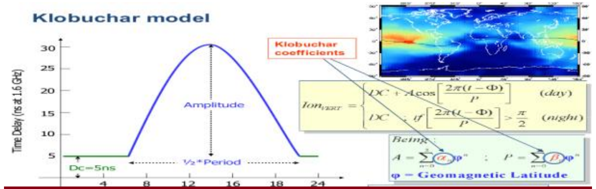
Coping with the ionosphere in GNSS (1)



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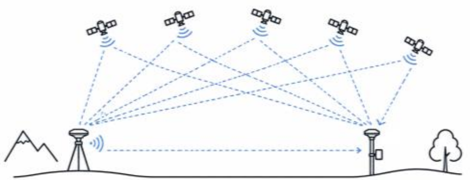


Single-frequency Broadcast Models

GPS Klobuchar model

- 8 parameters
- daily update
- corrects ~ 50% iono error

Galileo NeQuick-G

- 3 parameters
- daily update
- corrects ~ 60-70% error

Models fail under severe Space Weather

Dual-frequency Iono-free Combination

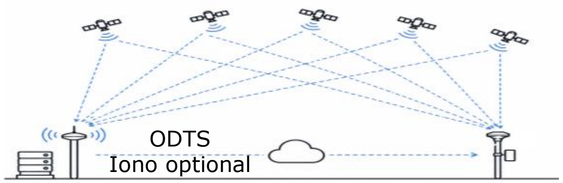
- Removed first order or iono delay
- ~3x noise amplification
- Standard for professional equipment and solutions

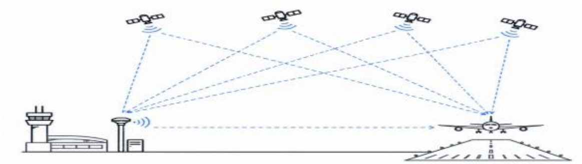
Differential GNSS and RTK

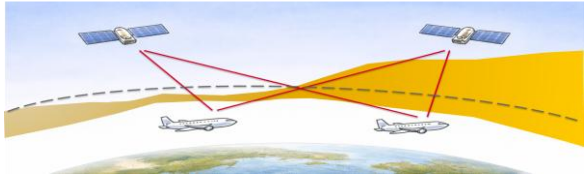
A reference station is used to correct the pseudoranges of the user measurements:

- It corrects most of the ionospheric error.
- Decorrelates in the range of 100 km
- It requires permanent data link

Coping with the ionosphere in GNSS (2)







PPP
Precise Point Positioning

Standard PPP:
- Precise sat. clocks and orbits transmitted in real time.
- Based on dual frequency.
- Lack of iono information extends the convergence period.

PPP with iono corrections:
- Very short convergence time (seconds)
- Required a dense network of stations.
- High bandwidth to transmit iono corrections

GBAS – Ground Based Augmentation Systems

GBAS is a Differential GNSS for civil aviation:
- Integrity is a must
- Serving a single airport
- Limitations when and where the ionosphere is very active

SBAS – Satellite Based Augmentation Systems

SBAS used for civil aviation:
- Integrity is a must
- Current std: L1 SBAS GPS L1
- Next std: DFMC SBAS GPS L1/L5 + Gal E1/E5a

L1 SBAS iono (current std)
- Thin-shell model, fixed height
- Updated every 5 min
- Key: overbound error
- Dense network of stations

DFMC SBAS iono (from 2030?)
- Dual-freq iono-free comb. used

Ionospheric Variability Drivers

Solar Activity (F10.7)

TEC strongly correlates with solar activity:

- F10.7 proxy of iono activity
  - Low (~70 sfu): quiet iono
  - High (~150 sfu): active iono
- 11-year solar cycle modulates global TEC by ~3× - 5×.

Geomagnetic Latitude

Three distinct regimes:

- Equatorial (±20°): anomaly (EIA), plasma bubbles (EPB), strong TEC gradients.
- Mid-lat (20–60°): moderate, predictable.
- Polar/auroral (>60°): particle precipitation, polar cap patches.

Local Time (LT)

Strong diurnal cycle from solar ionization:

- Pre-dawn (~04:00 LT): minimum TEC.
- Afternoon peak (~14–16 LT): maximum TEC.
- Post-sunset equatorial: secondary EIA peak, plasma bubble (EPB) activity

Season

High dependency in year seasons:

- Equinoxes (Mar/Apr, Sep/Oct):
  - Higher TEC and variability
- Solstices (Jun/Jul, Dec/Jan):
  - Lower TEC and variability

Longitude

Iono behavior depends on longitude:

- Geomagnetic field geometry and thermospheric winds create longitudinal asymmetries
- Critical for SBAS network and coverage design.

Space Weather Events

Space weather events can significantly perturb the ionosphere:

- Solar flares can rapidly increase ionization and TEC.
- Coronal Mass Ejections (CMEs) are the main drivers of severe geomagnetic storms.