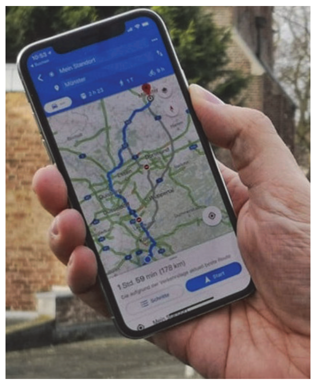
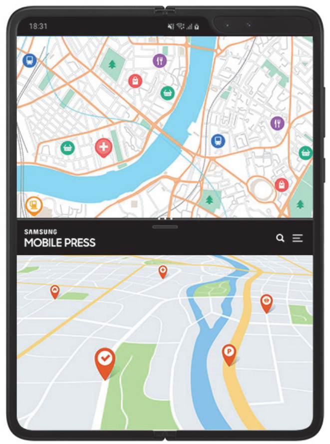
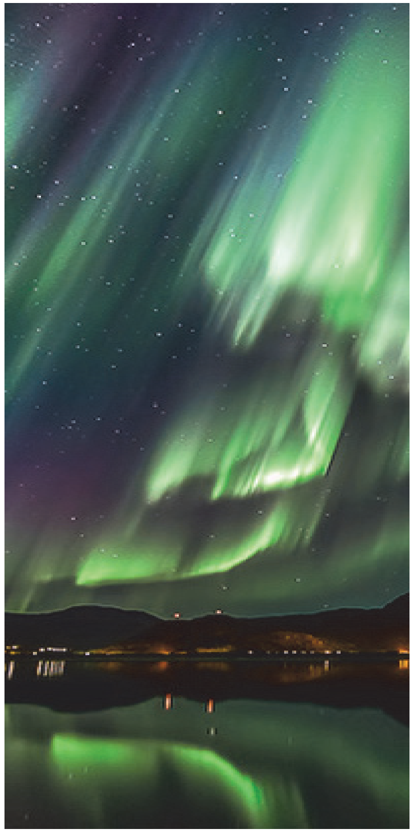
Ionospheric Correction for Galileo Single-frequency Receivers

Bertram Arbesser-Rastburg





Contents



- The Ionosphere and ist effect on satelitte navigation signals
- Ionospheric correction in the GPS system (Klobuchar)
- Ionospheric correction in WAAS & EGNOS
- The NeQuick Ionospheric Model
- The global Galileo ionospheric correction

Single Frequency GNSS* Receivers

Application	Augmentation
Hiking	-
Sailing	-
Drone Navigation	-
Cars, Truck, Motorbikes	Map matching
Aircraft	SBAS, GBAS
Inland waterway transport	SBAS

etc .....

*) *Global Navigation Satellite System*

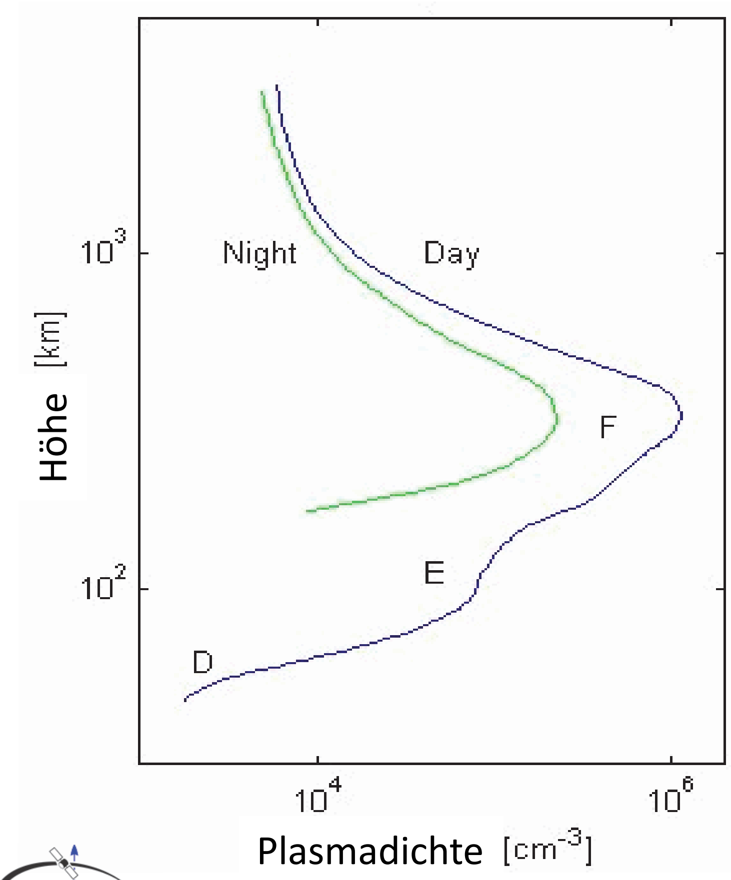
Own Experience...

Positioning of boundary piles in the forest

Mountain hiking in fog or darkness...

Sailing in poor visibility....

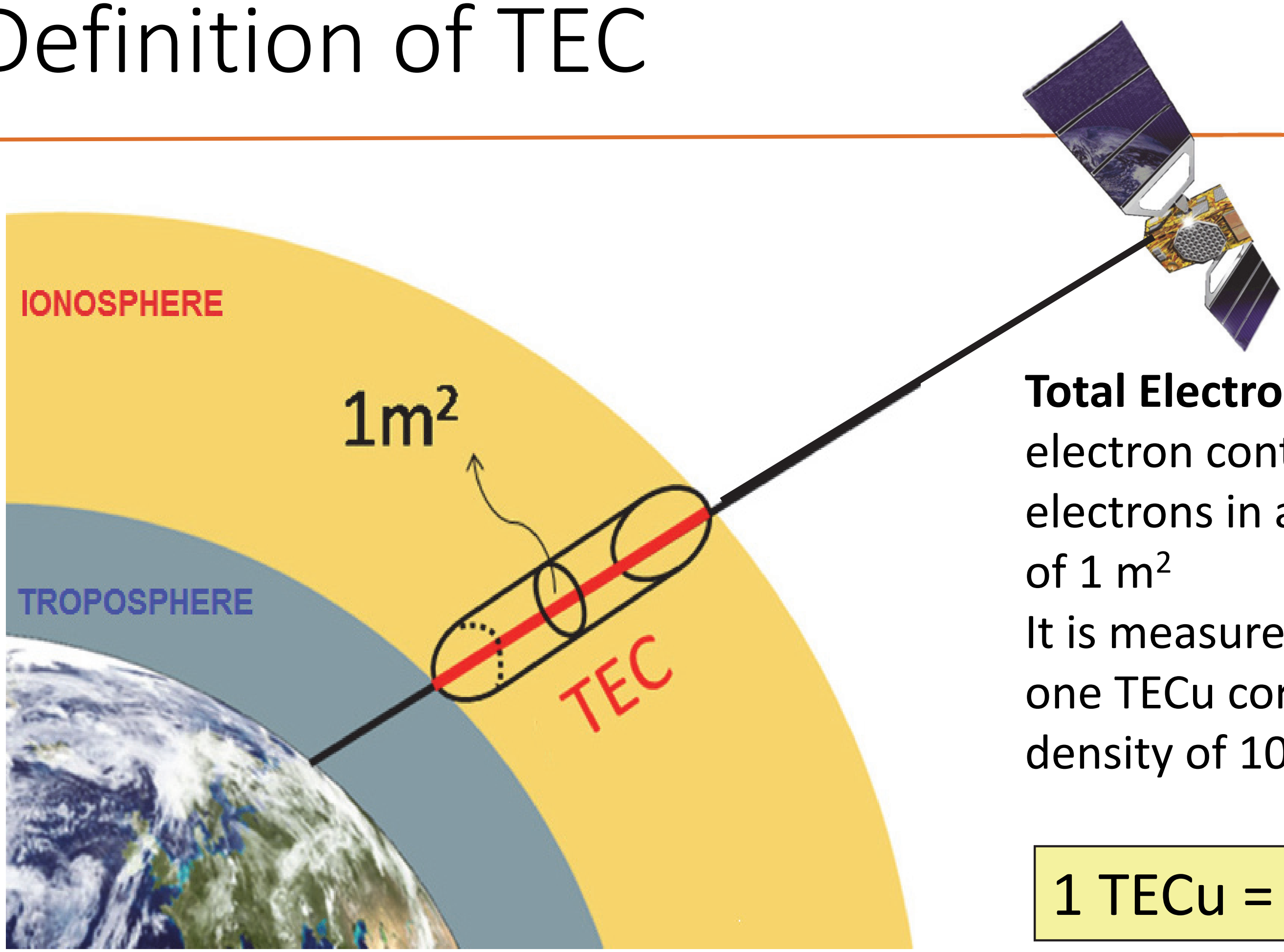
Profile of the ionosphere



The ionosphere is the area of the atmosphere from 50 – 2000 km altitude. It has two main layers:
The lower layer "E layer" is between 80 and 110 km above the earth's surface – it reflects low-frequency radio waves. The upper layer "F layer" reflects higher-frequency radio waves.

In 1902, Guglielmo Marconi succeeded in transmitting a transatlantic radio signal. Oliver Heaviside and Arthur E. Kennelly found the explanation for this phenomenon (EM waves are reflected). In 1947, Sir Edward Appleton was awarded the Nobel Prize in Physics for his contribution to the understanding of the ionosphere.

Definition of TEC



Total Electron Content (TEC = Total electron content) is the total number of electrons in a column with a cross-section of 1 m^2

It is measured in TECu (TEC Units)

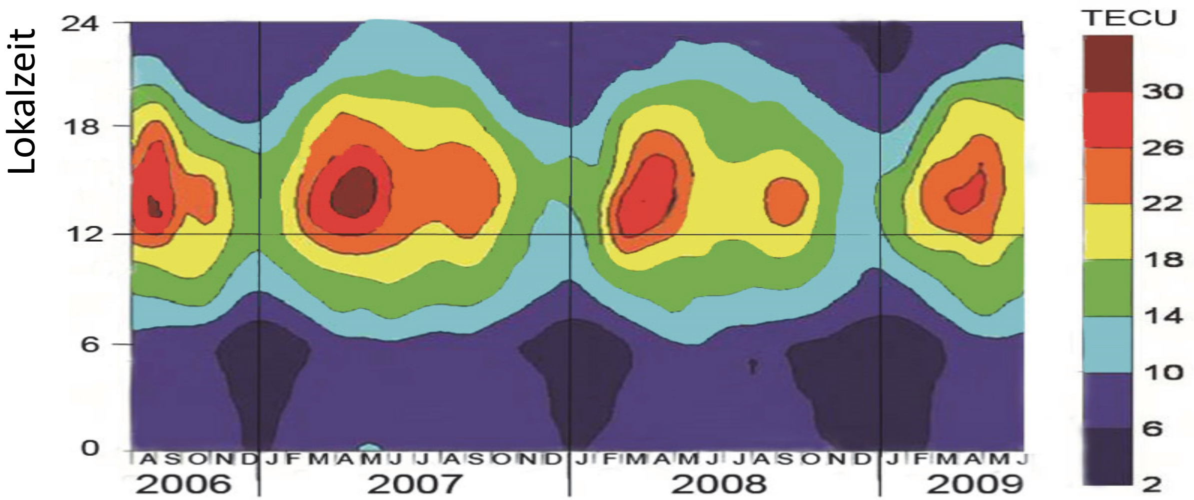
one TECu corresponds to an electron density of 10^{16} electrons/m^2

$$1 \text{ TECu} = 10^{16} \text{ el} / m^2$$

Source: Charles S. Carrano, Boston College

24-hour and seasonal variation of TEC

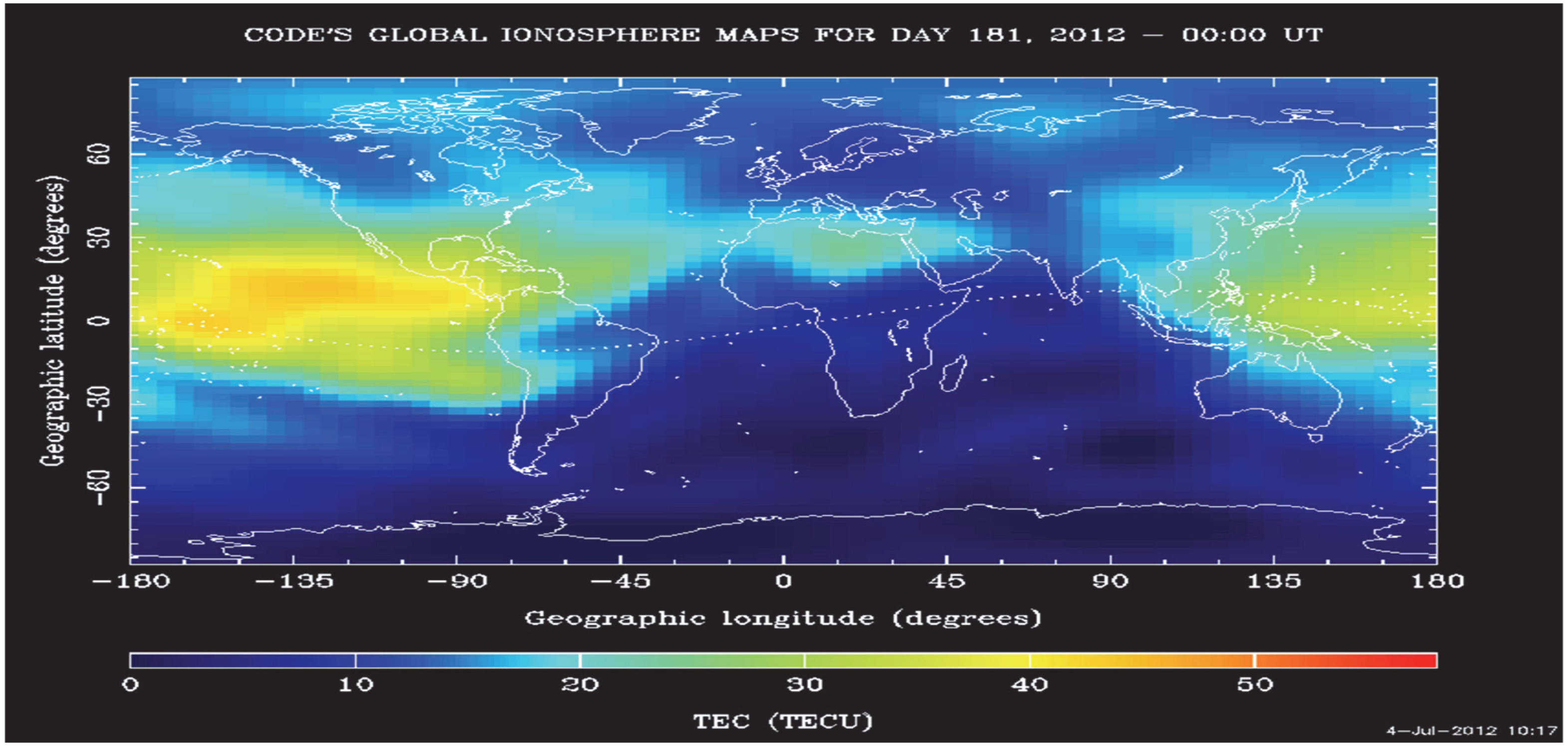
- **Ultraviolet (UV) radiation and X-rays from the sun create an ionized gas (plasma) in the upper atmosphere.**
- **The ion concentration depends on the irradiation and is therefore dependent on both the time of day and the season.**
- **The concentration is expressed in "Total Electron Content Units" (TECu).**



vTEC (Vertical TEC)
in Agra, India (27.12N, 78.89E)
measured over 3 years
You can see both the time of day and the seasonal variations.
The highest TEC values were observed at spring equinox between 1 and 3 p.m. local time.

Quelle: V. Chauhan et al. IJRSP Vol 40, 2011

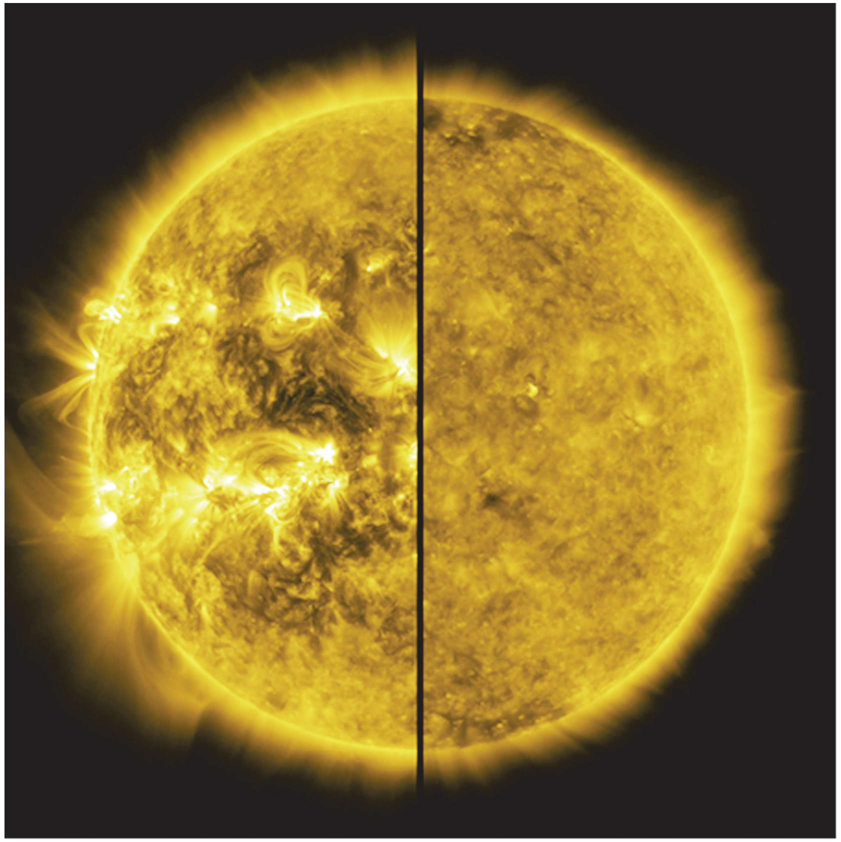
24-hour variation of TEC



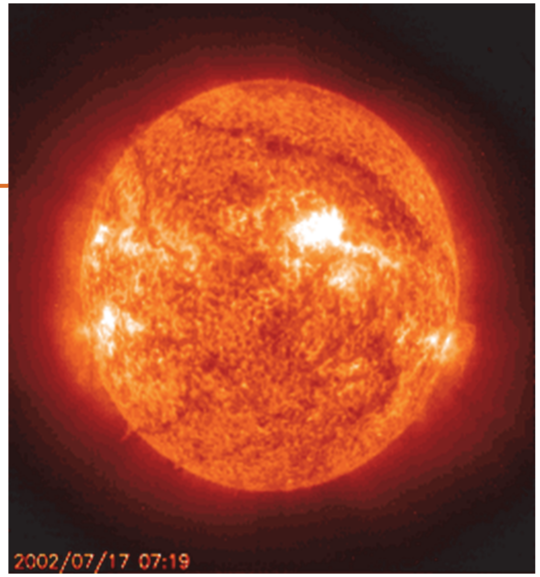
Source: CODE Analysis Center, University of Berne, Switzerland

TEC follows the sun; the maximum typically occurs at 2 p.m. local time in the range of +/- 10 degrees north and south of the geomagnetic equator.

Sunspots



Source: NASA Solar Dynamics Laboratory



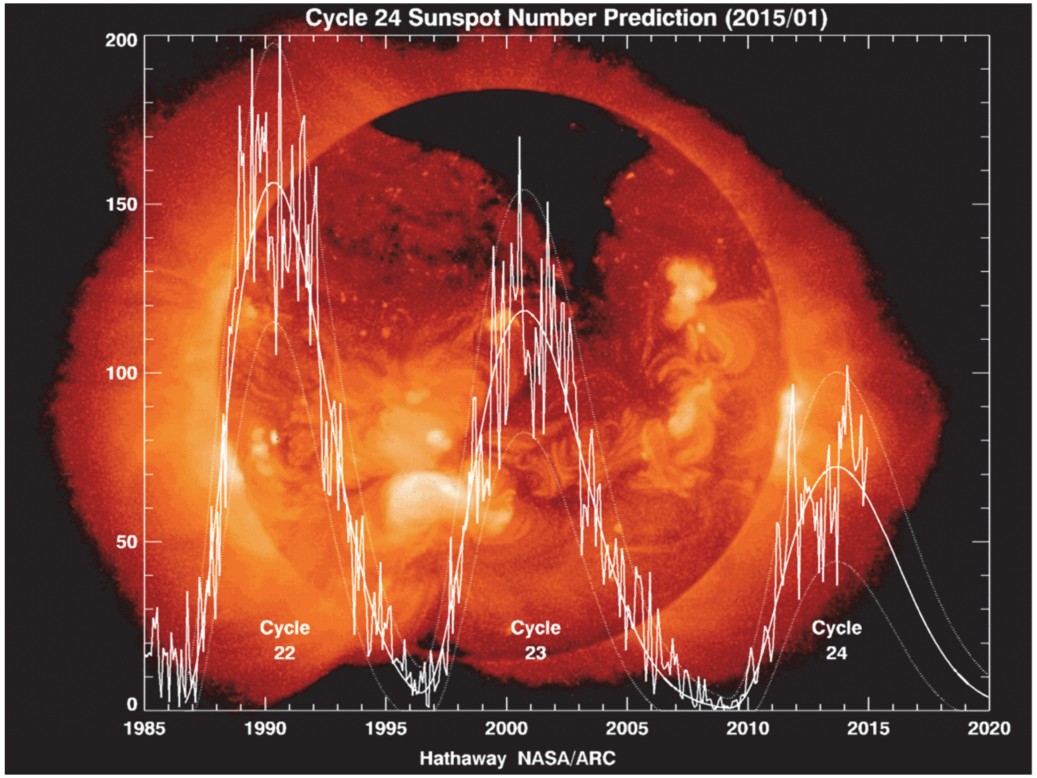
Sunspots:

- Left half of the image: April 2014 (near maximum)
- Right half of the image: December 2020 (minimum)

The more sunspots, the more radiation, the more ionization.

The sunspots are subject to a cycle of about **11 years.**

Cyclic variation of sunspots

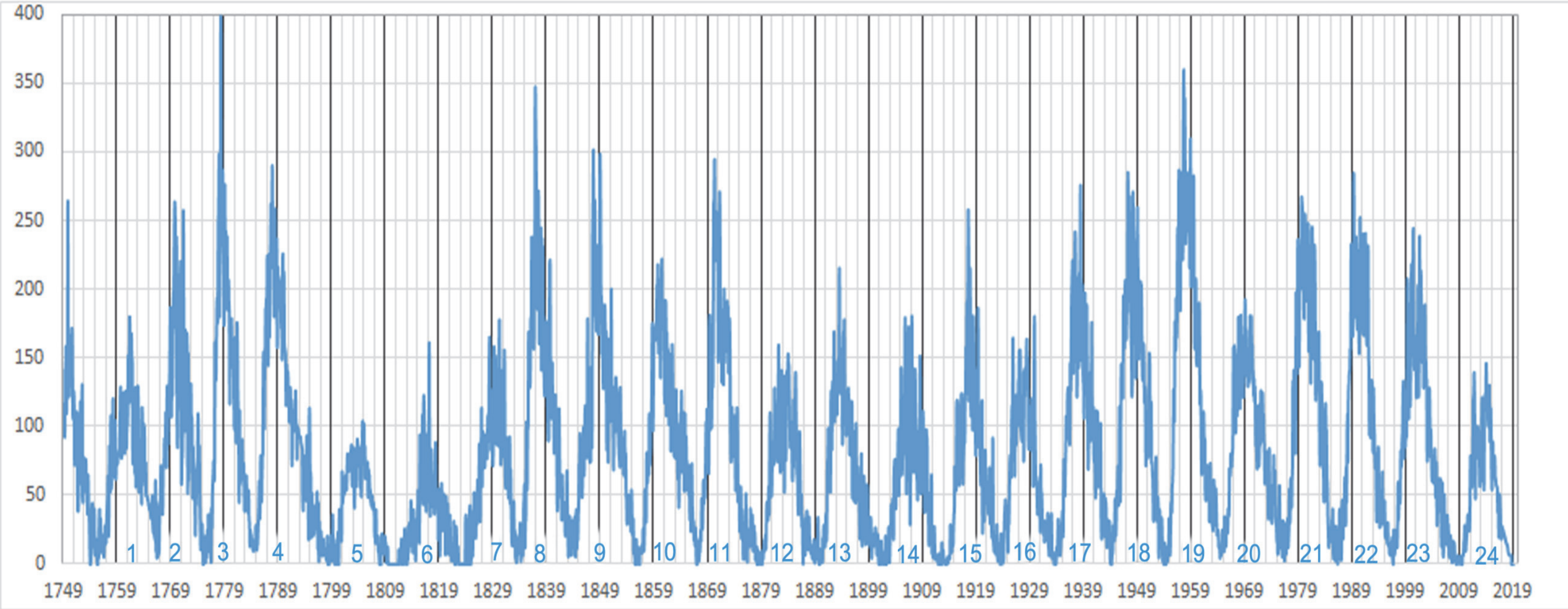


Source: NASA/ARC

With a period of about 11 years, the number of sunspots reaches a maximum and then disappears again.
One theory is that the Sun's magnetic field is affected by the gravitational forces of Venus, Earth, and Jupiter, resulting in this cyclic behaviour.

(Source: Helmholtz-Zentrum Dresden-Rossendorf doi: 10.1007/s11207-019-1447-1)

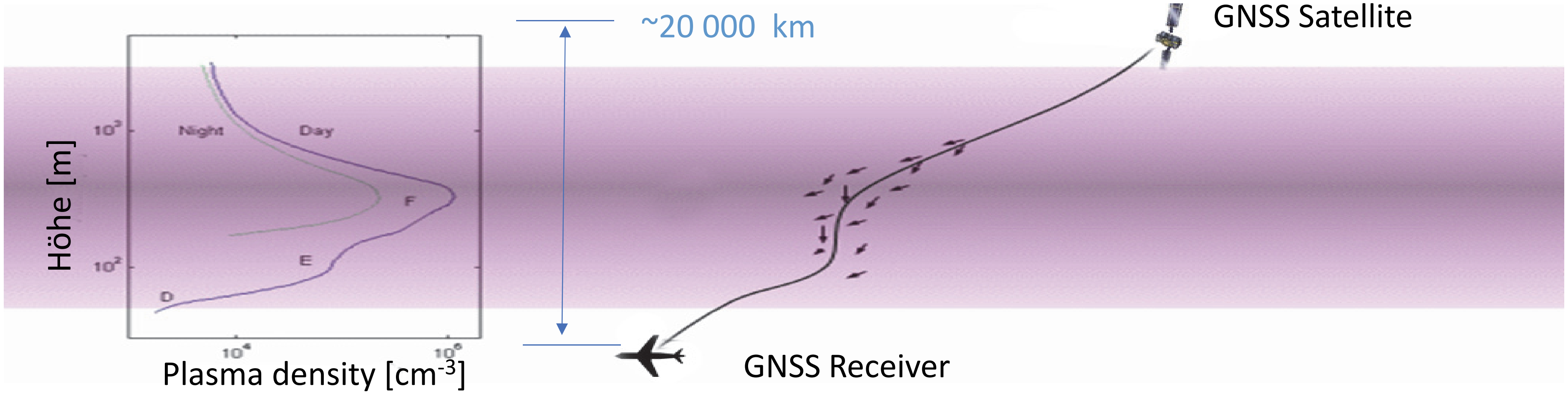
The 11-year sunspot cycle



Monthly sunspot averages 1749 -2019

Source: WDC-SILSO, Royal Observatory of Belgium, Brussels

Ionospheric effects for GNSS



- Refractive index → <u>Group runtime</u>, (diffraction)
- Irregularities & Turbulence → <u>Scintillations</u>
- Magnetic field and electron density → (Faraday rotation)

(Effects in parentheses can be ignored for GNSS systems)

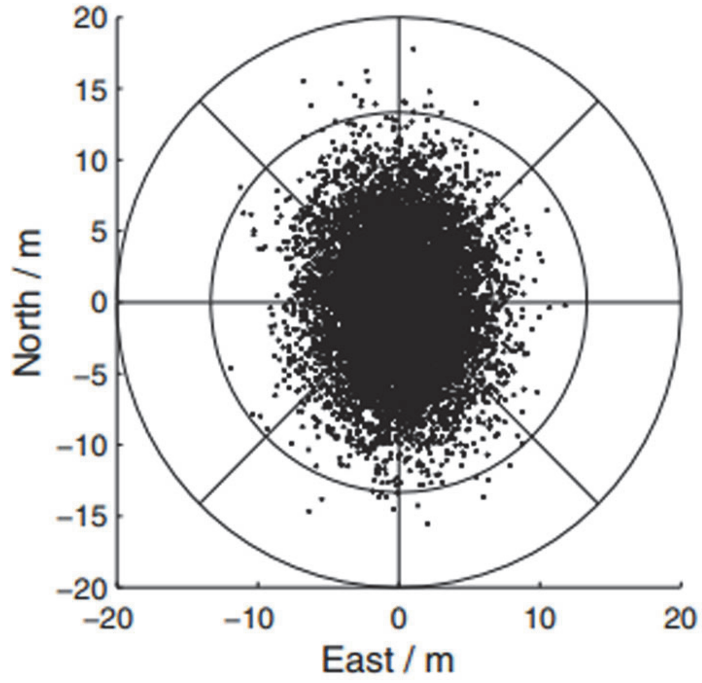
What does that mean?

The ionospheric change of length (pseudorange error) is

$$\Delta r = \frac{40.3\ x\ TEC}{f^2}\ [\text{m}]$$

The L1/E1 frequency is 1575.42 MHz, this results in a delay of 0.163 m at 1 TECu

With an sTEC of the 100 TECu the 16.3 m In addition, there are other errors

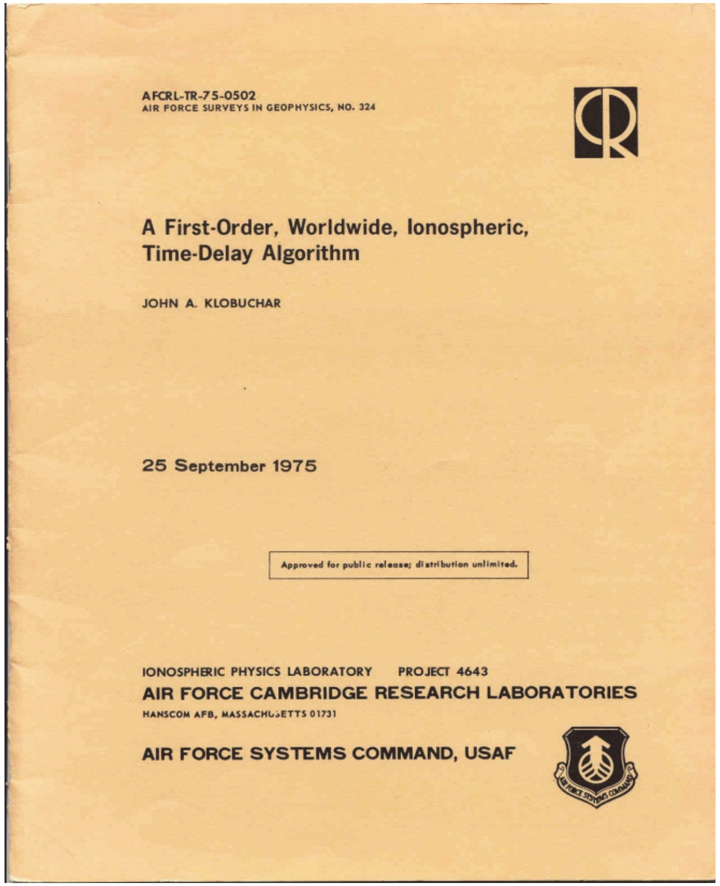


Position error with a pseudorange error of 5.3 m

Source: J. Fan, GPS Solutions, Oct 2014

Ionosphere correction in GPS (1)

Jack Klobuchar developed an ionospheric correction algorithm (ICA) for GPS in 1975. It represents the TEC distribution per day as a cosine function, where amplitude and period are presented with 8 coefficients in the Navigation message. The maximum is at 2 p.m. local time above the geomagnetic equator.
The ionospheric model corresponds to the Bent model.
The coefficients are renewed every 10 days in calm ionosphere. In the case of special ionospheric events, the update takes place at shorter intervals.


AFCRL-TR-75-0502
AIR FORCE SURVEYS IN GEOPHYSICS, NO. 324

A First-Order, Worldwide, Ionospheric, Time-Delay Algorithm

JOHN A. KLOBUCHAR

25 September 1975

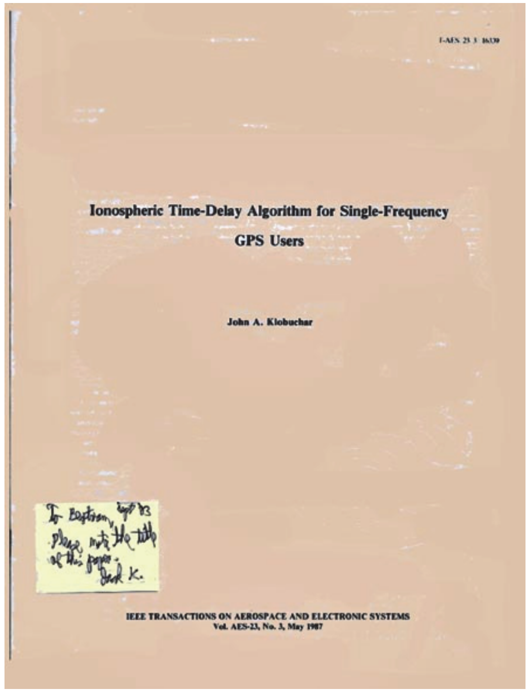
Approved for public release; distribution unlimited.

IONOSPHERIC PHYSICS LABORATORY PROJECT 4643
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
HANSCOM AFB, MASSACHUSETTS 01731

AIR FORCE SYSTEMS COMMAND, USAF

Ionosphere Correction in GPS (2)

The navigation message contains 8 coefficients, which are used in the receiver with the help of the ICA model to calculate the ionospheric delay.


Ionospheric Time-Delay Algorithm for Single-Frequency GPS Users

John A. Klobuchar

IEEE TRANSACTIONS ON AEROSPACE AND ELECTRONIC SYSTEMS Vol. AES-23, No. 3, May 1987

<u>Running time during the day:</u>

$$\Delta t_v = DC + A \cos [2\pi(t-\phi) / P]$$

where

$$A = \sum_{n=0}^{3} \alpha_n \varphi^n \qquad P = \sum_{n=0}^{3} \beta_n \varphi^n$$

where

$\alpha_{0-3}, \beta_{0-3}$: 8 coefficients

DC : 5 ns

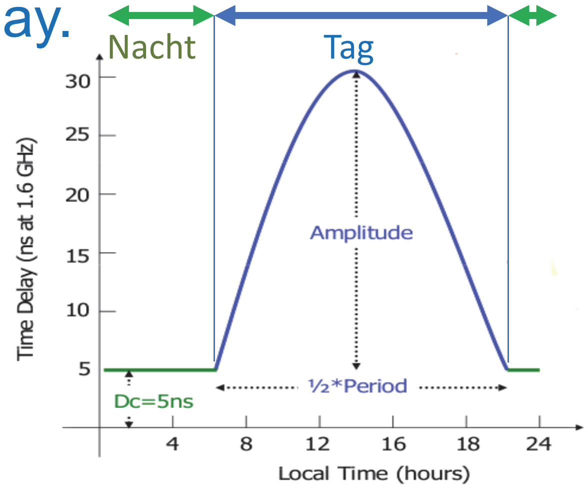
φ : geomagnetic latitude

ϕ : 14 [h] (Time of the maximum)

t : Local time [h]

<u>Running time during the night:</u>

$$\Delta t_v = DC$$



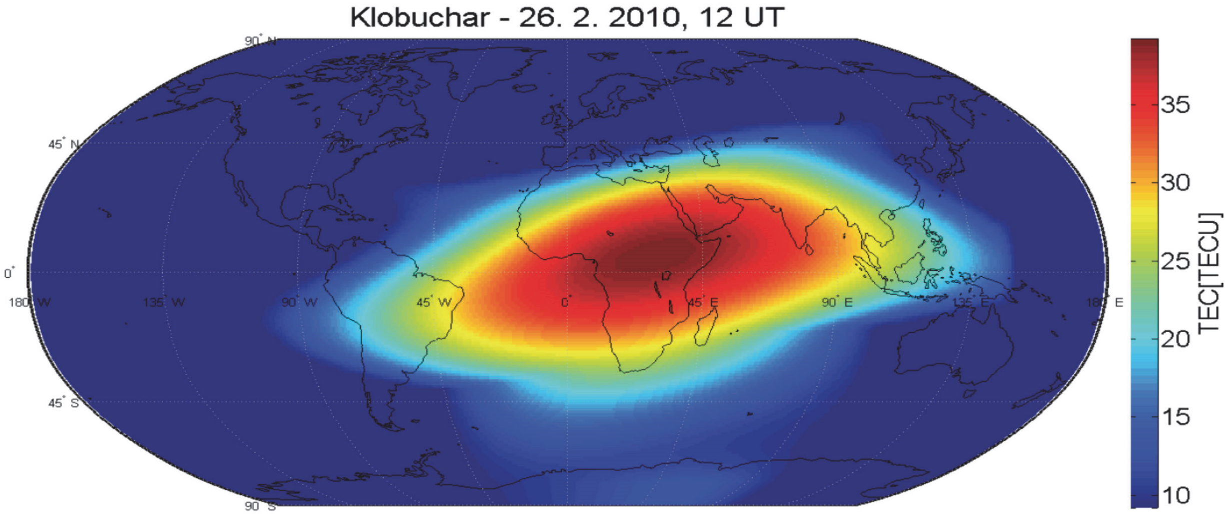
Mapping function vertical to oblique:

$$\Delta t_{sl} = \Delta t_v \, [1+16(0.53- \varepsilon / \pi)]^3$$

where ε : elevation angle

Ionosphere Correction in GPS (3)

Klobuchar model for the 26.02.2010 12:00 UT

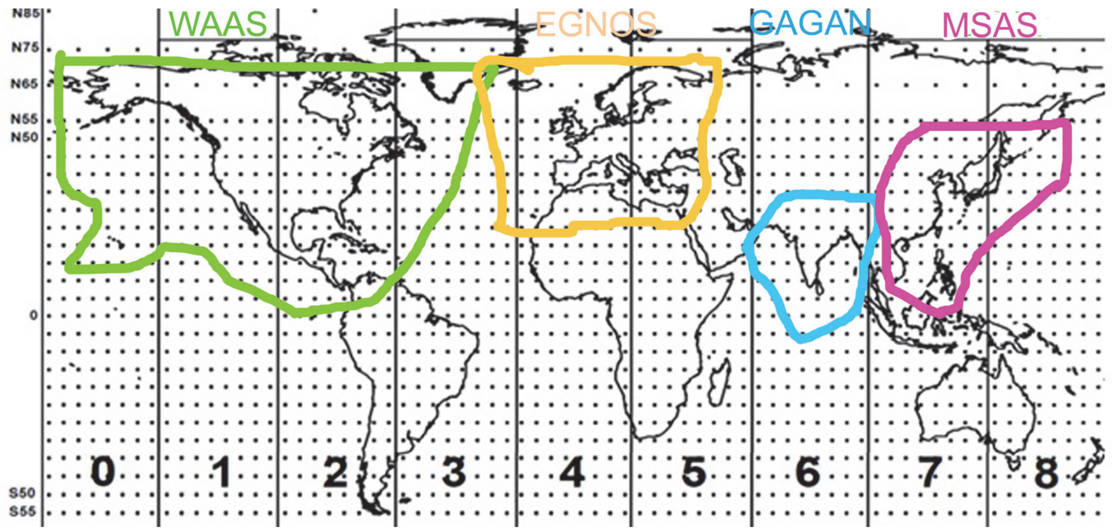


The model works very well at mid-latitudes, but does not represent the "equatorial anomaly". The correction requires little computing time in the receiver. The US Airforce* was initially not very interested in the correction, as all main users used (olive green) two-frequency receivers, where no ionospheric correction is necessary. [*Since 20.12.2019 GPS belongs to the US Space Force...]

Ionospheric correction in SBAS

SBAS: **S**pace **B**ased **A**ugmentation **S**ystem (WAAS, EGNOS, MSAS. GAGAN…).

- Improves accuracy and availability
- Gives the user information about the trustworthiness (integrity) of the displayed position
-



Global ionospheric 5 x 5 degree mesh

Reference stations (WRS, RIMS) measure the current status of the ionosphere with 2-frequency receivers. In the SBAS navigation message, the delay is transmitted through the ionosphere as a 5 x 5 degree grid at the altitude of 350 km. The **GIVD** (Grid-point Ionospheric Vertical Delay) and the **GIVE** (Grid-point Ionospheric Vertical Error) are transmitted.

The Nequick Ionospheric Model

Nequick was developed by
Sandro Radicella (ICTP Trieste) and **Reinhart Leitinger** (U Graz).

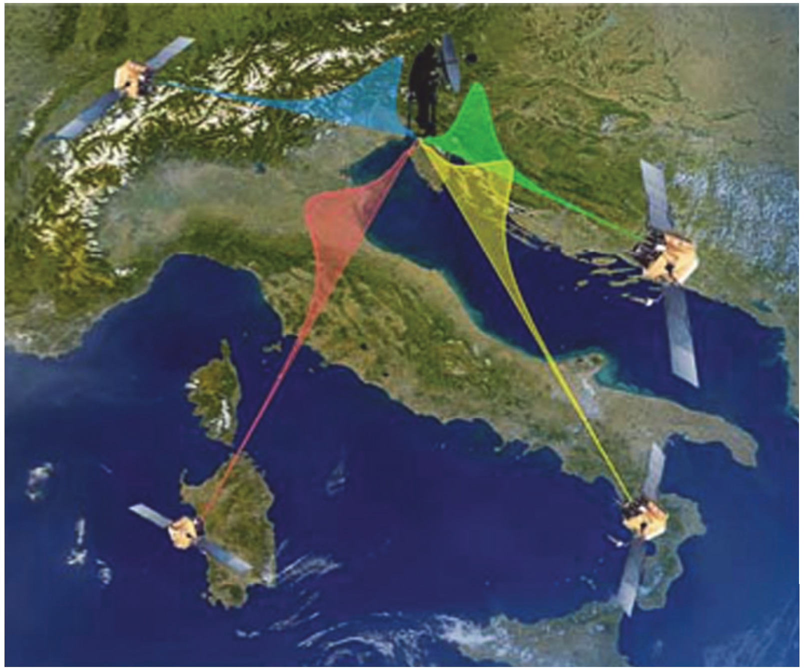
As part of a collaboration between ICTP Trieste and the University of Graz under COST Action 251, 3 different ionospheric models based on the DGR (Di Giovanni & Radicella) Profiler were developed:

- NeQuick – quick model specific to trans-ionospheric applications
- COSTprof - a complex model of the ionosphere & plasmasphere
- NeUoG-plas – a model for satellite-to-satellite geometry.

The NeQuick Model - Output

The model delivers:

- Electron density as a function of altitude, place and time (LT or UT)
- Electron density along a path from any location on the Earth's surface to any satellite position (integrated is the "slant TEC")



Electron profile along 4 receiving vectors for a recipient in Trieste

NeQuick Ionospheric Profile and Coefficients

Profile:

Bottomside: from 100 km to F2 peak, the ion density is represented by 5 semi-Epstein layers (see DGR profile)

Topside: Above the F2 peak there is a semi-Epstein layer

Coefficients:

ITU-R (formerly CCIR) coefficients are used (described in ITU-R Rec. P. 1239):

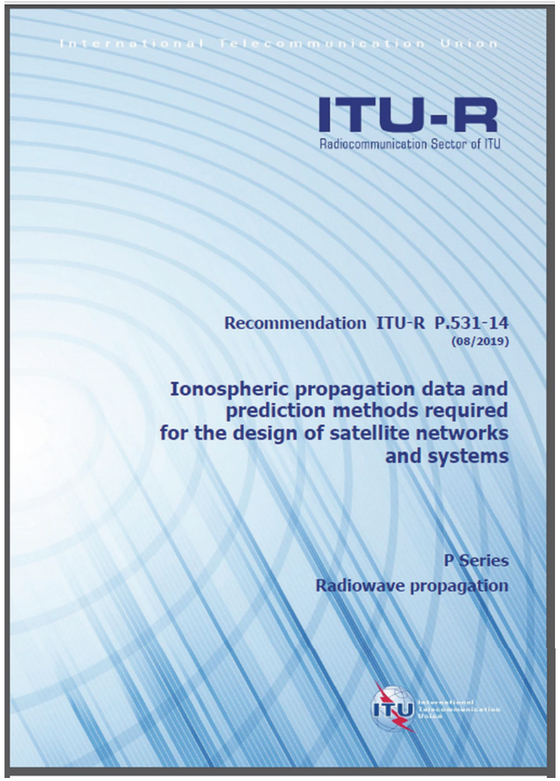
foE, foF2, M(3000)F2 and R12 and monthly average of F10.7

Or measured values of R12 and F10.7.

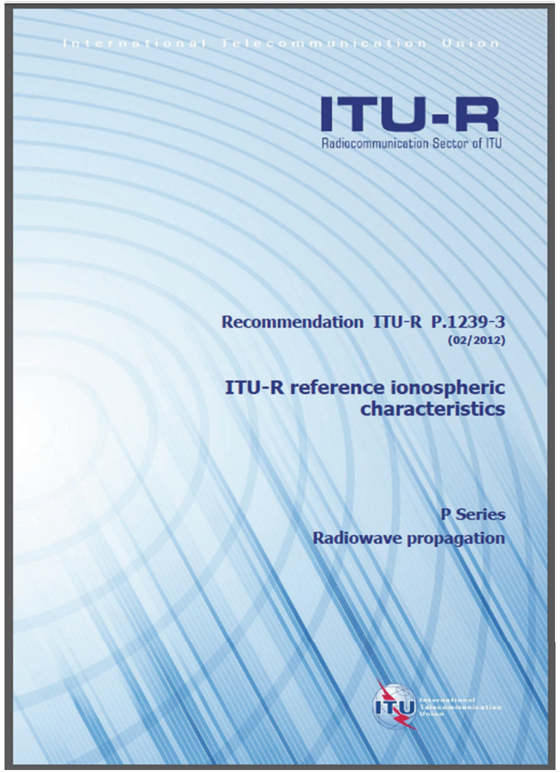
Furthermore required: Geographical coordinates (are converted into geomagnetic coordinates "MODIP").

For the NeQuick-G version (Galileo), instead of R12 and F10.7, an "effective ionization value" Az determined by the sensor stations is used.

ITU-R Explanatory Documents



ITU-R P.531



ITU-R P.1239

ITU-Tower Geneva

Origin of the Galileo correction model

In 1999, after an intensive discussion of EGNOS Integrity during ionospheric storms, Sandro Radicella and Reinhart Leitinger were at dinner in the restaurant "Les Caves de la Maréchal" in the center of Toulouse. As an appetizer, there was Coquille Saint-Jacques – the discussion revolved around a single-frequency correction for Galileo that should work well around the world.
The constraint was: as little bandwidth as possible.

At dessert it was clear: The recipients must have built in an ionospheric model and be able to reproduce the current ionosphere with only 3 coefficients from the navigation message and thus calculate the correction of the ionospheric group delay. The obvious model was **NeQuick.**

The global Galileo ionospheric correction

The receiver with NeQuick G needs 3 coefficients (a0, a1, a2)

The ionosphere is measured in global Galileo Sensor Stations [GSS] for 24 hours.

The optimal effective ionization parameter for NeQuick is calculated in the Galileo Control Center [GCC]

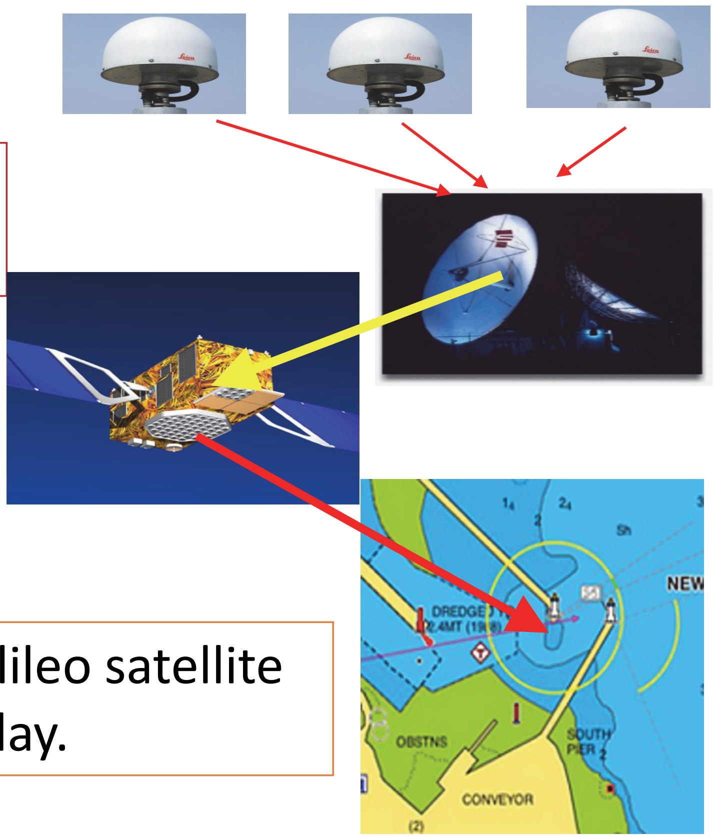
The **effective ionization parameter Az** is sent in the Galileo navigation message [ULS]

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

$a_{0\text{-}2}$: broadcast coeffizients

μ: geomagnetic latitude

The receiver calculates the TEC value for each observed Galileo satellite with the NeQuick G model and corrects the ionospheric delay.



NeQuick G – The effective ionization parameter Az

Az { a_{i0}, a_{i1}, a_{i2} }

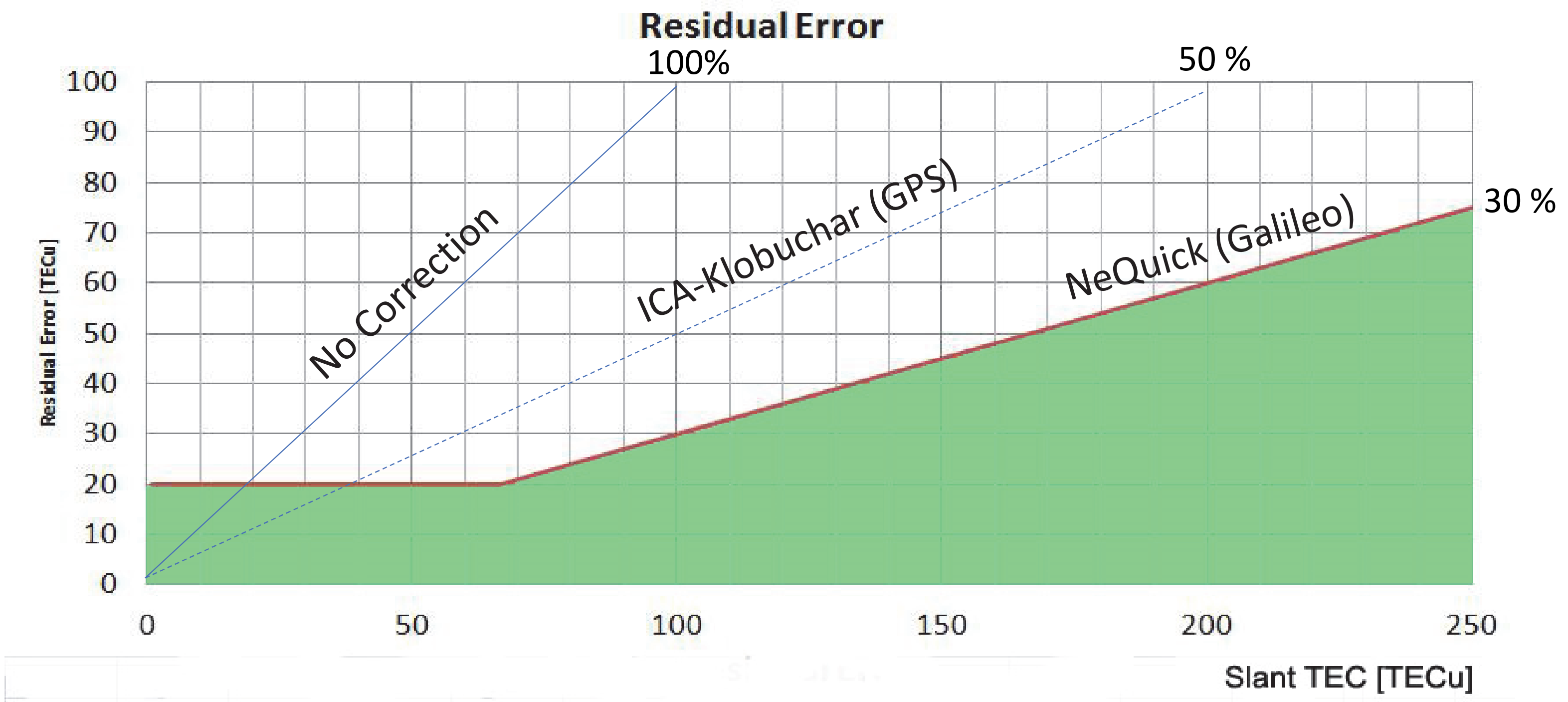
Parameter	Description	Parameter	Description
a_{i0}	Ionisation 1st order	φ_2	Longitude sat
a_{i1}	Ionisation 2nd order	λ_2	Latitude sat
a_{i2}	Ionisation 3rd order	h_2	Height sat
φ_1	Longitude Rx	UT	Time UTC
λ_1	Latitude Rx	mth	Month (1-12)
h_1	Height Rx		

$$Az = a_0 + a_1\mu + a_2\mu^2$$

Equivalent to F10.7 R_{12} In NeQuick2

https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo_Ionospheric_Model.pdf

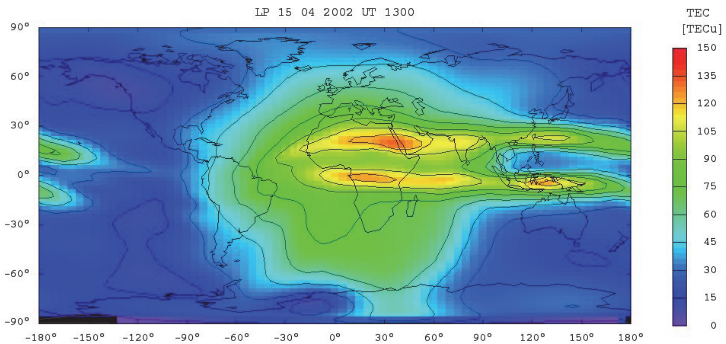
Specification of single-frequency corrections



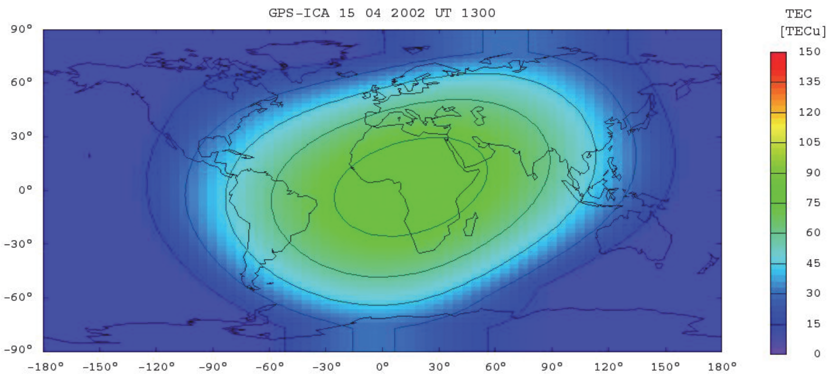
ICA(Klobuchar): $|sTEC_{act} – sTEC_{mod}|$ should be less than **50%** of $sTEC_{act}$

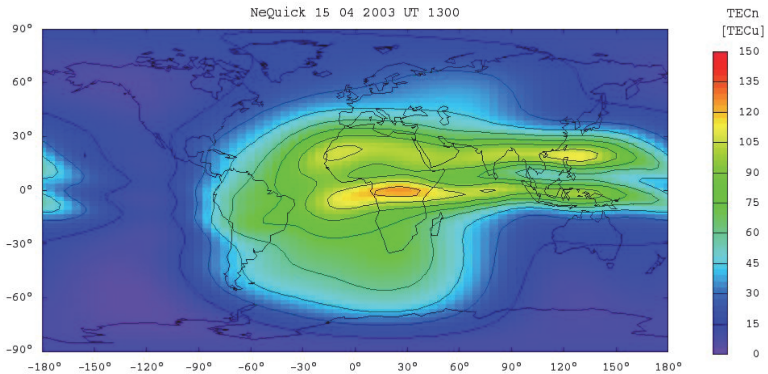
NeQuick: $|sTEC_{act} – sTEC_{mod}|$ should be less than 20 TECu or **30%** of $sTEC_{act}$ (whichever is larger)

Comparison ICA and NeQuick



Measured vTEC on
15.04.2002 at 13:00 UT



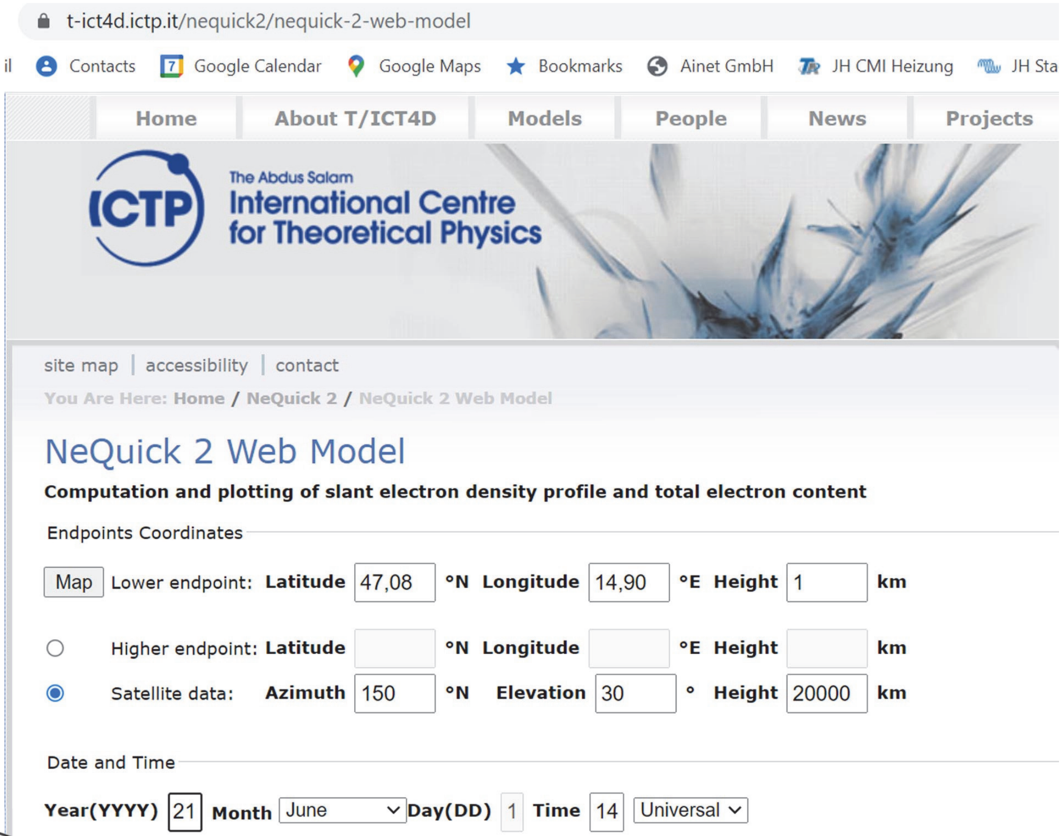


ICA Model

NeQuick Model

NeQuick Version 2 on the Web

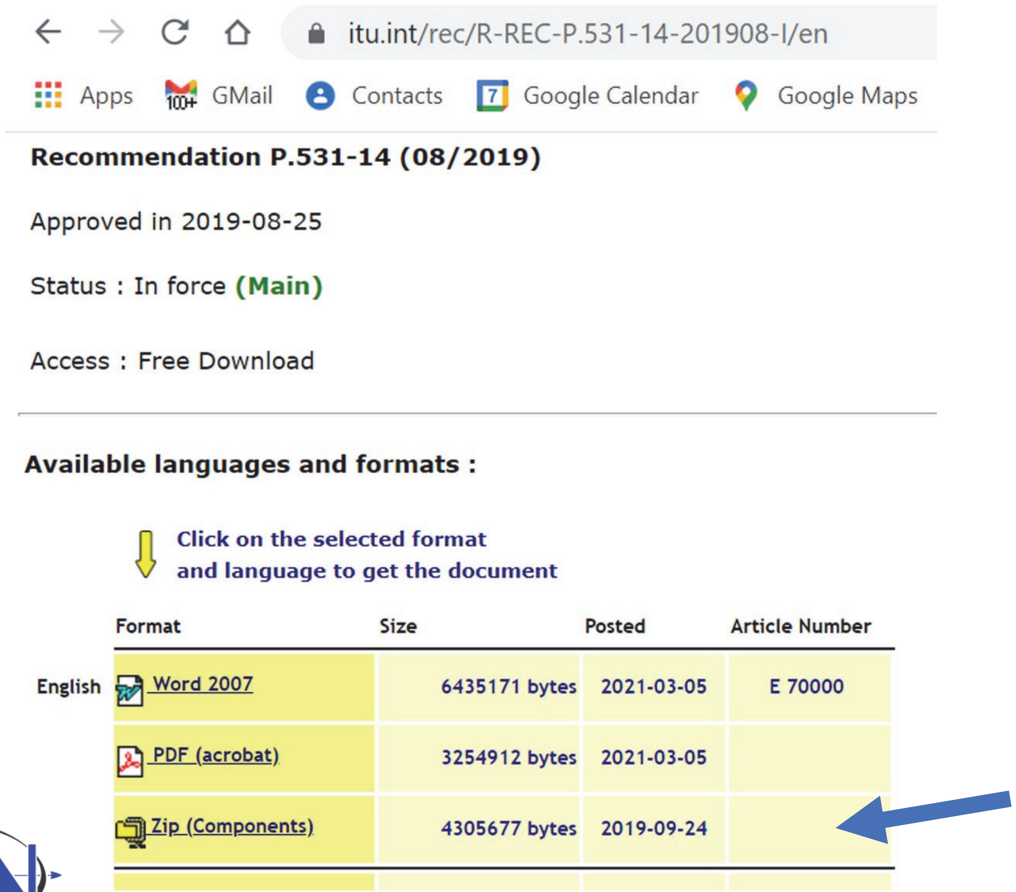
https://t-ict4d.ictp.it/nequick2/nequick-2-web-model



The model can be operated online on the ICTP portal (free of charge and anonymously)

NeQuick Version 2 at ITU-R

https://www.itu.int/rec/R-REC-P.531-14-201908-I/en

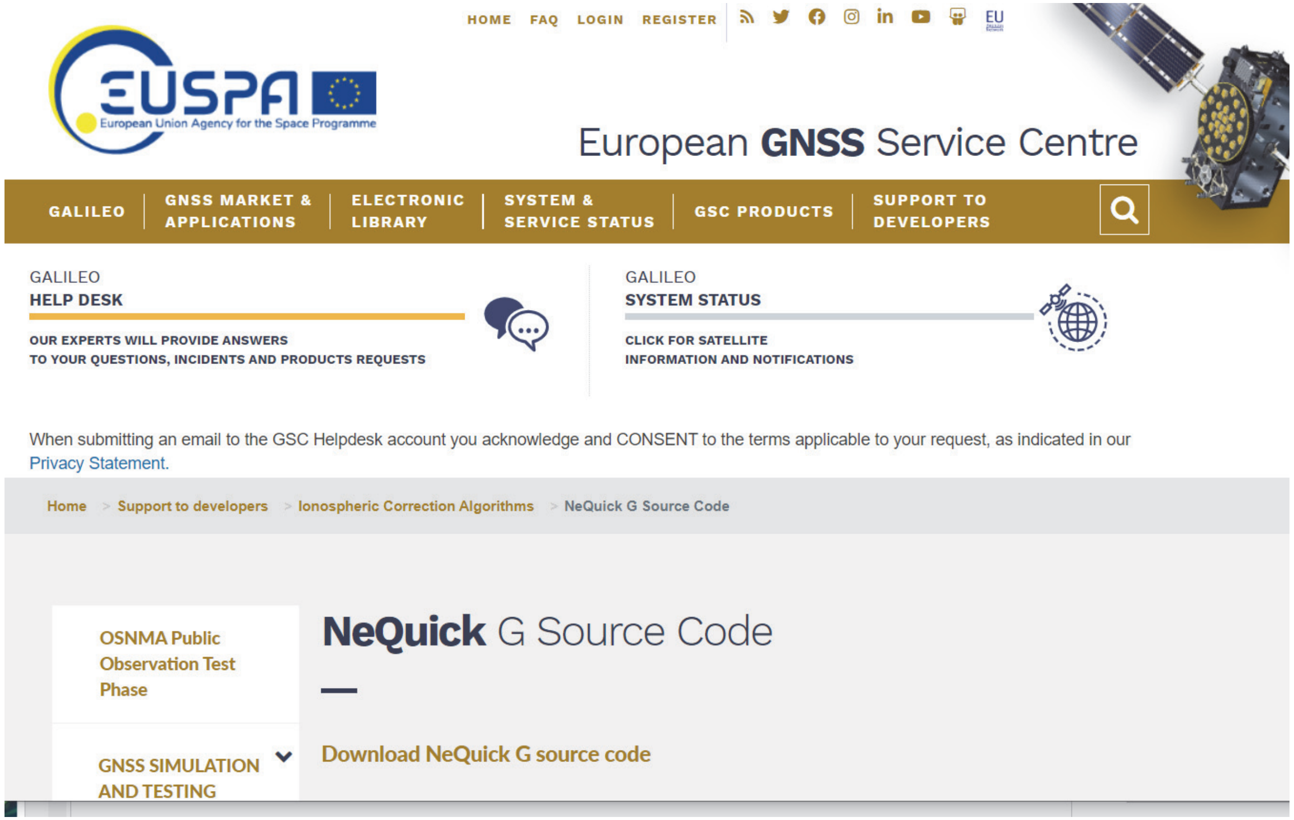


NeQuick is recommended by the ITU-R Study Group3 in Recommendation P.531.

The Fortran source code can be found here (in the zip file).

NeQuick Version G Source code in C

https://www.gsc-europa.eu/support-to-developers/ionospheric-correction-algorithms/nequick-g-source-code



The portal of the EU provides the source code of NeQuick G for all manufacturers of Galileo receivers.

Language: C


Thanks for the
Attention