SPACE WEATHER INTRODUCTORY COURSE

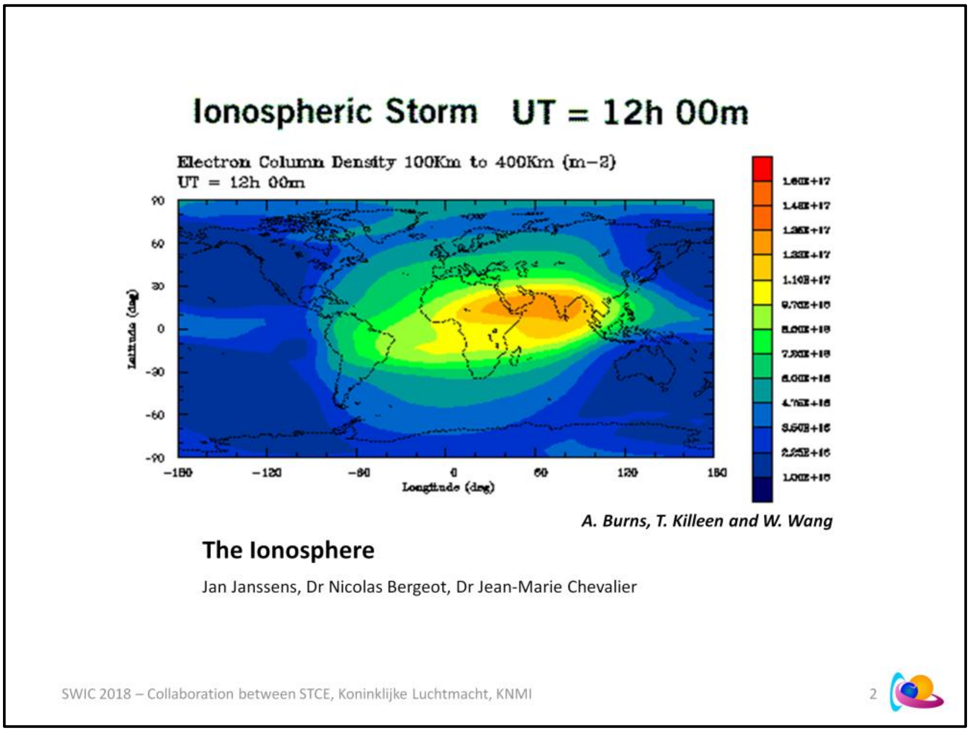
Collaboration of

Solar-Terrestrial Centre of Excellence

Koninklijke luchtmacht

Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

June 2018



Movie courtesy of A. Burns, T. Killeen and W. Wang at the University of Michigan

Movie and text from Windows to Universe:
https://www.windows2universe.org/spaceweather/disturbed_ionosphere.html
You are viewing a 24-hour long simulation of the total electron content in a column above the Earth's surface (between 100 and 400 km altitude) during the April 10-11, 1997 ionospheric storm event. This storm occurred in association with a magnetic storm that began in near-Earth space at ~21 UT on April 10 due to the arrival of a coronal mass ejection from the Sun. The storm subsided at around 9 UT on April 11 but the changes to the ionosphere lasted much longer.

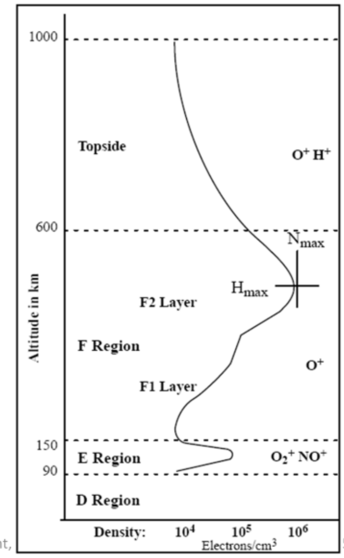
The ionosphere - Contents

The ionosphere - Contents

- Introduction
- Units and Terminology
  - TEC, foF2, Ionogram, MUF,…
- Main features
  - Coupling magnetosphere
  - EIA, EPB, TID
  - Ionospheric scintillation
- Ionospheric variability
- GNSS
  - What & How
  - Error sources
  - Error remedies
- ROB/RMI GNSS products

The ionosphere

- A shell of partially ionized atmosphere surrounding the Earth
  - Altitude: +/- 60-1000 km
  - Inner edge of the magnetosphere
- … is ionized by short wavelength solar radiation
- Affects radio comms



Picture from NOAA/SEL: https://commons.wikimedia.org/wiki/File:IonosphereProfileNOAA.png
Various layers of the ionosphere and their predominant ion populations are listed at their respective heights above ground. The density in the ionosphere varies considerably, as shown.

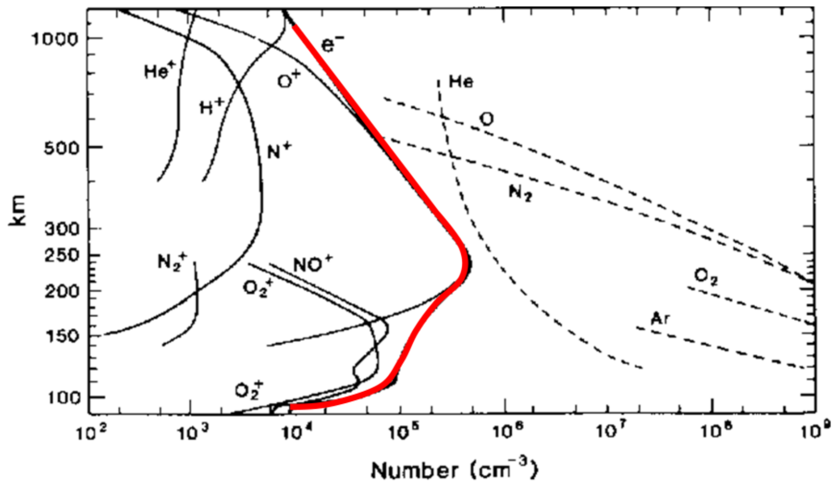
Definition from NASA: https://www.hq.nasa.gov/iwgsdi/Ionosphere.html
A shell of partially ionized atmosphere surrounding the Earth from approximately 60-1000 km. Absorption of short wavelength radiation from the Sun photo-ionizes gases in the atmosphere to produce the ionosphere. Gas dynamics and electromagnetic interactions dominate the behavior of the ionized gases. The gases ionize during daytime and recombine during night.

Definition from ROB/GNSS at http://gnss.be/ionosphere_tutorial.php#x2-10000
The ionizing action of the sun's radiation on the Earth's upper atmosphere produces free electrons. Above about 60km the number of these free electrons is sufficient to affect the propagation of electromagnetic waves. This "ionized" region of the atmosphere is a plasma and is referred to as the ionosphere.

Definition from Wikipedia at https://en.wikipedia.org/wiki/Ionosphere
The ionosphere is the ionized part of Earth's upper atmosphere, from about 60 km to 1,000 km altitude, a region that includes the thermosphere and parts of the mesosphere and exosphere. The ionosphere is ionized by solar radiation. It plays an important role in atmospheric electricity and forms the inner edge of the magnetosphere. It has practical importance because, among other functions, it influences radio propagation to distant places on the Earth.

From NOAA/SWPC Glossary at https://www.swpc.noaa.gov/content/space-weather-glossary#i
The region of the Earth’s upper atmosphere containing free electrons and ions produced by ionization of the constituents of the atmosphere by solar ultraviolet radiation at short wavelengths < 100nm) and energetic precipitating particles. The ionosphere influences radiowave propagation of frequencies less than about 300 MHz. (See D region, E region, F region.)

The ionosphere



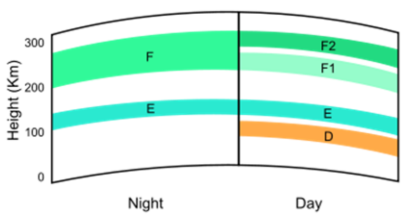
From: Earth's atmosphere (Iver Cairns, 1999)
http://www.physics.usyd.edu.au/~cairns/teaching/lecture16/node2.html

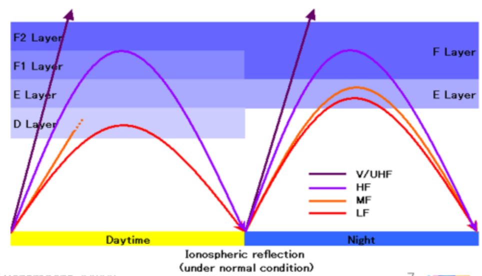
International Quiet Solar Year daytime ionospheric and atmospheric composition based on mass spectrometer measurements (Johnson, 1969; Luhmann, 1995).

IRI model: http://irimodel.org/ & https://ccmc.gsfc.nasa.gov/modelweb/models/iri_vitmo.php

Ionospheric layers

Main	Layer	Altitude (km)	Peak (km)	Constituents	Radiation	Day/Night	Radio reflection
F	F2	200 - 1000	+/- 350	O^+, H^+, e^-	UV	Day/Night	HF (3-30 MHz)
	F1	140 - 200	+/- 200	O^+, e^-	UV and EUV	Day	
E	*Es*	*Short-lived and unpredictable clouds of intense ionization*				*Min. to hours*	*VHF (30 - 300 MHz)*
	E	85 - 140	120	O_2^+, NO^+, e^-	EUV and SXR	Day/Night	MF (0.3 - 3 MHz)
D	D	60 - 85	65	O_2^+, NO^+, e^-	Ly-α , HXR	Day	LF (30 - 300 kHz)





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The table was created from inputs from:

NASA: https://www.hq.nasa.gov/iwgsdi/Ionosphere.html
ROB/GNSS at http://gnss.be/ionosphere_tutorial.php#x2-10000
Wikipedia at https://en.wikipedia.org/wiki/Ionosphere
NOAA/SWPC Glossary at https://www.swpc.noaa.gov/content/space-weather-glossary#i
INGV: http://roma2.rm.ingv.it/en/research_areas/4/ionosphere

The figure on the left is from Wikipedia: https://en.wikipedia.org/wiki/Ionosphere#/media/File:Ionosphere_Layers_en.svg
The figure on the right is from Wikimedia: https://commons.wikimedia.org/wiki/File:Ionospheric_reflectionDay_and_Night.PNG
Alternative: https://radiojove.gsfc.nasa.gov/education/educ/radio/tran-rec/exerc/iono.htm

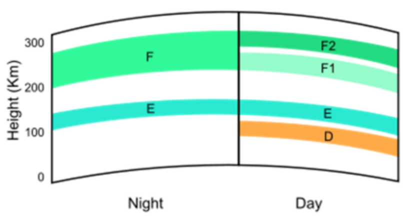
Ly-α (Lyman alpha): the Lyman-alpha line … is a spectral line of hydrogen … its wavelength of 1215.67 angstroms (121.567 nm …), … , places the Lyman-alpha line in the vacuum ultraviolet part of the electromagnetic spectrum, which is absorbed by air.

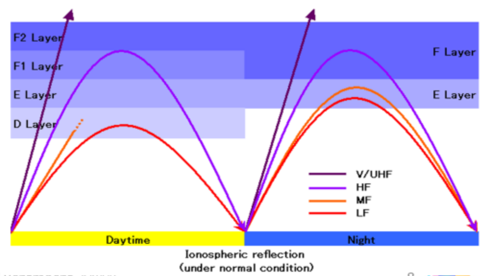
From Electronics notes (https://www.electronics-notes.com/articles/antennas-propagation/ionospheric/ionospheric-layers-regions-d-e-f1-f2.php) and Kenneth Davies (1990) Ionospheric Radio (*https://books.google.be/books?isbn=086341186X*)
There is a C-layer at about 55 km caused by galactic Cosmic Rays (hence C), but the level of ionisation is so low that it does not affect radio signals/communications.

From Electronics notes (https://www.electronics-notes.com/articles/antennas-propagation/ionospheric/sporadic-e-es.php) and Wikipedia (https://en.wikipedia.org/wiki/Sporadic_E_propagation):
Sporadic E propagation, by its name is sporadic and unpredictable by nature, but it enables radio signals to travel over much greater distances and often at higher frequencies than would normally be possible via the ionosphere. … Sporadic E, Es, arises when intense clouds of ionisation form in the E region of the ionosphere. The level of ionisation is up to about five times that of the levels reached during the peak of a sunspot cycle when they would normally be at their highest. The high levels of ionisation resulting from Sporadic E enable signals well into the VHF region of the spectrum to be refracted by these ionised clouds - frequencies up to 150 MHz may be affected. The levels of ionisation also mean that losses are particularly low - often low power transmitters may be heard via sporadic E.

Ionospheric layers

Main	Layer	Altitude (km)	Peak (km)	Constituents	Radiation	Day/Night	Radio reflection
F	F2	200 - 1000	+/- 350	O^+, H^+, e^-	UV	Day/Night	HF (3-30 MHz)
	F1	140 - 200	+/- 200	O^+, e^-	UV and EUV	Day	
E	*Es*	*Short-lived and unpredictable clouds of intense ionization*				*Min. to hours*	*VHF (30 - 300 MHz)*
	E	85 - 140	120	O_2^+, NO^+, e^-	EUV and SXR	Day/Night	MF (0.3 - 3 MHz)
D	D	60 - 85	65	O_2^+, NO^+, e^-	Ly-α , HXR	Day	LF (30 - 300 kHz)





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.../...

... Although Sporadic E may appear to give an improvement in some HF communications, while also allowing communications / interference to propagate on frequencies well into the VHF portion of the spectrum, it can also have the effect of degrading some HF communications.
The very high levels of ionisation in the clouds will reflect any signals in the HF portion of the radio spectrum. This may prevent them from reaching the higher F regions, thereby preventing them from being able to achieve much greater distances.
... The mechanism behind sporadic E is not well understood. It is thought that there may be several phenomena that give rise to its formation: Meteors, electrical (thunder) storms, auroral activity, upper atmospheric winds.

There seems to be a seasonal (more often during hemispheric summer) and solar cycle (more openings during sunspot minima) effects.

Sporadic E is not normally used for communications purposes (although radio amateurs use it) because of the sporadic nature of its occurrence, and it cannot be relied upon. Instead its occurrence should be noted as it can result in raised levels of interference as signals are propagated over much greater distances than would normally be expected.

Raulin et al. (2013): Response of the low ionosphere to X-ray and Lyman-alpha solar flare emission
https://hal-insu.archives-ouvertes.fr/insu-01179432/document
http://adsabs.harvard.edu/abs/2013JGRA..118..570R

MUF maps_ http://www.spacew.com/www/realtime.php

HF radio propagation: http://www.sws.bom.gov.au/Educational/5/2/2

INGV: MUF and such: http://roma2.rm.ingv.it/en/themes/24/ionospheric_sounding

SID _ MUF LUF: http://slideplayer.com/slide/8022458/

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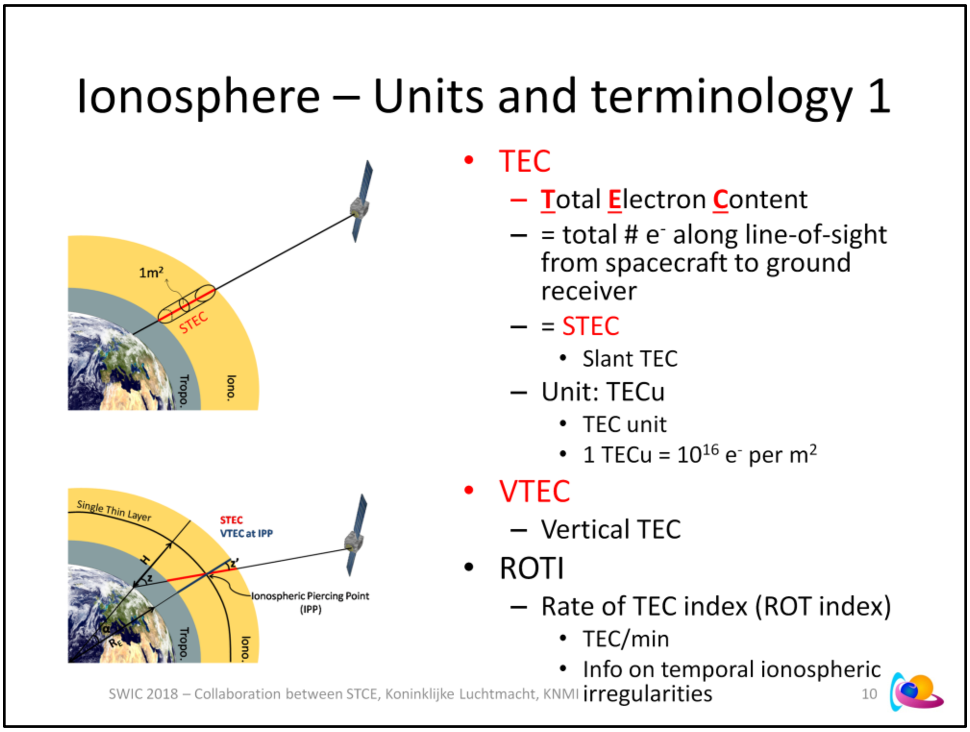
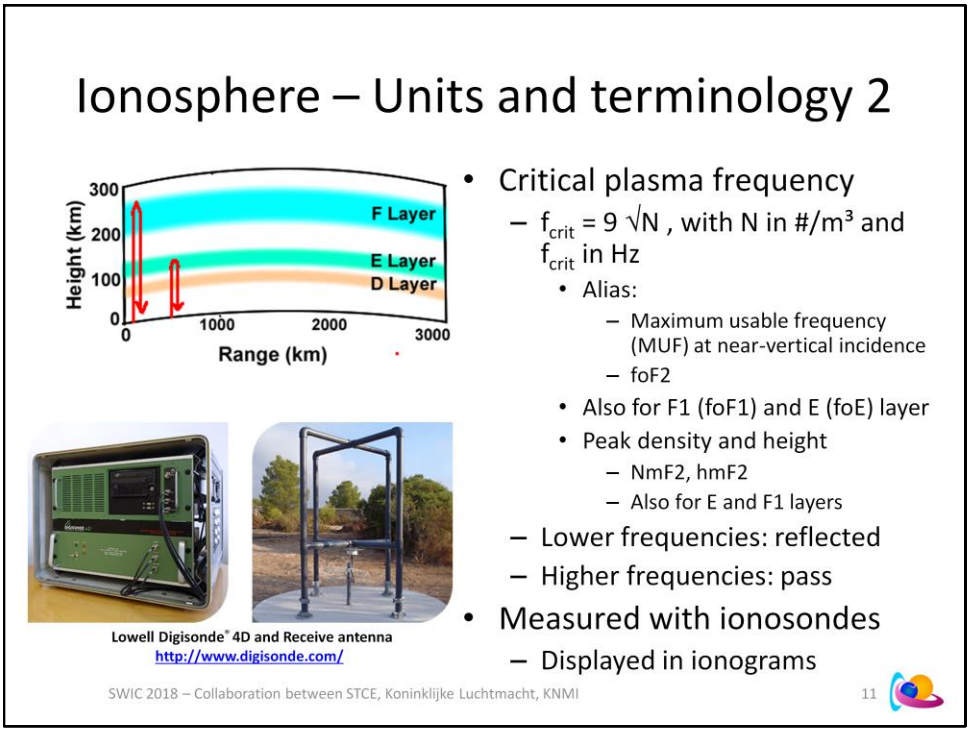


Oryema et al. (2015): Investigation of TEC variations over the magnetic equatorial and equatorial anomaly regions of the African sector
https://www.sciencedirect.com/science/article/pii/S0273117715003774
… TEC is defined as a measure of the total number of electrons in a unit area along the line of sight of GPS signal from space satellite to ground receiver (Bhuyan and Borah, 2007).

Patel et al. (2016): Comparison of GPS-derived TEC with IRI-2012 and IRI-2007 TEC predictions at Surat, a location around the EIA crest in the Indian sector, during the ascending phase of solar cycle 24
https://www.sciencedirect.com/science/article/pii/S0273117716306524
The … receiver tracks up to 11 GPS satellites at the L1 (1575.42 MHz) and L2 (1227.60 MHz) frequency at a time which are at different elevation angles (Van Dierendonck et al., 1996). The computed values of TEC from … receiver are slant TEC (STEC), defined as the integral of the electron density along the satellite to the receiver line of sight. These are then converted into vertical TEC (VTEC) using suitable mapping function at different IPP (Ionospheric Pierce Point) positions which are determined by the established formulae (Mannucci et al., 1993; Langley et al., 2002).

IMPC/DLR: http://impc.dlr.de/products/ionospheric-perturbations/
The Rate of TEC index (ROTI) is defined as standard deviation of the rate of TEC (ROT) assuming the ionosphere as a thin layer. Hence the index provides information about temporal ionospheric irregularities.

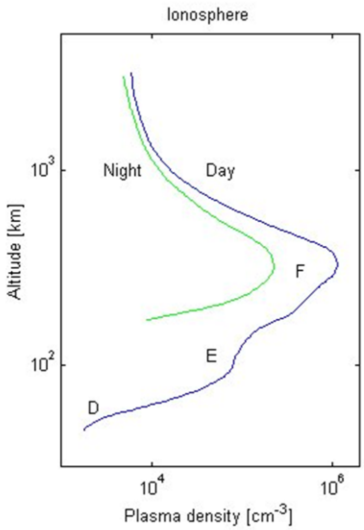
Norsuzila et al. (2008): Leveling Process of Total Electron Content (TEC) Using Malaysian Global Positioning System (GPS) Data
http://thescipub.com/pdf/10.3844/ajeassp.2008.223.229
ROTI maps can be found at the ESA page http://swe.ssa.esa.int/web/guest/swaci-federated (SWACI/DLR)



From
- Wikipedia: https://en.wikipedia.org/wiki/Critical_frequency
- Naval Post-graduate School: http://www.met.nps.edu/~psguest/EMEO_online/module3/module_3_2b.html
- Lowell Digisonde International: http://www.digisonde.com/instrument-description.html
- World Data Center A for Solar-Terrestrial Physics – URSI Handbook of Ionogram Interpretation and Reduction (1972)
  ftp://ftp.ngdc.noaa.gov/ionosonde/documentation/UAG_23A_Searchable.pdf

There are several « critical » frequencies e.g. foF2, foE,…
The critical frequency for the ionosphere is the foF2 as the F2 layer has the highest density and hence the highest frequency at which vertically indicent waves are still reflected. Hence, it’s also called the MUF.

Exercise – Calculation of critical f



- What's the critical frequency for the F2 layer (day)?
  - ✗ 9 kHz
  - ✗ 900 kHz
  - ✓ 9 MHz
- What happens if a 90 MHz radio signal is sent up vertically?
  - ✗ The signal gets reflected
  - ✓ The signal gets straight through
  - ✗ The signal gets absorbed

Figure from University of Oulu at Wikipedia: https://wiki.oulu.fi/display/SpaceWiki/Ionosphere

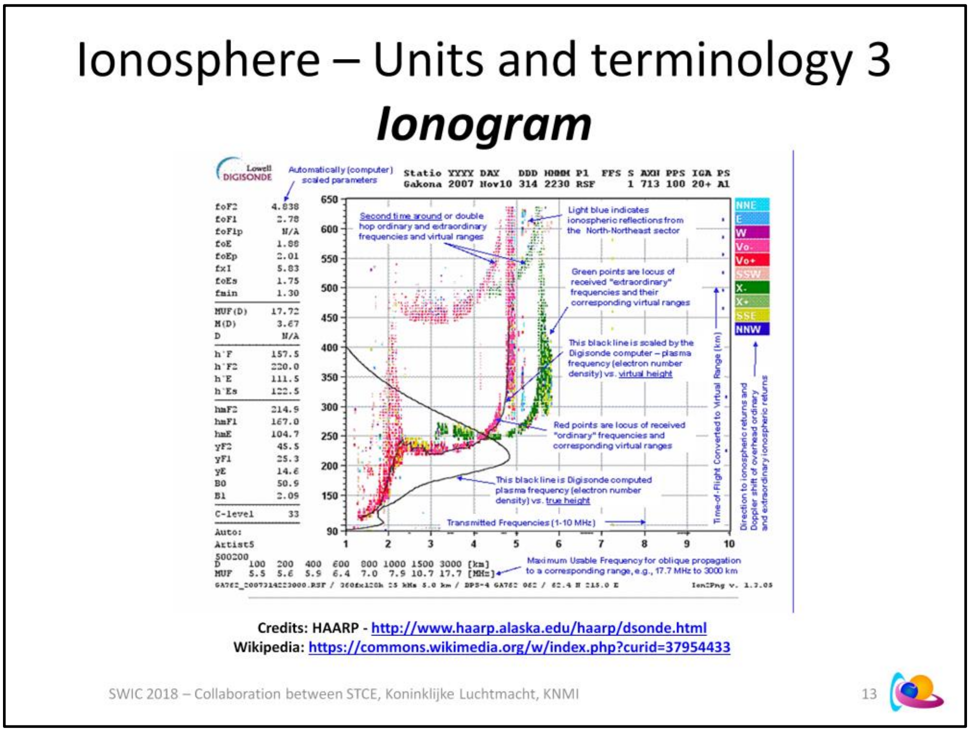


Figure:
Credits: HAARP - http://www.haarp.alaska.edu/haarp/dsonde.html
Wikipedia: https://commons.wikimedia.org/w/index.php?curid=37954433

Text from World Data Center A for Solar-Terrestrial Physics – URSI Handbook of Ionogram Interpretation and Reduction (1972) ftp://ftp.ngdc.noaa.gov/ionosonde/documentation/UAG_23A_Searchable.pdf (Chapter 1)

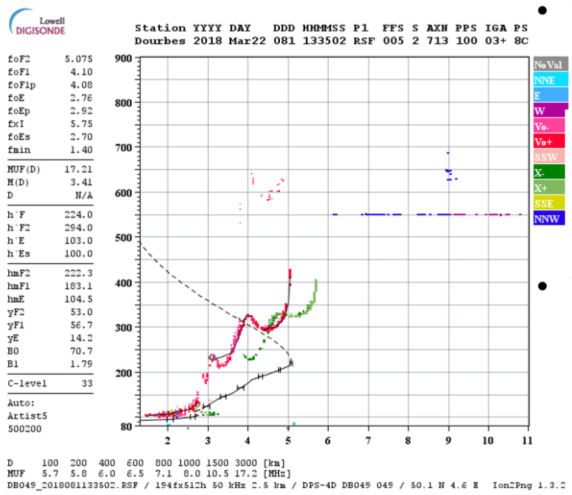
The ionograms actually show the time of travel of the pulse signal from the transmitter to the cathode ray tube, reflection in the ionosphere normally occurring at vertical incidence. As this signal always travels more slowly in the ionosphere and in the receiver than in free space, the heights observed always exceed the true heights of reflection.

⇒ Hence the difference between h' (the virtual height, e.g. h'mF2) and h (the true height, e.g. hmF2), with h' always higher than h (for the same frequency).

1.03. The Earth's magnetic field, in general causes a radio wave incident on the bottom of the ionosphere to be divided into two waves of different polarization which are reflected independently in the ionosphere … . These waves are known as magneto-ionic or, preferably, magneto-electronic component waves. They are due to the interaction of the electrons in the plasma with the magnetic field. Modern plasma theory shows that the presence of ions can introduce additional modes and waves which can be observed experimentally and are accurately described as magneto-ionic waves. By analogy with optical double refraction, one is called the **o**rdinary wave and the other, the e**x**traordinary wave. [BvdO: In general, one speaks only of left and right-handed polarized waves, which is when the wave vector is along the (external) magnetic field. If the wave vector is perpendicular to the MF, one uses the terms "ordinary" and "extraordinary" wave.].
… Since the conditions of reflection for the two components are different, each produces its own h'(f) pattern. These are similar but displaced in frequency, the extraordinary ray having the higher critical frequency … . The magneto-electronic theory shows that the reflection levels of the two modes (o and x) depend on the ratio of the exploring frequency f to the gyrofrequency fB.
=> Hence, the ionograms mention parameters such as fxF2 next to foF2. We work with the lower (« o »rdinary) frequency, i.e. the foF2.

Ionograms frequently show multiple and mixed reflections. A multiple reflection is the name given to a trace which has been reflected from the ionosphere more than once. An echo which results from two reflections from the same layer, with an intermediate reflection from the ground, is called a second order; three reflections give a third order, and so on. Orders as high as fifteen or more occasionally occur when absorption is extremely low.

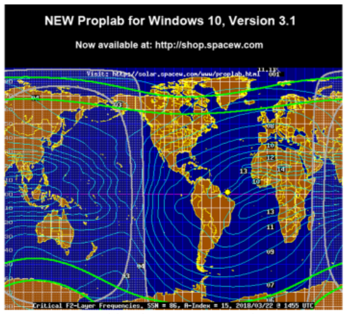
Exercise – Ionogram

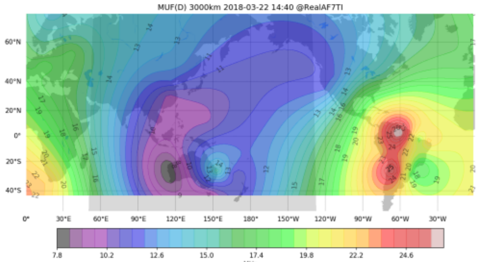


- The critical ionospheric frequency in this ionogram is at
  - ✗ 4.10 MHz
  - ✓ 5.07 MHz
  - ✗ 5.75 MHz
  - ✗ 17.21 MHz
- The height of the F2 layer is at
  - ✗ 104 km
  - ✓ 222 km
  - ✗ 294 km
  - ✗ 580 km

Credits: Dourbes GC - http://digisonde.oma.be/

Ionosphere – Units and terminology 4





- Key frequency parameters
  - MUF
    - Maximum Usable Frequency
      - foF2
    - MUF(X): MUF over X km path
      - Maps usually 3000 km
      - Ionograms: 100-3000 km
    - EMUF
      - E-layer MUF (foE)
  - LUF
    - Lowest Usable Frequency
      - Due to D-region absorption
  - FOT
    - Frequency of Optimum Transmission
      - Due to ionospheric variability
      - ~ 0.85 MUF

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Near-real time graphs available at DXZone: https://www.dxzone.com/catalog/Propagation/
MUF: vertical incidence: http://www.spacew.com/www/realtime.php

Info on critical frequencies from Naval Post-graduate School:
http://www.met.nps.edu/~psguest/EMEO_online/module3/module_3_2b.html

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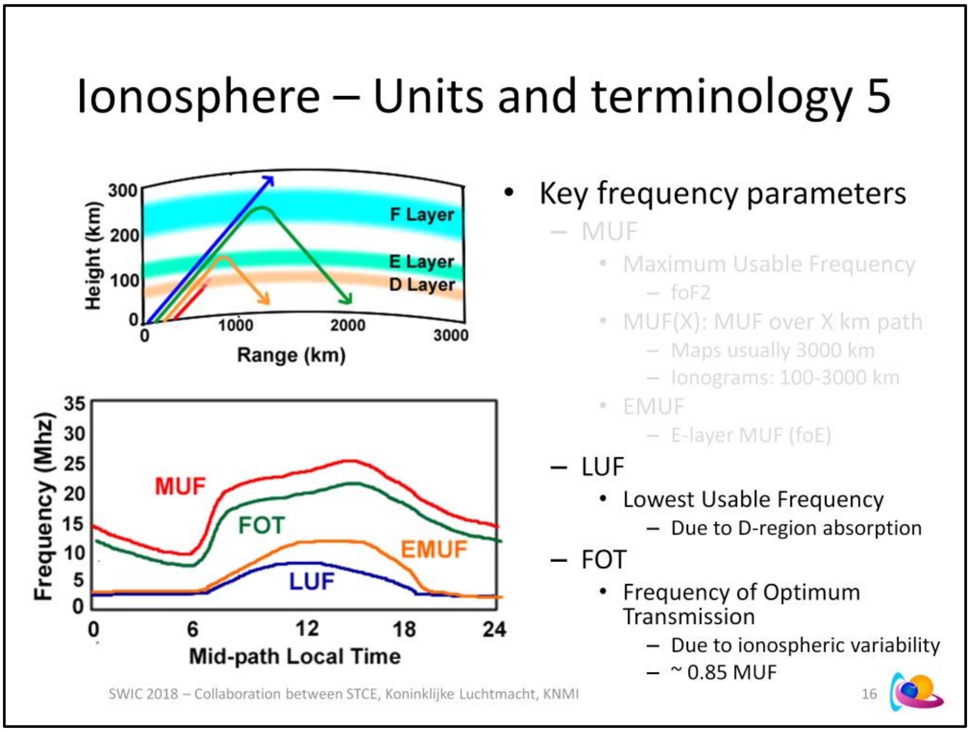

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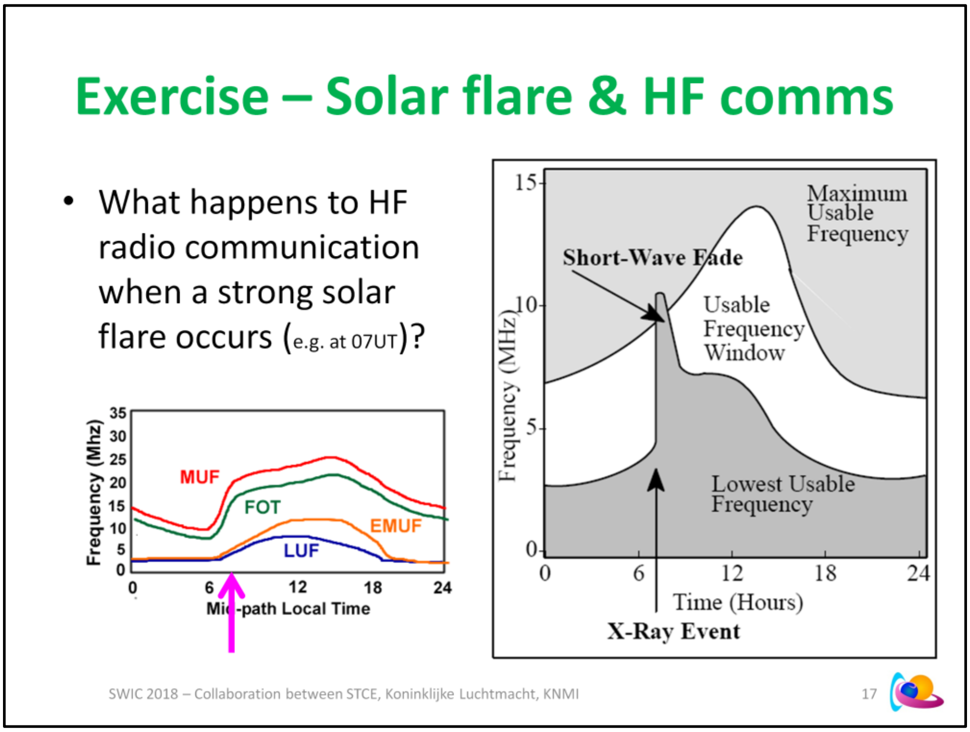
http://www.met.nps.edu/~psguest/EMEO_online/module3/module_3_2b.html
Top Figure: …Figure 11. Ray diagram showing the effect of using different frequencies at the same transmission angle. The blue ray frequency is greater than the MUF and passes into space. The green ray frequency is less than the MUF but greater than the E layer MUF. This is usually the best frequency region to use for long range communications and is usually where the FOT (equal to 0.85 x MUF) exists. The orange ray frequency is less than the E layer MUF and greater than the LUF. This is best for medium range (around 500 to 1500 km) transmissions. The red ray is less than the LUF and is absorbed in the D layer.
Bottom Figure: … Plot of typical diurnal changes in the maximum usable frequency (MUF), the frequency of optimum transmission (FOT), the E layer maximum usable frequency (EMUF) and the lowest usable frequency (LUF). This particular diagram is representative of the parameters for a San Francisco, CA to Honolulu HI in October using a 5000 W transmitter.

MUF maps_ http://www.spacew.com/www/realtime.php
HF radio propagation: http://www.sws.bom.gov.au/Educational/5/2/2
INGV: MUF and such: http://roma2.rm.ingv.it/en/themes/24/ionospheric_sounding
SID _ MUF LUF: http://slideplayer.com/slide/8022458/



What happens to the MUF and LUF when a strong solar flare occurs?

Figure from https://commons.wikimedia.org/wiki/File:ShortWaveFadeNOAA.png
Source: NOAA: http://www.sel.noaa.gov/info/Iono.pdf
Also in B. Poppe (2006): Sentinels of the Sun (pp. 33) - https://books.google.be/books?id=WMh4REf3iZQC

The usage frequency window for radio propagation lies between the lowest and maximum usable frequencies. When the window closes, as shown here, a shortwave fade occurs.

The MUF depends on foF2 and the angle of incidence of the radio wave
The LUF is determined by the amount of absorption in the D- and E-region
Then the LUF can only be used by increasing the frequency.
If the frequency is increased above the MUF, so when it will not even get reflected by the F2-layer (or still gets absorbed by the D/E region) then no HF communication os possible. This is called a short wave fade (or radio black out).

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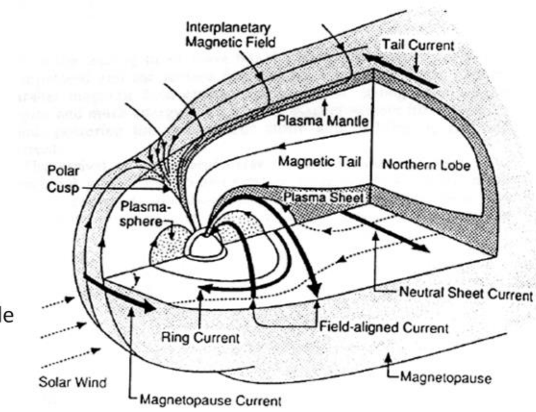
Ionosphere – Main features

Coupling with magnetosphere

- By magnetic field lines
  - Magnetopause
    - Footpoints of cusps
  - Tail lobes
    - Polar caps
  - Plasma sheet
    - Auroral oval
  - Plasmasphere
    - Ionosphere at low altitude



Russell and Luhmann , 1997

Potzdam figure taken from http://www-app2.gfz-potsdam.de/pb1/op/champ/science/magnetic_SCIENCE.html

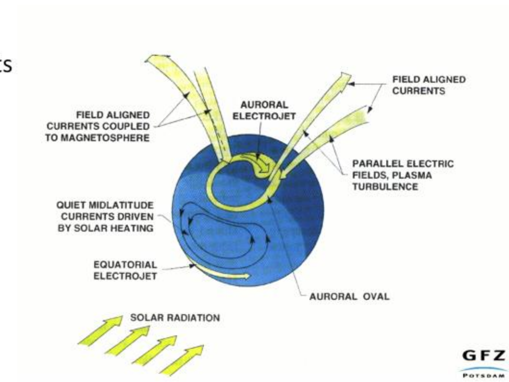
More on the connection between ionosphere and magnetosphere and the related electrical currents is at

- http://www.aeronomie.be/en/topics/solarsystem/magnet-couplingionosphere.pdf (De Keyser, 1999)
- https://wiki.oulu.fi/download/attachments/11767976/ionos_ch5.pdf (Oulu, Finland)
- ftp://ccar.colorado.edu/pub/forbes/ASEN5335/Magnetospheres/Lecture%2021/21.-Magnetospheres-4%2009.pdf

Ionosphere – Main features

Coupling with magnetosphere

- By magnetic field lines
  - Creation of electrical currents in ionosphere
    - Auroral electrojets
      - North & South pole
      - D- & E-region
    - Equatorial electrojet
      - Solar driven
      - Solar quiet current
      - E-region



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Potzdam figure taken from http://www-app2.gfz-potsdam.de/pb1/op/champ/science/magnetic_SCIENCE.html

Basic definitions on electrojets at
- https://en.wikipedia.org/wiki/Electrojet
- https://en.wikipedia.org/wiki/Equatorial_electrojet
- https://web.archive.org/web/20100705021933/http://www-star.stanford.edu/~vlf/ejet/electrojet.html

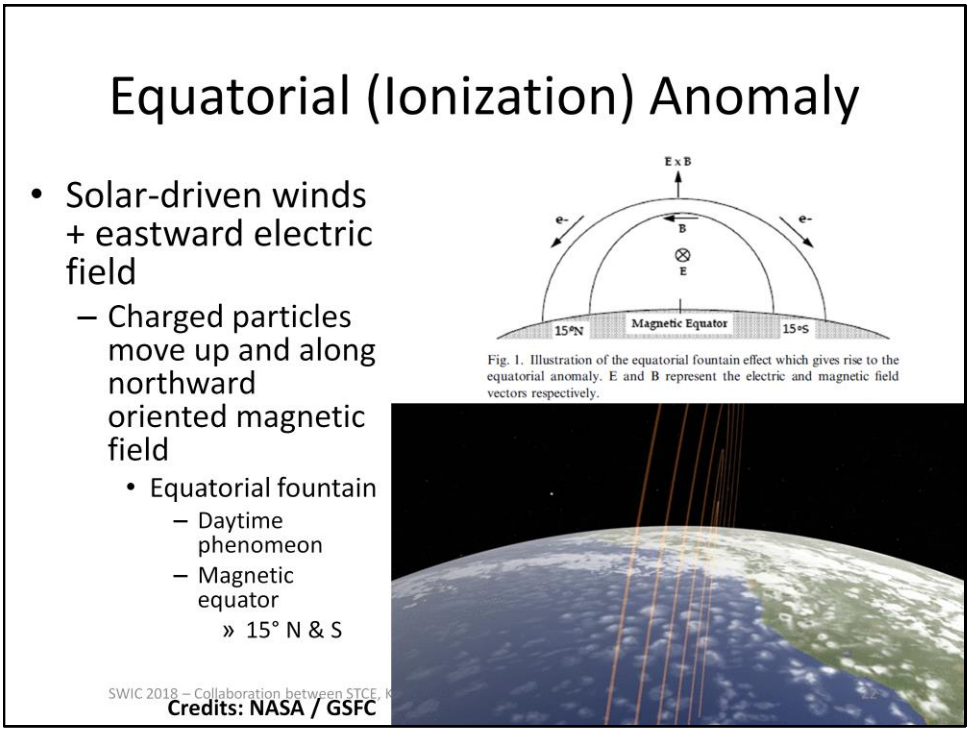
The term “auroral electrojet” is the name given to the large horizontal currents that flow in the D and E regions of the auroral ionosphere. … the auroral electrojet currents are remarkable for their strength and persistence. … During magnetically quiet periods, the electrojet is generally confined to the auroral oval. However during disturbed periods, the electrojet increases in strength and expands to both higher and lower latitudes. This expansion results from two factors, enhanced particle precipitation and enhanced ionospheric electric fields. … Kristian Birkeland was the first to suggest that polar electric currents (or auroral electrojets) are connected to a system of filaments (now called "Birkeland currents") that flow along geomagnetic field lines into and away from the polar region.

Yizengaw et al. (2014), The longitudinal variability of equatorial electrojet and vertical drift velocity in the African and American sectors
http://adsabs.harvard.edu/abs/2014AnGeo..32..231Y
The worldwide solar-driven wind results in the so-called Sq (solar quiet) current system in the E region of the earth’s ionosphere (100–130 km altitude). The Sq current in turn causes the generation of an east–west electrostatic field at the equatorial ionosphere, which is directed eastward during dayside. At the magnetic dip equator, where the geomagnetic field is horizontal, this electric field results in an enhanced eastward current flow along the magnetic equator, known as the equatorial electrojet (EEJ) (e.g., Stening, 1995). The EEJ is a narrow (within ± 3° of the magnetic equator) ribbon of current flowing eastward in the daytime equatorial region of the earth’s ionosphere.

Ionosphere – Main features

- Equatorial anomaly
- Plasma bubbles
- Traveling Ionospheric Disturbances

→ Sources of ionospheric scintillation



Equatorial anomaly
Movie clip from NASA/GSFC : https://svs.gsfc.nasa.gov/4617
This is a visualization of the Equatorial Fountain process in the ionosphere, whereby ions are driven away from the equator forming ion density enhancements to the north and south of the equator. This visualization is depicted near 50 degrees west longitude, where the magnetic equator crosses the geographic equator. Magnetic field lines near Earth are represented by the gold lines. Particles appear in a blue-white flash, representing the point where atoms are ionized, becoming positively charged and releasing an electron. Now these charged particles can 'feel' the near-Earth electric and magnetic fields. Their motion becomes a combination of circular gyromotion (see Plasma Zoo: Gyromotion in Three Dimensions) due to the magnetic field and ExB drift (see Plasma Zoo: ExB Drift). At higher altitudes, the electric field is weaker, reducing the vertical motion, and the ion motion becomes dominated by the magnetic field and gravity, allowing the ion to 'slide' down the magnetic field line back to Earth. At lower altitudes, the ions combine with free electrons in a process called recombination, represented by a red flash and fading of the particle trail.

Aylward (Summerschool 2012): http://star.arm.ac.uk/summerschool2012/Aylward.pdf
Thermospheric winds in the equatorial E region drag ions across the magnetic field lines B, creating during the daytime an eastward dynamo electric field, which is mapped along the magnetic field lines into the F region. This, combined with a northward B field creates an upward E×B plasma drift.

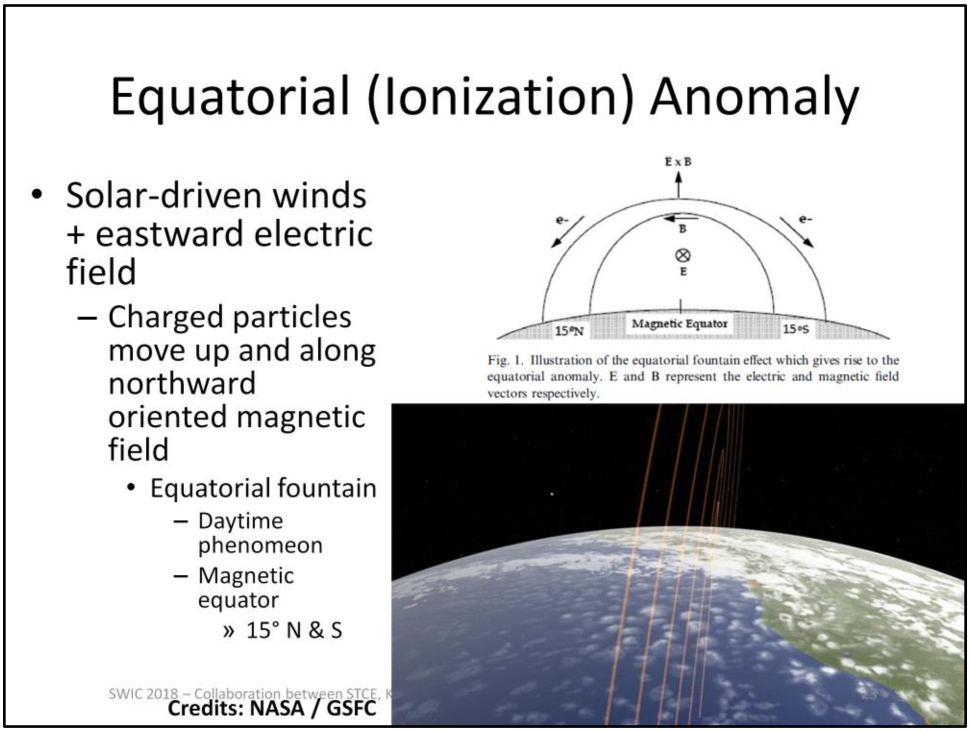
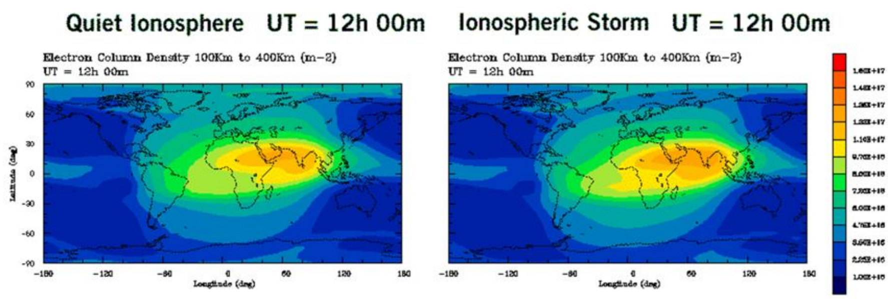


Figure and text from Oryema (2015): Investigation of TEC variations over the magnetic equatorial and equatorial anomaly regions of the African sector
https://www.sciencedirect.com/science/article/pii/S0273117715003774
The Earth's ionosphere along the equatorial (low latitude) region is quite unique and different from that at the mid and high latitudes (Chakraborty and Hajra, 2009). This is because the low latitude ionospheric F-region is dominated by a phenomenon called equatorial ionization anomaly (EIA), which is characterized by an electron density trough region around the magnetic equator, and a dual band of enhanced electron density (crest regions) at about
15 degrees north and south of the trough as shown in Fig. 1 (Schunk and Nagy, 2000). The EIA is formed as a result of the diurnal variation of the zonal electric field, which primarily points eastward during the day and reverses at night. In conjunction with the horizontal northward geomagnetic field at equatorial latitudes, the ionospheric plasma is lifted upward by vertical E x B drift (Stolle et al., 2008).
Once the plasma is transported to higher altitudes, it diffuses downward along the geomagnetic field lines into both hemispheres due to gravitational and pressure gradient forces (Goodman, 2005). This combination of electromagnetic drift and diffusion produces a fountain like pattern of plasma motion called the equatorial fountain effect, leaving region around the magnetic equator with little electron density concentration and higher electron density concentrations at the crests or equatorial anomaly regions (Schunk and Nagy, 2000). This implies that ionospheric effects are higher around the equatorial crests than at the trough region or magnetic equator. However, the latitudes of the anomaly crests and strength of the anomaly vary with condition of the day, season of the year and solar activity (Chakraborty and Hajra, 2009).

Equatorial (Ionization) Anomaly

- Effect on EIA from geomagnetic storm



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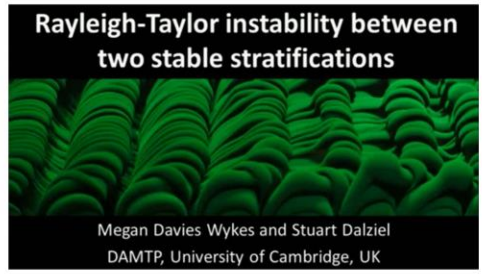
Equatorial anomaly
Animation from Radio Jove: https://radiojove.gsfc.nasa.gov/education/educ/radio/tran-rec/exerc/iono.htm
Below is an animation comparing the ionospheric conditions during a typical day with that of a day containing an ionospheric storm. An ionospheric storm is caused by a coronal mass ejection from the sun that strikes the Earth's atmosphere. These mass ejections contain large amounts of particles that smash into the ionosphere and knock electrons loose from atoms. As discussed above the loose electrons reflect radio waves from astronomical sources back into space. The addition of loose electrons as a result of a mass ejection makes observations and communications difficult. The dark blue and purple areas are the areas where the number of loose electrons is low. In these areas there are few electrons to reflect radio waves and thus lower frequency waves are able to reach the ground. As can be seen from the animations the night time and early morning hours are best for observations due to the fact that the sun is not in the sky and its ultraviolet light is not reaching the atmosphere at this time. The density of electrons (how many electrons there are per every cubic centimeter) is represented by the varying colors. Bands of high density that appear at high latitudes during the storm but disappear rapidly as it subsides are due to the high velocity particles smashing into the atoms in the atmosphere and knocking electrons free. These same high velocity particles produce the auroral lights. We can use these maps and the varying colors to find the lowest frequency that is detectable from the ground. The lowest frequency detectable, known as the critical frequency, is related to the density of electrons by the equation: f = 9x10^-3 x sqrt(N) MHz. In this equation f is the critical frequency and N is the electron density, sqrt means to take the square root of the electron density. In the maps above the electron density ranges from 33300 electrons/cm^3 (dark blue) to 249750 electrons/cm^3 (green) to 552780 electrons/cm^3 (red).

Movie courtesy of A. Burns, T. Killeen and W. Wang at the University of Michigan
Movie and text from Windows to Universe: https://www.windows2universe.org/spaceweather/disturbed_ionosphere.html
You are viewing a 24-hour long simulation of the total electron content in a column above the Earth's surface (between 100 and 400 km altitude) during the April 10-11, 1997 ionospheric storm event. This storm occurred in association with a magnetic storm that began in near-Earth space at ~21 UT on April 10 due to the arrival of a coronal mass ejection from the Sun. The storm subsided at around 9 UT on April 11 but the changes to the ionosphere lasted much longer.

Plasma bubbles

- Small scale structures
  - +/- 100 km
  - Bubbles of low-density (<10%) plasma
  - Bottomside F-layer
  - Post-sunset
  - At equatorial and high-latitude
- More EPBs during
  - Solar cycle maximum
    - Also during relatively quiet geomagnetic conditions
      - Can occur anytime during SC
  - Equinoxes
- Source of ionospheric scintillation
  - Loss of satellite lock, blackout



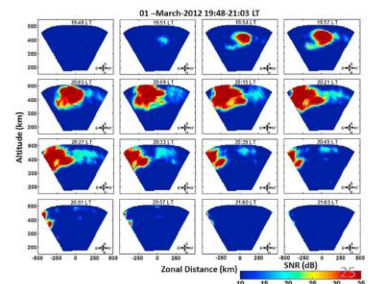


Figure 1. An example showing the genesis and successive development of EPB (evolving-type) over Kototabang observed from the fan sector maps of EAR on

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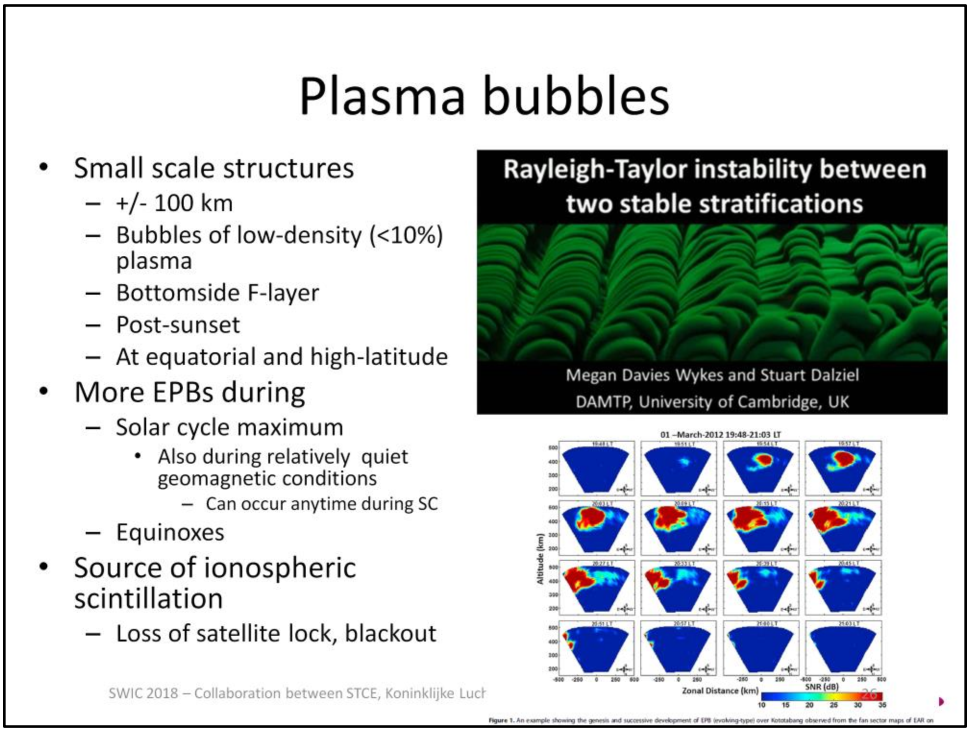
Movie and text from
The Conversation: Bad space weather may have caused fatal Afghan gun battle
http://theconversation.com/bad-space-weather-may-have-caused-fatal-afghan-gun-battle-32081
Original movie from https://www.youtube.com/watch?v=NI85oC-3mJ0

Plasma bubbles, as the name suggests, are essentially bubbles of low density plasma that rise into high density plasma in the Earth’s upper atmosphere. The bubbles are the result of a plasma instability that is triggered shortly after sunset, known as the generalised Rayleigh-Taylor instability.
The situation is analogous to a heavy fluid sitting on top of a lighter fluid, which rises up into the heavy fluid, and the heavy fluid flows downwards under gravity.
The only difference with the ionosphere bubbles is that electric and magnetic fields govern their drift. These bubbles strongly affect any radio waves that propagate through them, causing random fluctuations in amplitude and phase, called scintillations.
From the perspective of a GPS receiver, the signals no longer resemble the normal GPS signals, and the receiver ultimately loses lock on the satellite. During severe events, a series of adjacent plasma bubbles can span from horizon to horizon, creating significant GPS positioning and timing errors.



Bottom Picture taken from

Ajith et al. (2015): Explicit characteristics of evolutionary-type plasma bubbles observed from Equatorial Atmosphere Radar during the low to moderate solar activity years 2010-2012

http://adsabs.harvard.edu/abs/2015JGRA..120.1371A

The equatorial plasma bubbles (EPBs)/equatorial spread F (ESF) irregularities are an important topic of space weather interest because of their impact on trans-ionospheric radio communications, satellite-based navigation and augmentation systems. This local plasma-depleted structures develop at the bottom side F layer through Rayleigh-Taylor instability and rapidly grow to topside ionosphere via polarization electric fields within them.

The EPBs are essentially a nighttime phenomena when the E region conductivity becomes negligible that liberates the polarization electric fields in F region to grow nonlinearly. The steep vertical gradients due to quick loss of bottom side ionization and rapid uplift of equatorial F layer via pre-reversal enhancement (PRE) of zonal electric field makes the post-sunset hours as the most preferred local time for the formation of EPBs [Kelley, 1989; Fejer et al., 1999; Tulasi Ramet al., 2006]. Once developed, these EPBs generally drift eastward with velocities ranging from 50 to 200 m/s [Aarons et al., 1980; Bhattacharyya et al., 2001; Rama Rao et al., 2005]. The seasonal and longitudinal variability of EPBs are influenced by the alignment between sunset terminator and magnetic meridian.

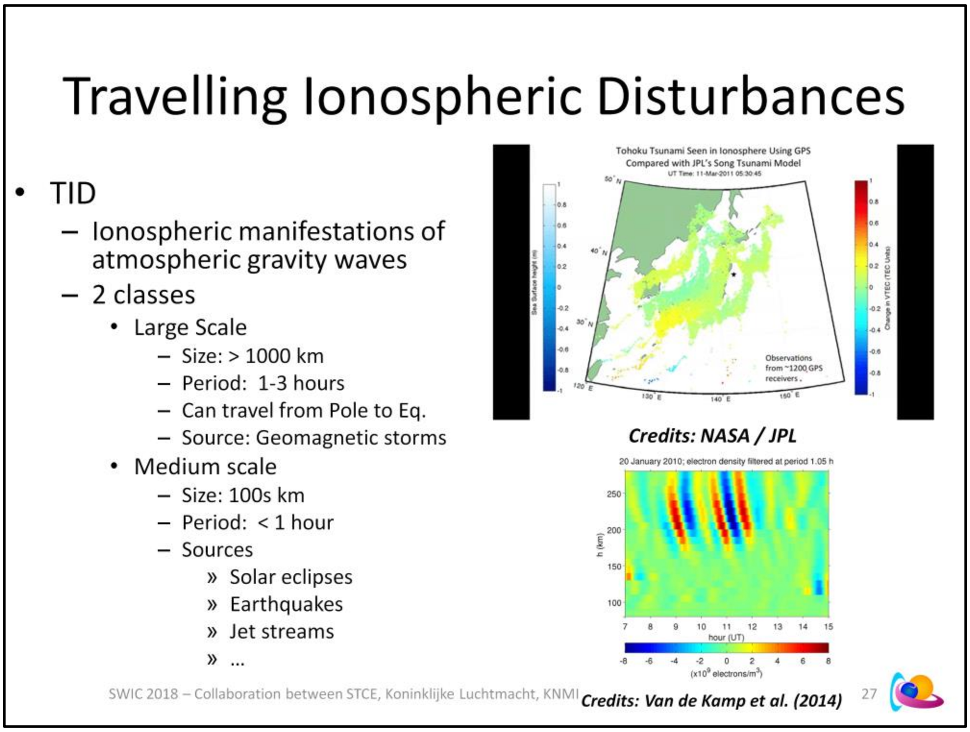
From the STCE Newsitem:

http://www.stce.be/news/420/welcome.html

The main cause of the ionospheric unrest is the presence of equatorial plasma bubbles, i.e. depletions of electron density in the ionosphere. Their number correlates with the solar activity level, and they also are more numerous during the equinoxes (spring and autumn) than during the solstices (summer and winter). They usually form after sunset at the bottom of the F-region (main ionospheric layer), where small low-density irregularities can grow into turbulent bubbles - see a model underneath (covering 40 minutes) developed by Dr Yokoyama (NICT/AERI). The bubbles have a typical size of about 100 km and their effects usually end around midnight. They can occur during relatively minor levels of geomagnetic activity, especially during solar maximum. Radio wave propagation can be severely affected in terms of power and intensity as these waves travel through small scale structures in the ionosphere (i.e. scintillation of radio waves).

More info on ionospheric scintillation: SWS: http://www.sws.bom.gov.au/Satellite/6/3

More on (equatorial) spread F: https://www.hsu.edu/academicforum/1998-1999/1998-9AFA%20Review%20of%20Equatorial%20Spread%20F.pdf (McDaniel, 1998)

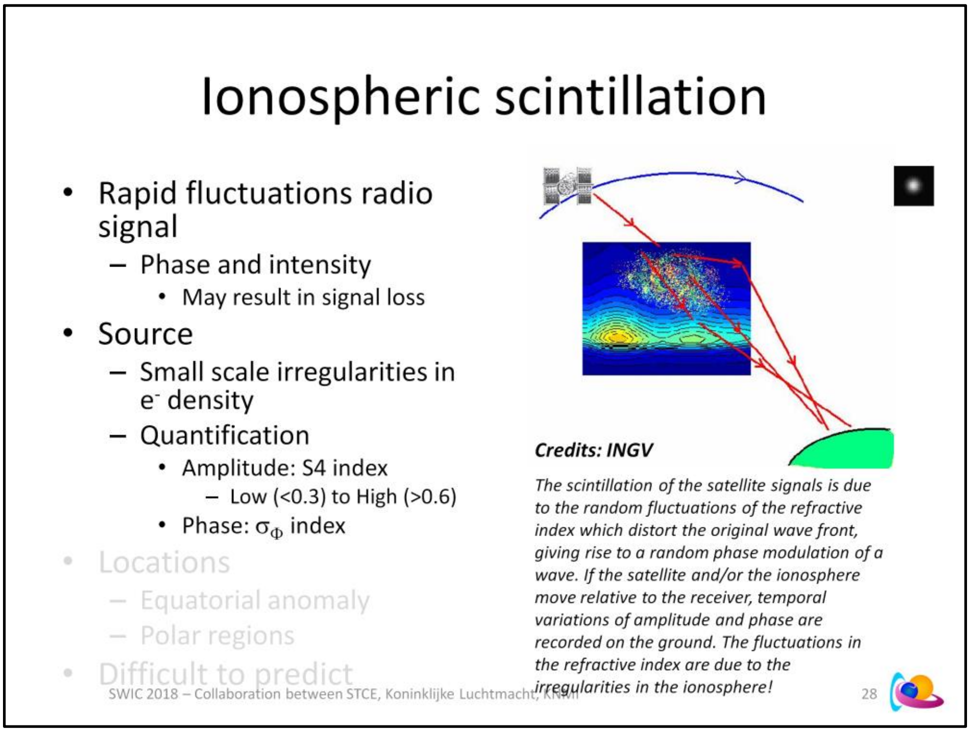


Animation from NASA/JPL: https://photojournal.jpl.nasa.gov/catalog/PIA14430

Katamzi et al. 2011: Observations of traveling ionospheric disturbances associated with geomagnetic storms
http://ieeexplore.ieee.org/document/6050928/

Van de Kamp et al. (2014): Waves in the ionosphere detected by ground GPS receiver network
https://www.ucl.ac.uk/mssl/space-plasma-physics/nuggets/mssl-plasma-nuggets/2014/pokhotelov-gps

Figure and text from Van de Kamp et al. (2014): TID characterised using joint effort of incoherent scatter radar and GPS
https://www.ann-geophys.net/32/1511/2014/
Travelling ionospheric disturbances (TIDs) are waves in the ionosphere with time periods from tens of minutes up to 2–3 h and wavelengths typically longer than 100 km. The waves can travel globally over distances of thousands of km, including travels between high latitudes and the equatorial region. TIDs were first noted in ionosonde data in Australia in 1937–1939, as periodic disturbances in the reflection height, which were noted to travel between different locations. Munro (1950) reported the first systematic measurement and analysis of the vertical and horizontal wave parameters of these disturbances, using multiple-location ionosondes around Sydney. … TIDs are caused by atmospheric gravity waves (AGWs) propagating in the neutral thermosphere. These waves are generated in the lower atmosphere and travel upwards. In the ionosphere, the resulting wave patterns of the ionised gas are a measurable signature of the neutral wave. … TIDs can be grouped into two categories: large-scale TIDs with horizontal wavelength over 1000 km and oscillation periods of 30–180 min, and medium-scale TIDs with horizontal wavelengths of several hundreds of km and periods of 15–80 min. Large-scale TIDs propagate with phase velocities of 200–1000ms−1, comparable to the speed of sound in the thermosphere, while medium-scale TIDs typically propagate more slowly, with phase velocities of 50–250ms−1. Modern understanding is that medium-scale TIDs are caused by both AGWs and ionospheric processes, while large-scale TIDs result mainly from magnetosphere–ionosphere coupling processes (Hunsucker, 1982; Hocke and Schlegel, 1996).



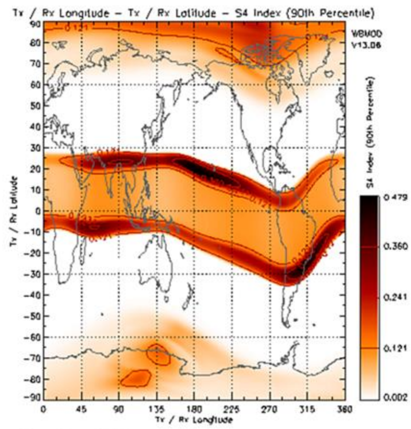
Ionospheric scintillation to radio signals is very similar as atmospheric scintillation to visible light
Atmospheric scintillation: http://www.islandnet.com/~see/weather/elements/twinkle.htm
The technical term for twinkling is scintillation, the rapid variation in apparent position, colour or brightness of a luminous object when viewed through a turbulent media, in this case, the atmosphere. Stars, as we know, are large masses of glowing gas similar to our sun, but they are located so far away that they appear to us as bright pin-points. Their light travels relatively straight and true across the light-years of interstellar space, reaching the top of Earth's atmosphere as a steady point of light (how they would appear to viewers on the International Space Station). When starlight enters the relatively dense atmosphere (compared to the vacuum of space), its rays are diverted from their direct path by changes in air density on their way toward the surface. This is called refraction.

Figures and text from SWS: http://www.sws.bom.gov.au/Satellite/6/3

What is Ionospheric Scintillation?
Ionospheric scintillation is a rapid fluctuation of radio-frequency signal phase and/or amplitude, generated as a signal passes through the ionosphere. Scintillation occurs when a radio frequency signal in the form of a plane wave traverses a region of small scale irregularities in electron density. The irregularities cause small-scale fluctuations in refractive index and subsequent differential diffraction (scattering) of the plane wave producing phase variations along the phase front of the signal. As the signal propagation continues after passing through the region of irregularities, phase and amplitude scintillation develops through interference of multiple scattered signals.
The figure shows "WBMOD" model predictions of the 90th percentile S_4 index at 2300 Local Time (everywhere) at the Southern Hemisphere's autumnal equinox (DOY 091) for GPS L1 (1575.42MHz), low magnetic activity (Kp=1) and high solar activity (SSN=150). Apart from the two strong scintillation bands following ~15° geomagnetic latitude contours, also obvious is the enhanced scintillation between the two bands of maxima and in the polar regions. The mid- latitude regions are relatively free of scintillation, especially at GHz frequencies, however at lower frequencies, closer to 100MHz there can at times be significant scintillation activity.
In terms of diurnal distribution, equatorial ionospheric scintillation generally peaks several hours after dusk
Also at NOAA/SWPC: https://www.swpc.noaa.gov/phenomena/ionospheric-scintillation
Ionospheric scintillation is the rapid modification of radio waves caused by small scale structures in the ionosphere. Severe scintillation conditions can prevent a GPS receiver from locking on to the signal and can make it impossible to calculate a position. Less severe scintillation conditions can reduce the accuracy and the confidence of positioning results.
Scintillation of radio waves impacts the power and phase of the radio signal. Scintillation is caused by small-scale (tens of meters to tens of km) structure in the ionospheric electron density along the signal path and is the result of interference of refracted and/or diffracted (scattered) waves. Scintillation is usually quantified by two indexes: S4 for amplitude scintillation and … / …

Ionospheric scintillation

- Rapid fluctuations radio signal
  - Phase and intensity
    - May result in signal loss
- Source
  - Small scale irregularities in e^- density
  - Quantification
    - Amplitude: S4 index
      - Low (<0.3) to High (>0.6)
    - Phase: σ_ϕ index
- Locations
  - Equatorial anomaly
  - Polar regions
- Difficult to predict



Credits: SWS

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… / … σϕ (sigma-phi) for phase scintillation. The indexes reflect the variability of the signal over a period of time, usually one minute. Scintillation is more prevalent at low and high latitudes, but mid-latitudes, such as the United States, experience scintillation much less frequently. Scintillation is a strong function of local time, season, geomagnetic activity, and solar cycle but it also influenced by waves propagating from the lower atmosphere.

Also at Inside GNSS, Kintner et al. (2009): GNSS and Ionospheric Scintillation How to Survive the Next Solar Maximum http://www.insidegnss.com/node/1579 or http://www.insidegnss.com/auto/julyaug09-kintner.pdf

What Is Scintillation?

Scintillation is a form of space-based multipath. Instead of radio waves reflecting from nearby surfaces and then adding at the antenna, a planar radio wave strikes a volume of irregularities, and then emerges as a surface of nearly constant amplitude but variable phase. The variable phase is introduced by the varying TEC along different signal paths. …

Because the ionosphere is the densest and the thickest in two bands surrounding the magnetic equator, as shown in Figure 1, this is where scintillation is most intense. At high latitudes, the threat to GPS comes during magnetic storms in which blobs of ionosphere from the dayside are swept over the polar cap onto the nightside. During the last solar maximum, magnetic storms were observed to fatten the ionosphere over the dayside United States and then carry blobs of it over the North Pole and polar cap into Europe.

Also at SWS (Australia) : http://www.sws.bom.gov.au/Satellite/1/1

The graphs on this page show ionospheric Scintillation indices over the last 24 hours, as measured by SWS Ionospheric Scintillation Monitor (ISM) sites. In each graph, the signal from each of the 31 active GPS satellites is shown with a different colour.

Graphs in the left hand column display amplitude scintillation, a measure of the short timescale fluctuation in the signal to noise. This is quantified by the S4 index. Values over ~0.6 indicate strong scintillation which can cause loss of lock on a GPS signal. A scintillation index below 0.3 is unlikely to have any affect on GPS. Amplitude scintillation seen in the Darwin and Weipa scintillation monitors is commonly due to an ionospheric phenomena called "plasma bubbles".

Graphs in the right hand column show phase scintillation, a measure of the short timescale fluctuation in the phase of the GPS signal. This is quantified by σ60, the standard deviation of the signal phase in radians, over 60 second intervals. Phase scintillation seen in the Macquarie Island scintillation monitor is generally a sign of auroral activity.

Scintillation maps can be found at the ESA page http://swe.ssa.esa.int/web/guest/swaci-federated (SWACI/DLR)

Also at INGV / Roma2: http://roma2.rm.ingv.it/en/themes/11/ionospheric_scintillation

Also at SWS (Australia) : http://www.sws.bom.gov.au/Satellite/1/1

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- GNSS
  - What & How
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  - Error remedies
- ROB/RMI GNSS products

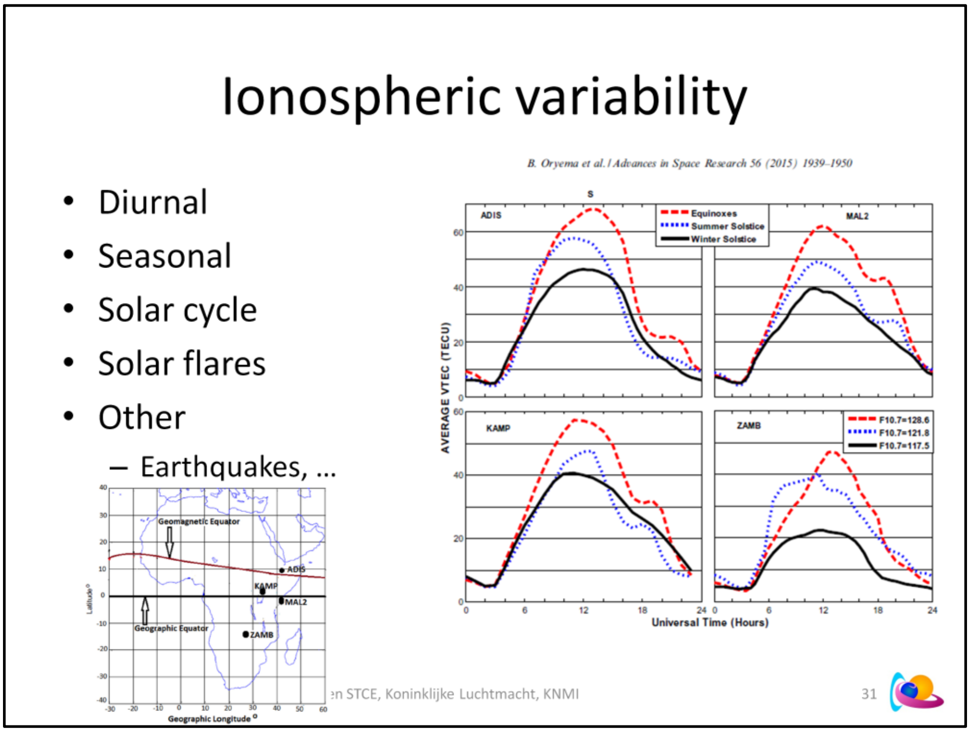

Figure from Oryema (2015): Investigation of TEC variations over the magnetic equatorial and equatorial anomaly regions of the African sector
https://www.sciencedirect.com/science/article/pii/S0273117715003774

High TEC values recorded in the equinoctial months can be attributed to have been caused by changes in the sun's position (Adewale et al., 2012). During equinoctial months, the sun is overhead the equator and temperature at the equator are hotter than at the pole. This makes thermospheric meridional wind blow towards the poles from the equator. This meridional wind changes the neutral composition and O/N2 ratio increases at equatorial and low latitude regions (due to stronger effect of wind transport during high solar activity) (Kherani et al., 2013). Increase in O/N2 ratio results in higher electron density and therefore during equinoxes, equatorial ionization anomaly is expected to be more developed than during the solstices. This is referred to as semi-annual variation.
This mechanism works perfectly for solar maximum periods because of high wind effectiveness due to high rate of photoionization. The semi-annual variation of the EIA could also be due to the combined effect of the solar zenith angle and geomagnetic field effects (Torr and Torr, 1973; Wu et al., 2004). The low TEC values recorded over all stations during winter solstice is expected. This is because in winter solstice, the rate of photoionization at the equator decreases and fountain effect becomes weak (Olusegun, 2013).
For all the seasons considered, TEC has higher values during day-time compared with nighttime values over all the stations. Aggarwal (2011) explained this in terms of recombination of ionized particles in the ionosphere. During daytime as the temperature increases, loss rate of ionized particles also increases and when loss rate overcomes the production rate, it results into gradual decrease in TEC. In the evening since the primary source of production is no longer present, TEC values maintain the minimum values. …
TEC values measured at the equatorial crest regions are usually expected to be higher than the values measured at equatorial trough region (Bhuyan and Borah, 2007). This is because of the existence of equatorial fountain effect which lifts and deposits plasma at F-region altitudes around 15 geomagnetic latitudes. However, as can be seen from Fig. 4, ADIS station which is located at the trough region recorded higher TEC values than MAL2 and KAMP stations which are closer to the southern crest region. … ZAMB station generally registered low TEC values since it is far beyond the southern equatorial anomaly crest region. …
… As seen from Fig. 2, ADIS station is located close to the trough of the EIA, and yet this study reveals that it recorded an abnormally high TEC value during the high solar activity year 2012. This abnormality could be due to the influence of solar activities. According to Bittencourt et al. (2007), ionospheric TEC values increase with increasing solar activity. This implies that since the year 2012 was at the maximum of solar cycle 24, the global vertical F-region drifts became large during this period. Coupled with the influence of the enhanced ExB vertical drift at the equator, this could have raised further the F-region plasma (Tariku, 2015). This could have delayed the decay time of the plasma, which resulted in an abnormally high-level background density recorded at ADIS station.

Ionospheric variability

- Diurnal
- Seasonal
- Solar cycle
- Solar flares
- Other
  - Earthquakes,…

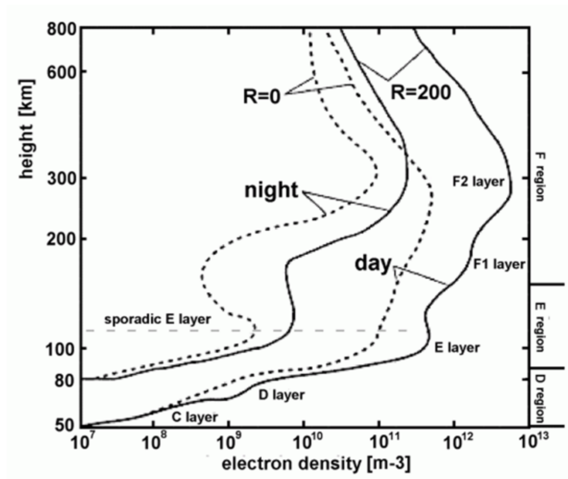

Figure from INGV: http://roma2.rm.ingv.it/en/research_areas/4/ionosphere showing the day-to-night and the solar cycle variation (their Figure 1)

Figure 1 shows typical day and night profiles of electron density in the ionosphere. It shows several regions in which the electron density increases with height (the D, E, and F regions). The existence of different ionospheric regions is caused by the fact that the atmosphere is a mixture of gases that differ in their susceptibility to ionizing radiation, and thus produce maximum ionization at different altitudes. The degree of ionization and height of each ionospheric region vary greatly with time (sunspot cycle, seasonally, and diurnally), with geographical location (polar regions, mid-latitudes, and equatorial regions), and with certain solar-related ionospheric disturbances. In Figure 1, R represents the monthly median solar index.

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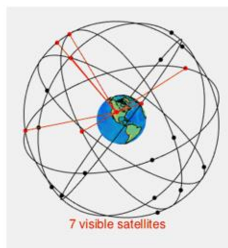
- GNSS
  - What & How
  - Error sources
  - Error remedies
- ROB/RMI GNSS products

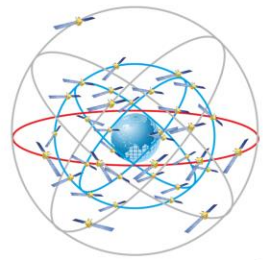
GNSS - Global Navigation Satellite System

GNSS		GPS	Galileo	Glonass	Beidou
Country		USA	EU	Russia	China
Satellites	Ops	31	14	25	15
	Launched	72	24	135	33
Accuracy (metres)	Public	5-10	4-8	4-7	< 10
Frequencies (MHz)	Min.	L2: 1227.60	E5a: 1176.45	G2: 1246	B2: 1207.14
	Max.	L1: 1575.42	E1: 1575.42	G1: 1602	B-1: 1561.098
Orbital height (km)		20180	23222	19130	21528 + GEO + IGSO

India (NAVIC) and Japan (QZSS) have their own regional GNSS.

Accuracy is without the many possible space-/ground-based augmentation systems.





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Situation in February 2018
The number of satellites launched is higher than the operational number, because part of the satellites have been replace (GPS started in 1978!), and a significant part are in storage and/or under testing.

Main article: GNSS applications: https://en.wikipedia.org/wiki/GNSS_applications

Galileo freq. : ESA:
http://www.esa.int/Our_Activities/Navigation/Galileo/Galileo_navigation_signals_and_frequencies

Beidou constellation orbit from https://www.glonass-iac.ru/en/guide/beidou.php
By 2020, the BeiDou orbital constellation will include 35 satellites:
- 5 BeiDou-G satellites in the geostationary orbit (GEO) (58.75° E, 80° E, 110.5° E, 140° E and 160° E);
- 27 BeiDou-M satellites in medium Earth orbit (MEO) (in three planes with the nominal altitude of 21 528 km and nominal period of 12 hours 53 min inclined at 55° relative to the equator);
- 3 BeiDou-I satellites in inclined geosynchronous orbits (IGSO) with the altitude of 35 786 kilometers and an inclination of 55° to the equatorial plane. The sub-satellite tracks for those satellites coincide while the longitude of the intersection point is at 118°E.

How to determine your position with GPS:
NASA Space Place: https://spaceplace.nasa.gov/gps-pizza/en/
Techtitude: http://techtitude.blogspot.be/2010/10/triangulationtrilateration-in-gps.html

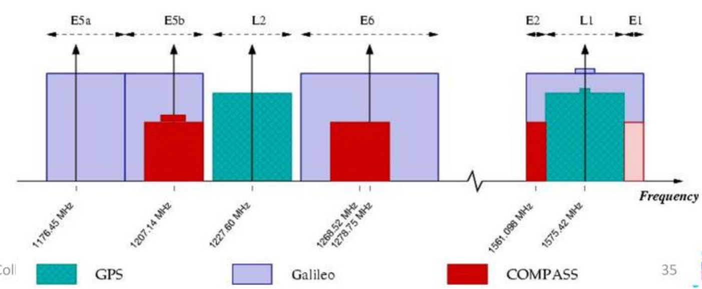
Accuracy of the GNSS systems:
GPS: http://www.navipedia.net/index.php/GPS_Performances
Galileo: http://www.navipedia.net/index.php/GALILEO_Performances
GLONASS: http://www.navipedia.net/index.php/GLONASS_Performances
Beidou: http://www.navipedia.net/index.php/BeiDou_Performances
India: https://en.wikipedia.org/wiki/Indian_Regional_Navigation_Satellite_System
Japan: https://en.wikipedia.org/wiki/Quasi-Zenith_Satellite_System

GNSS - Global Navigation Satellite System

GNSS		GPS	Galileo	Glonass	Beidou
Country		USA	EU	Russia	China
Satellites	Ops	31	14	25	15
	Launched	72	24	135	33
Accuracy (metres)	Public	5-10	4-8	4-7	< 10
Frequencies (MHz)	Min.	L2: 1227.60	E5a: 1176.45	G2: 1246	B2: 1207.14
	Max.	L1: 1575.42	E1: 1575.42	G1: 1602	B-1: 1561.098
Orbital height (km)		20180	23222	19130	21528 + GEO + IGSO

India (NAVIC) and Japan (QZSS) have their own regional GNSS.

Accuracy is without the many possible space-/ground-based augmentation systems.



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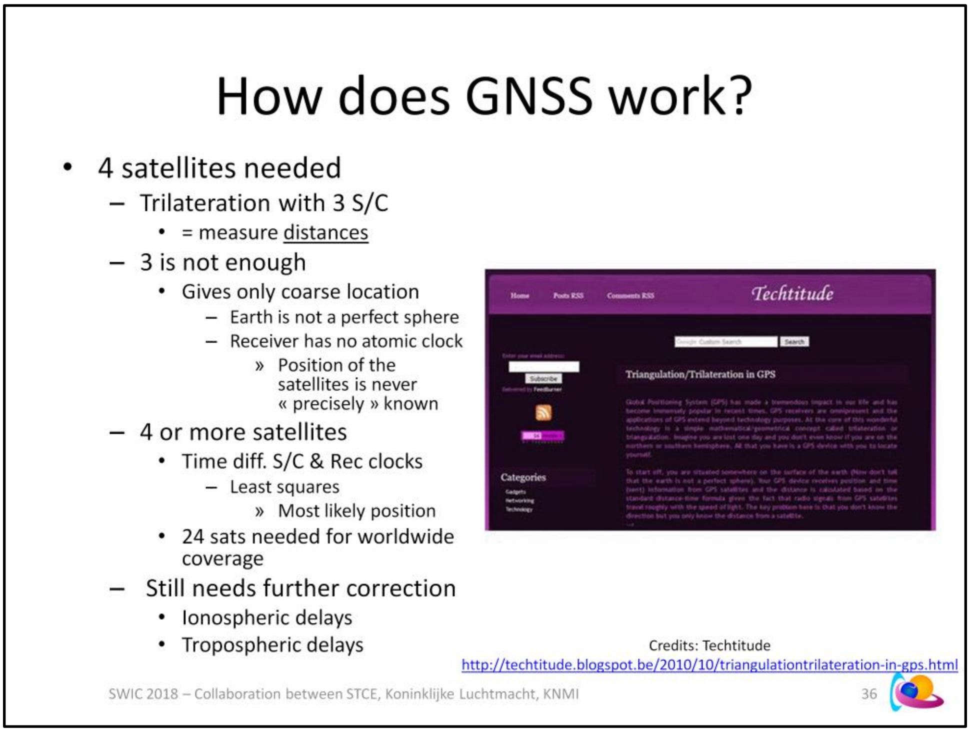
Situation in February 2018

Main article: GNSS applications: https://en.wikipedia.org/wiki/GNSS_applications

Galileo freq. : ESA:
http://www.esa.int/Our_Activities/Navigation/Galileo/Galileo_navigation_signals_and_frequencies

GPS_Galileo_COMPASS: A. Simsky:
https://upload.wikimedia.org/wikipedia/commons/6/64/Gps_compass_galileo_frequency_allocation_Asimsky_05_2008.jpg



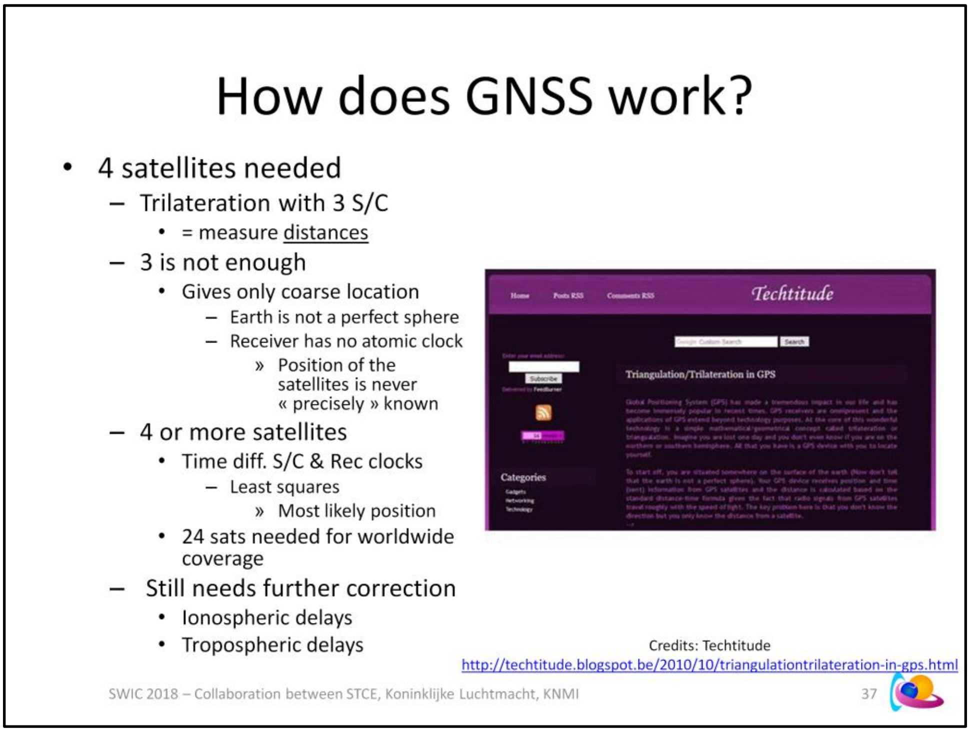
Animation created from Techtitude: http://techtitude.blogspot.be/2010/10/triangulationtrilateration-in-gps.html

To start off, you are situated somewhere on the surface of the earth (Now don't tell that the earth is not a perfect sphere). Your GPS device receives position and time (sent) information from GPS satellites and the distance is calculated based on the standard distance-time formula given the fact that radio signals from GPS satellites travel roughly with the speed of light. The key problem here is that you don't know the direction but you only know the distance from a satellite.

When your GPS device calculates the distance x from satellite say S1, you know that you might be located anywhere on the surface of a sphere of radius x with S1 as the centre. But you don't know in which precise angle you are located in the 360 degrees. Now when your GPS device gets hold of another satellite S2 and calculates the distance y from it, you can apply the geometric principle that spheres intersect in a perfect circle to narrow down your position to somewhere on the perimeter of a circle. Now, the point at which this circle intersects with the earth should give your location on earth. Now when your GPS device calculates the distance z from a third satellite S3, the sphere of radius z with S3 as centre will intersect the circle of intersection of the other two spheres at two points. Only one of those two intersection points will actually lie on the surface of the earth and the other point will lie in space. The point on the surface of the earth will give your location on earth.

GPS satellites transmit time information derived from high accuracy atomic clocks but the GPS receivers cannot afford such high precision clocks. There are several factors that might introduce errors in GPS like clock inaccuracies, rounding errors, multipath and atmospheric effects, etc. Since the earth is also not a perfect sphere, GPS receivers generally look to four or more satellites to compute the precise location.

See also these sites for further explanations:
ROB / GNSS: http://gnss.be/how_tutorial.php
Wikipedia: https://en.wikipedia.org/wiki/Global_Positioning_System#Basic_concept_of_GPS



See also these sites for further explanations:
ROB / GNSS: http://gnss.be/how_tutorial.php
Wikipedia: https://en.wikipedia.org/wiki/Global_Positioning_System#Basic_concept_of_GPS

From the Course « Space Weather for Engineers » (2014) pp. 216:
GNSS (Global Navigation Satellite Systems) positioning is based on measuring the distance to satellites of which the position is accurately known at all times.
If the distance to at least four satellites is known, the receiver can compute its own position and time. The distance is obtained by measuring the travel time of precisely-timed signals transmitted by the GNSS satellites, and multiplying this travel time by the speed of light.

Since GNSS receivers typically do not incorporate accurate time standards, they can only measure the travel time with respect to their unperfect time reference. This introduces an offset in the travel-time measurements, and hence in the distance measurements to the satellites. This is the reason why at least four satellites are required to compute a 3D position fix. A fourth satellite is needed to remove the time offset due to the receiver clock bias. A standalone GNSS receiver is always estimating the time together with its position.

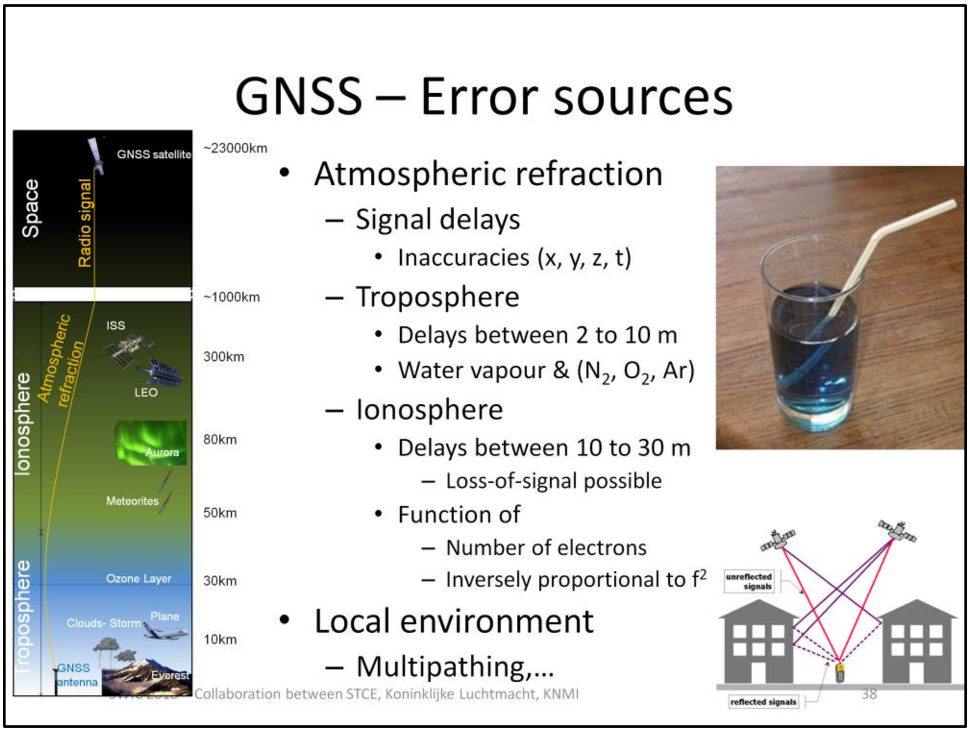


Figure from ROB/GNSS: http://gnss.be/atmosphere_tutorial.php
Figure from http://psychology.wikia.com/wiki/Light_refraction

http://gpsworld.com/innovation-the-european-way/
The local environment may affect the navigation signal in various ways, too, such as signal fading or complete signal blockage by vegetation or obstacles such as buildings, and multipath, where the signal is broadened in the time and frequency domains due to reflections and diffraction by surrounding objects.

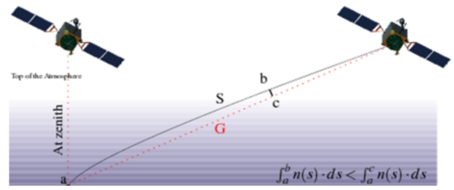
More info on multipathing at Wikipedia: https://en.wikipedia.org/wiki/Multipath_propagation

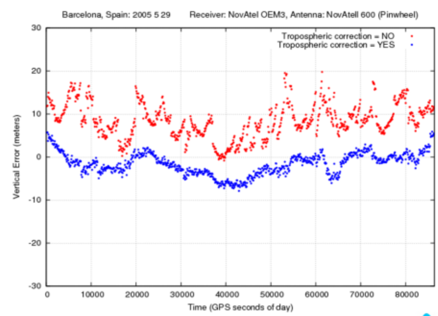
Figure from http://www.jocosarblog.org/jocosarblog/2011/10/gps-multipath-errors-what-they-are-and-why-the-confuse-your-gps.html

GNSS – Error remedies

Troposheric corrections

- Errors are NOT f-dependent
- Models
  - « Dry » atmosphere
    - Main error source (90%)
      - Well modeled from p and T at surface
  - « Wet » atmosphere
    - Water vapour
    - More unpredictable
      - For high-precision navigation
        - » coordinates





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From the GNSS/ROB website at http://gnss.be/troposphere_tutorial.php
And Navipedihttp://www.navipedia.net/index.php/Tropospheric_Delay

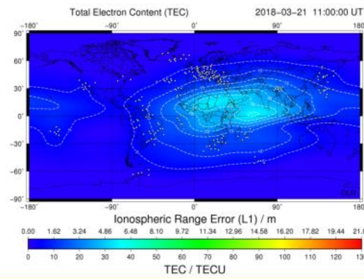
Troposphere is the atmospheric layer placed between earth's surface and an altitude of about 60 kilometres. The effect of the troposphere on the GNSS signals appears as an extra delay in the measurement of the signal traveling from the satellite to receiver. This delay depends on the temperature, pressure, humidity as well as the transmitter and receiver antennas location.
This refractivity can be divided in hydrostatic, i.e., *Dry gases* (mainly N and O), and wet, i.e., *Water vapour*, components. Each of these components has different effects on GNSS signals. The main feature of the troposphere is that it is a non dispersive media with respect to electromagnetic waves up to 15GHz, i.e., the tropospheric effects are not frequency dependent for the GNSS signals. Hence, the carrier phase and code measurements are affected by the same delay.
An immediate consequence of being a non-frequency dependent delay is that the tropospheric refraction can not be removed by combinations of dual frequency measurements (as it is done with the ionosphere). Hence, the only way to mitigate tropospheric effect is to use models and/or to estimate it from observational data. Nevertheless, fortunately, most of the tropospheric refraction (about the 90%) comes from the predictable hydrostatic component.

The dry atmosphere can be modeled from surface pressure and temperature using the laws of the ideal gases. The wet component is more unpredictable and difficult to model, hence for high precision navigation, this delay is estimated together with the coordinates.
The tropospheric delay depends on the signal path through the neutral atmosphere, and thence, can be modeled as a function of the satellite elevation angle. Due to the differences between the atmospheric profiles of the dry gases and water vapour it is better to use different mappings for the dry and wet components. Nevertheless, simple models as [RTCA-MOPS, 2006] use a common mapping for both components.
Several nominal tropospheric models are available in the literature, which differ on the assumptions made on the vertical profiles and mappings. Basically, they can be classified in two main groups: Geodetic-oriented or Navigation-oriented. The first group Sastamoinen, Hopfield, among others [Xu, 2007] are more accurate but generally more complex, and need surface meteorological data, being their accuracy affected by the quality of these data. The second group are less accurate, but meteorological data are not needed.

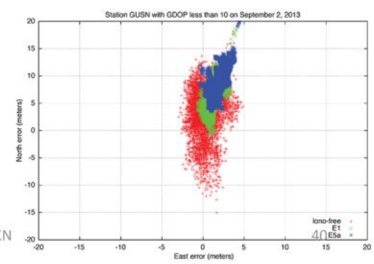
GNSS – Error remedies

Ionospheric corrections

- Errors <u>ARE</u> f-dependent
  - Dual frequency receivers
    - E.g. GPS: L1 and L2
    - Removes most of errors
  - Single frequency receivers
    - Differential Global Positioning System
      - DGPS: RTK, PPP
    - External ionospheric models
      - Global ionospheric maps
      - Klobuchar model
        - » GPS
      - International Reference Ionosphere (IRI)
      - Nequick model
        - » Galileo
        - » Removes 70% of errors



DLR / SWACI : http://swaciweb.dlr.de/data-and-products/



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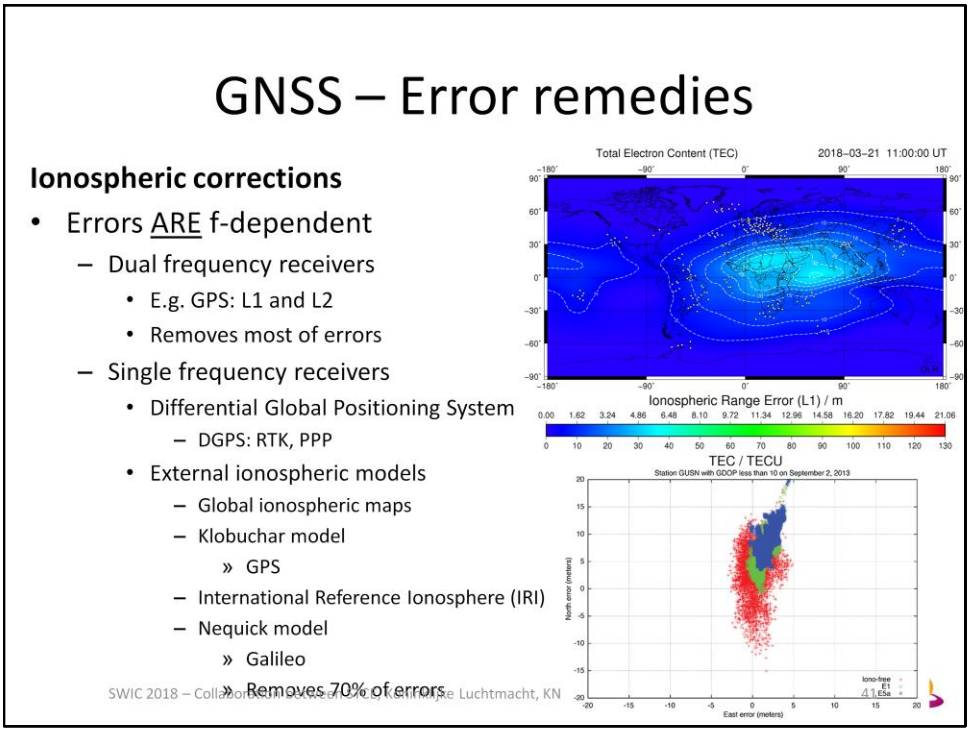
Top Figure from DLR/SWACI: http://swaciweb.dlr.de/fileadmin/PUBLIC/TEC/TEC_GB.png

Bottom figure from GPSWorld: http://gpsworld.com/innovation-the-european-way/
=> Horizontal Galileo In-Orbit-Validation positioning error on E1 and single-frequency NeQuick G correction (blue), E5a and single-frequency NeQuick G correction (red) and dual-frequency E1-E5a ionosphere-free (green) for mid-latitude station in Washington (doy 245, 2013).

From the GNSS/ROB website at http://gnss.be/ionosphere_tutorial.php#x2-40000
And ESA/Navipedia: http://www.navipedia.net/index.php/Ionospheric_Delay
And GPSWorld: http://gpsworld.com/innovation-the-european-way/
Wikipedia (DGPS): https://en.wikipedia.org/wiki/Differential_GPS

Double frequency users
For a given station, the GPS measurements, relative to the observed satellite, on the signal code $P_{1,2}$ and phase $\varphi_{1,2}$, at the two GPS frequencies (f_1=1575.42 MHz and f_2=1227.6 MHz) with corresponding wavelength $\lambda_{1,2}$, …
The first order ionosphere effect, which amounts to 99.9% of the total ionosphere perturbation on GNSS signals, is proportional to the inverse of the square frequency. Hence, when dual frequency GPS receiver is available, the so called "ionosphere-free" combination of the two frequencies code and phase signal … is used to remove thoroughly the first order ionosphere perturbation only…

… / …



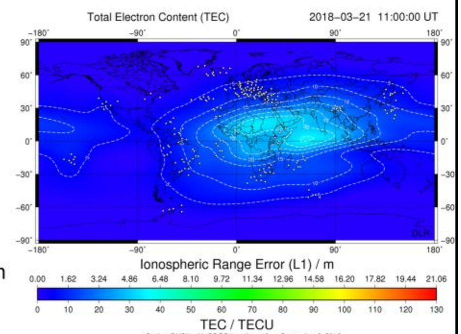
… / …

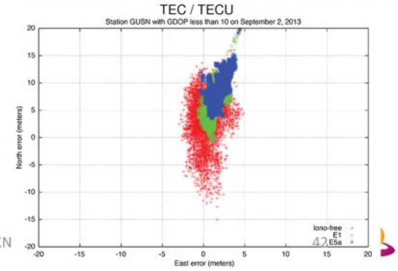
Single frequency users
Concerning single frequency receivers, the user need an external information to correct the signal delay. For that, different methods can be used:
A. The use of a network of nearby fixed stations with well-known positions. The difference between the estimated and predicted position of those reference stations is due to the ionospheric and tropospheric delays, the clock errors, the relativistic effect ... This information is transmitted to the single frequency user to correct its position. The main assumption of this method, called Differential Global Positioning System (DGPS), (See Tutorial on Positioning and Timing)), is to consider that the errors are the same for the reference stations and the single frequency station. … Each DGPS uses a network of fixed ground-based reference stations to broadcast the difference between the positions indicated by the GPS satellite systems and known fixed positions. These stations broadcast the difference between the measured satellite pseudo-ranges and actual (internally computed) pseudo-ranges, and receiver stations may correct their pseudo-ranges by the same amount. The digital correction signal is typically broadcast locally over ground-based transmitters of shorter range. … A similar system which transmits corrections from orbiting satellites instead of ground-based transmitters is called a Wide-Area DGPS (WADGPS) or Satellite Based Augmentation System.

GNSS – Error remedies

Ionospheric corrections

- Errors <u>ARE</u> f-dependent
  - Dual frequency receivers
    - E.g. GPS: L1 and L2
    - Removes most of errors
  - Single frequency receivers
    - Differential Global Positioning System
      - DGPS: RTK, PPP
    - External ionospheric models
      - Global ionospheric maps
      - Klobuchar model
        - » GPS
      - International Reference Ionosphere (IRI)
      - Nequick model
        - » Galileo
        - » Removes 70% of errors





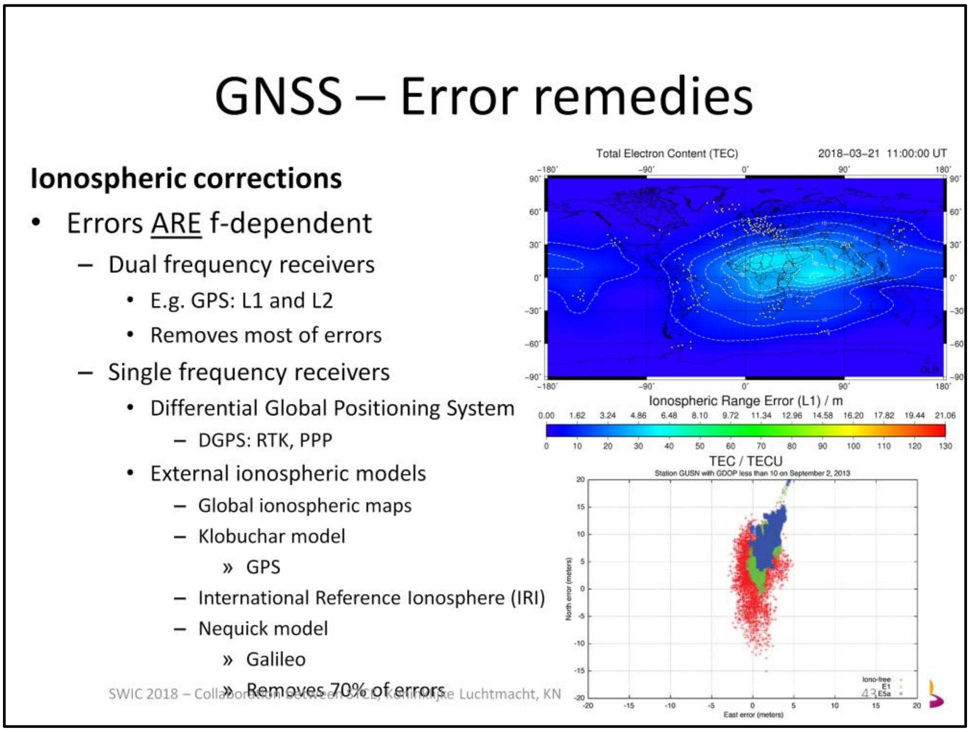
… / …

Single frequency users
Concerning single frequency receivers, the user need an external information to correct the signal delay. For that, different methods can be used:
A. … / …
RTK: Real Time Kinematics is a differential GNSS technique (DGPS). The RTK technique can be used for distances of up to 10 or 20 kilometers, yielding accuracies of a few centimeters in the rover position. RTK is extensively used in surveying applications.
http://www.navipedia.net/index.php/Real_Time_Kinematics

Network real-time kinematic (RTK) positioning is a processing technique in which a single user receiver receives supporting data about several types of GNSS error sources from a network of receivers (Frodge et al. 1994; Rizos 2003). This allows the user receiver to eliminate a large part of the errors in the signal and thus achieve an accurate position solution in real-time.
Jacobsen et al. (2016), Overview of the 2015 St. Patrick's day storm and its consequences for RTK and PPP positioning in Norway
http://adsabs.harvard.edu/abs/2016JSWSC...6A...9J

PPP: Precise Point Positioning is also a differential GNSS technique (DGPS). However, the difference with RTK is that it does not require access to observations from one or more close reference stations accurately-surveyed and that PPP provides an absolute positioning instead of the location relative to the reference station as RTK does. PPP just requires precise orbit and clock data, computed by a processing centre with measurements from reference stations from a relatively sparse station network (thousands of km apart would suffice). This makes PPP a very attractive alternative to RTK for those areas where RTK coverage is not available. On the contrary, the PPP technique is still not so much consolidated as RTK and requires a longer convergence time to achieve maximum performances (in the order of tens of minutes). Combining the precise satellite positions and clocks with a dual-frequency GNSS receiver (to remove the first order effect of the ionosphere), PPP is able to provide position solutions at centimeter to decimeter level.
http://www.navipedia.net/index.php/Precise_Point_Positioning

Precise Point Positioning (PPP) is a single receiver processing strategy for GNSS observations that enables the efficient computation of high-quality coordinates, utilizing undifferenced dual-frequency code and phase observations by using precise satellite orbit and clock data products.
Jacobsen et al. (2016), Overview of the 2015 St. Patrick's day storm and its consequences for RTK and PPP positioning in Norway
http://adsabs.harvard.edu/abs/2016JSWSC...6A...9J



Single frequency users

Concerning single frequency receivers, the user need an external information to correct the signal delay. For that, different methods can be used: …

B. The use of an external ionospheric model to correct the signal delay. Many models are now available: Global Ionospheric Maps, Klobuchar, IRI 2007 and the Nequick model. A description of these models is given at the end of this tutorial.

The delays on radio signals travelling through the ionosphere are directly proportional to STEC. Consequently, single frequency users can correct for the ionospheric delay by TEC estimation. Several products are now available to estimate the TEC every where and at any time.

<u>Global Ionospheric Maps (GIM)</u>:

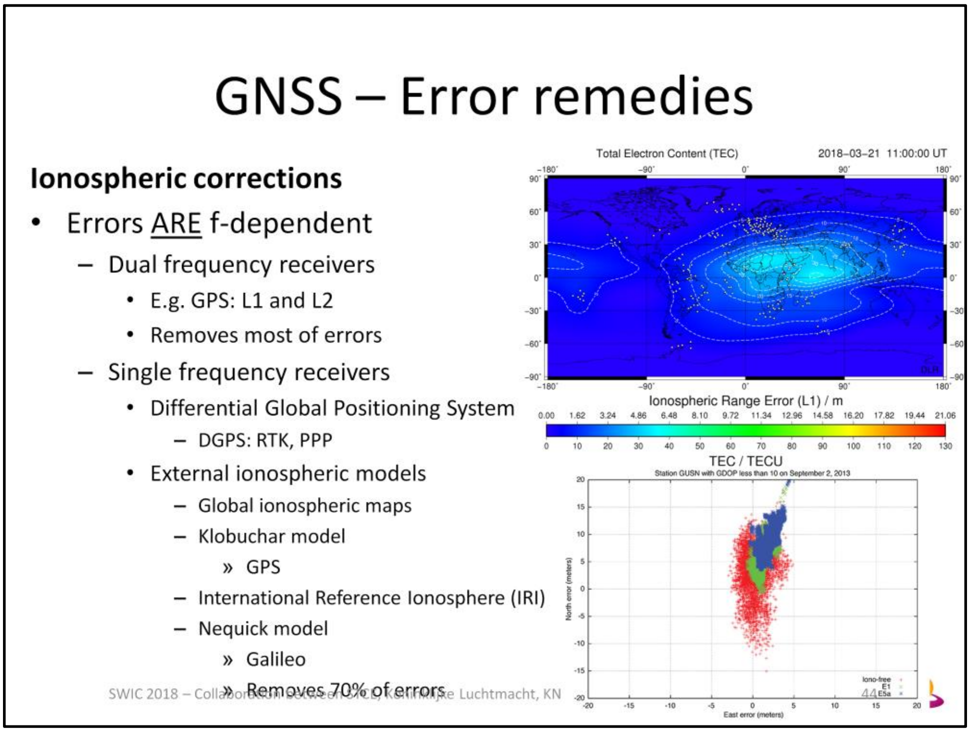
NASA: https://iono.jpl.nasa.gov//latest_rti_global.html

DLR (SWACI): http://swaciweb.dlr.de/data-and-products/public/tec/tec-global/?L=1

<u>Klobuchar</u>: http://gpsworld.com/innovation-the-european-way/

However, single-frequency devices such as most vehicle navigation and handheld receivers don't have the luxury of dual-frequency correction. These devices must rely on a single-frequency correction model. The coefficients for such a model are included in the navigation messages transmitted by all GPS satellites. Known as the Ionospheric Correction Algorithm or Klobuchar Algorithm, it removes at least 50 percent of the ionosphere's effect.

… / …



Single frequency users

Concerning single frequency receivers, the user need an external information to correct the signal delay. For that, different methods can be used: …

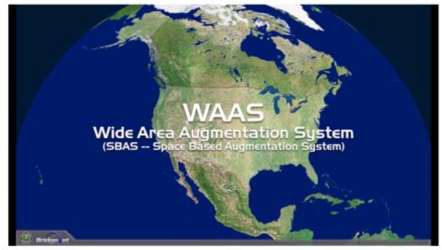
B. … / …

<u>IRI 2007 model</u>: The International Reference Ionosphere (IRI) (http://ccmc.gsfc.nasa.gov/modelweb/models/iri_vitmo.php) This model [e.g. Bilitza and Reinisch, 2008] is an empirical model based on a wide range of ground and space data. It gives monthly averages of electron density, ion composition (O^+, H^+,N^+,He^+, O^+_2,NO^+ and *Cluster*$^+$), ion temperature and ion drift in the altitude range 50-1500 km in the non-auroral ionosphere.

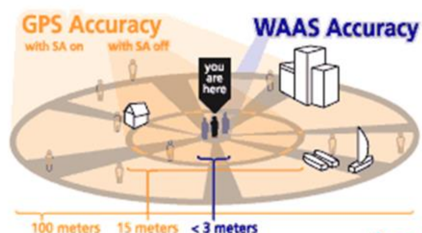
<u>Nequick</u>: The Galileo satellites also include the parameters of an ionospheric algorithm, called NeQuick G, in their navigation messages. … The original NeQuick model is a three-dimensional and time-dependent ionospheric electron density model based on an empirical climatological representation of the ionosphere, which predicts monthly mean electron density from analytical profiles, depending on solar-activity-related input values: sunspot number or solar flux, month, geographic latitude and longitude, height and UT. It allows us to calculate the TEC through numerical integration of electron density along a path between a beginning and an end point crossing the ionosphere. … The NeQuick model has been adapted for Galileo single-frequency ionospheric corrections (for convenience, the Galileo version is known as NeQuick G) in order to derive real-time predictions based a single input parameter, *Az*, which is determined using three coefficients broadcast in the navigation message. … The performance of the Galileo single-frequency ionospheric algorithm, designed to reach a correction capability of at least 70 percent of the ionospheric code delay, … It is observed that even for the "bad" day, the correction capability is above 70 percent, except for some stations in the equatorial regions.

GNSS – Augmentation systems

- Space Based Augmentation Systems (SBAS)
  - Based on corrections from ground-based stations
  - Use of GEO sats to distribute corrections
  - Significantly higher accuracy
    - Typical GPS: 15 metres
    - Typical DGPS: 3-5 metres
    - Typical WAAS: < 3 metres



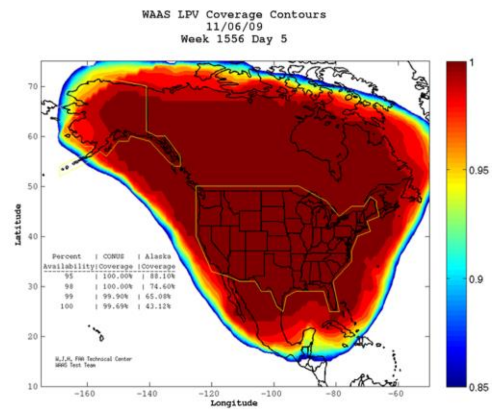
Credits: FAA



Info from and full movie at FAA:
https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas/howitworks/

GNSS – Augmentation systems

- Space Based Augmentation Systems (SBAS)
  - Systems
    - WAAS (USA)
    - EGNOS (Europe)
    - MSAS (Japan)
    - GAGAN (India)
  - Remaining problems
    - High latitude locations?
    - Expensive GPS receiver
      - > $10K
- Ground Based Augmentation System (GBAS)
  - LAAS
    - Local²
  - RTK & PPP



WAAS: **Wide Area Augmentation System**
Wikipedia: https://en.wikipedia.org/wiki/Wide_Area_Augmentation_System
Garmin: https://www8.garmin.com/aboutGPS/waas.html

EGNOS: **European Geostationary Navigation Overlay Service**
Wikipedia: https://en.wikipedia.org/wiki/European_Geostationary_Navigation_Overlay_Service
ESA: http://www.egnos-pro.esa.int/
ESA: http://www.esa.int/Our_Activities/Navigation/EGNOS/What_is_EGNOS

LAAS: **Local Area Augmentation System**
Wikipedia: https://en.wikipedia.org/wiki/Local-area_augmentation_system

Avionics: http://www.aviationtoday.com/2011/11/01/precision-approaches/
In very broad terms, the basic concepts of the two systems are similar — each uses a dedicated network of precision GPS monitor receivers dispersed at separate, accurately surveyed locations. In both cases each individual monitor's incoming "raw" GPS signals are compared with their precisely known positions to determine the actual errors and, ultimately, the correction that should be applied to a user's receiver at a given location. Only then do the similarities between LAAS and WAAS diverge, due to the way the corrections reach the user's receivers. In WAAS, a large number of monitors across North America pass their data to a satellite ground station that then continuously loft the corrections up to a geostationary satellite. In turn, the satellite re-transmits them down to all receivers within view, which automatically applies them to their own raw GPS data. In LAAS, which usually employs just four local monitors, the corrections are computed locally and transmitted over a VHF data link to aircraft in the local airspace where, again, the corrections are applied automatically. In both cases, however, the two systems offer the unique capability — assuming obstacle clearance and other airport conditions are met — of being able to provide precision approach service to all an airport's runways. Furthermore, the LAAS ground station and its supporting monitoring receivers and antennas can be located well away from the runway areas, while WAAS needs neither airport ground equipment nor special avionics. … WAAS became the Satellite Based Augmentation System (SBAS), and LAAS became the Ground Based Augmentation System (GBAS).

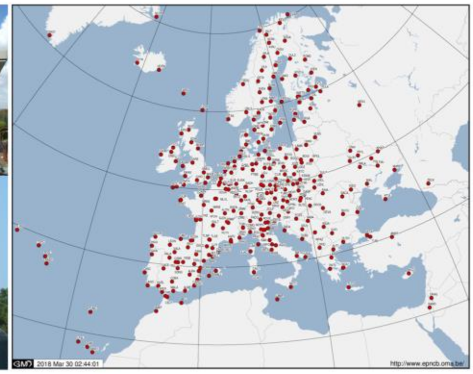
The ionosphere - Contents

- Introduction
- Units and Terminology
  - TEC, foF2, Ionogram, MUF,…
- Main features
  - Coupling magnetosphere
  - EIA, EPB, TID
  - Ionospheric scintillation
- Ionospheric variability
- GNSS
  - What & How
  - Error sources
  - Error remedies
- ROB/RMI GNSS products

ROB – GNSS products

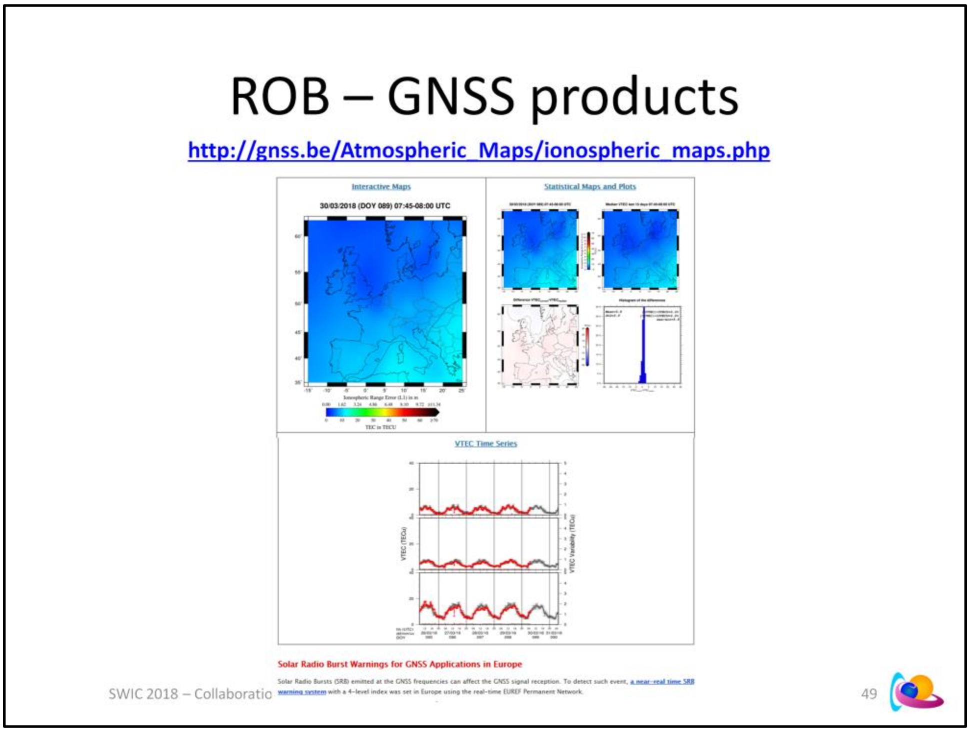
ROB GNSS antenna on telescope dome

EUREF Permanent GNSS Network



Technical details on the ROB GNSS station
http://epncb.oma.be/_networkdata/siteinfo4onestation.php?station=BRUX00BEL

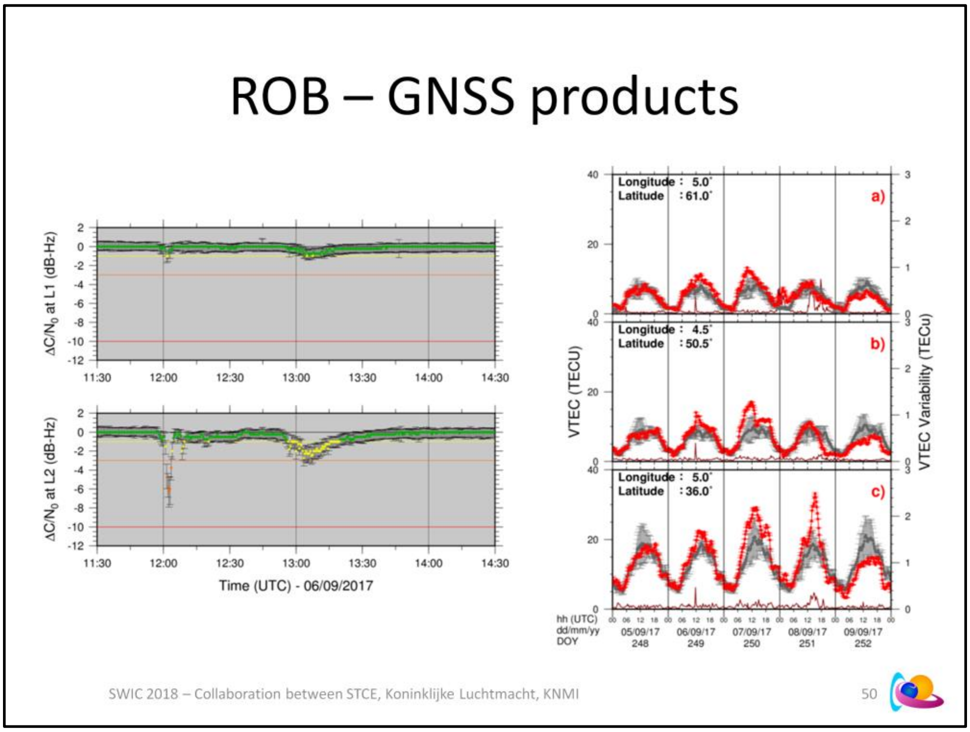
Details on the EUREF Permanent GNSS Network
http://epncb.oma.be/
The EUREF Permanent GNSS Network consists of a network of continuously operating GNSS reference stations, data centres providing access to the station data, analysis centres that routinely analyze the GNSS data, product centres or coordinators that generate the EPN products, and a Central Bureau that is responsible for the daily monitoring and management of the EPN.
All contributions to the EPN are provided on a voluntary basis, with more than 100 European agencies/universities involved. The EPN operates under well-defined international standards and guidelines which are subscribed by its contributors. These guidelines guarantee the long-term quality of the EPN products.



NRT and GNSS products and descriptions can be found at
http://gnss.be/Atmospheric_Maps/ionospheric_maps.php

Near-Real Time Ionospheric Products
Vertical Total Electron Content (VTEC) estimated in Near Real-Time (NRT) every 15 minutes from EUREF Permanent Network (EPN) GPS data.

- Interactive Maps: display animated VTEC maps (movie) for a requested period and VTEC value at a given location and time. (4-5 sec to load).
- Statistical Maps and Plots: statistics to compare the ionosphere for a requested time with respect to the 15 previous days.
- VTEC Time Series: the VTEC evolution over time and its median of the 15 previous days (24h prediction), extracted from the VTEC maps at 3 different locations (North of Europe, Brussels and South of Europe). A weekly overview can also be found in the STCE Newsletter at http://www.stce.be/newsletter/newsletter.php
- Data are publicly available in IONEX format at ftp://gnss.oma.be/gnss/products/IONEX/. We request that users include a citation or an acknowledgment when using ROB VTEC data or products results in a publication. See disclaimer and copyright for more information.



Solar Radio Burst Event 2017-09-06
http://gnss.be/Atmospheric_Maps/srb_event.php?date=2017-09-06

SUMMARY OF THE EVENT: The solar radio bursts of the 06/09/2017 impacted the GPS signal reception at both frequencies L1 and L2. On L1, two fades above 1dB-Hz were detected at 12h01 and 12h05. On L2, a first fade above 3dB-Hz which could potentially affect the GNSS application, occurred for 3 min with a maximum of -6.25±1.6dB-Hz at 12h02. It was followed by a second lower fade above 1dB-Hz at 13h03. For additional information about the burst on a larger frequency spectrum see at SIDC Humain Radioastronomy Station.

Figure [left] shows the abnormal evolution of the carrier-to-noise density (C/N0) from the EPN real-time GNSS network at L1 and L2 frequencies. Monitoring C/N0 fades over the whole EPN network allows detecting Solar Radio Burst (SRB) affecting the GNSS signal reception at 4 levels: quiet (green) ; moderate (yellow) : SRB detected but should not impact GNSS applications ; strong (orange) : potential impact on GNSS applications ; severe (red) : potential failure of the GNSS receivers.

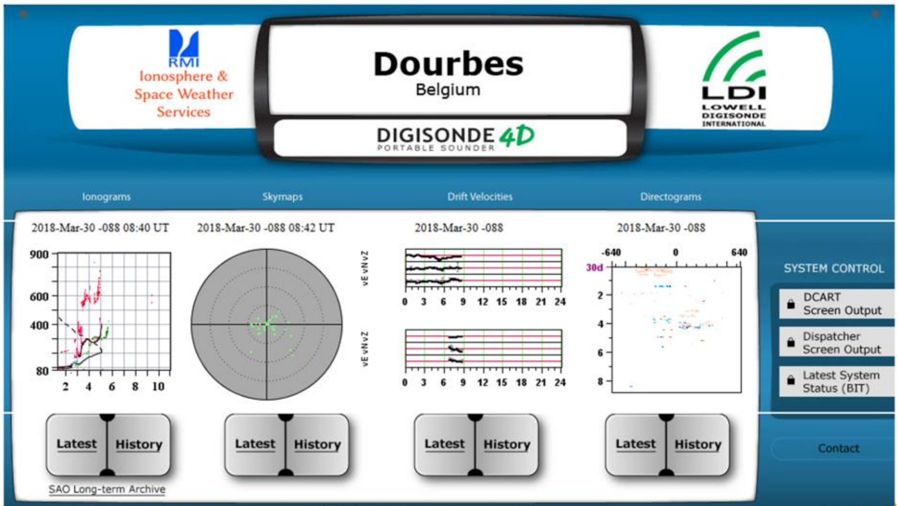
Ionospheric Event 2017-09-07
http://gnss.be/Atmospheric_Maps/ionospheric_event.php?date=2017-09-07

SUMMARY OF THE EVENT: A solar flare occurred the 6/09/2017 generating a sudden small increase of TEC at noon with higher variability of TEC. The next days, the arrival of the CME generated disturbances in the North during nighttime of the 7/09/2017 and at the end of the day 07/09/2017. An increase of TEC was also observed in the South the 07 and 08/09/2017. A depletion of TEC followed the following day 09/09/2017.

Figure [right] shows the time evolution of the Vertical Total Electron Content (VTEC) (in red) extracted from the near-real time VTEC maps at 3 different latitudes. … Also shown, the model based on the median from the 15 previous days (in grey) with its standard deviation represented as error bars and the VTEC variability (the dark red line). The VTEC variability is not the ROTI, but the variation of the VTEC at the Ionospheric Piercing Points (IPP) during the 15 minutes of time span.

RMI – GNSS products

http://digisonde.oma.be/



Summary

- Ionosphere is key element in
  - Radio communication
    - Satellites, Ground
  - Navigation
- Essential parameters
  - TEC, foF2, MUF, Ionogram,…
- Variable
  - Short to long timeframes
  - Solar activity dependent
    - Solar flares, ICMEs,…
  - EIA, EPB, TID, Scintillation
- GNSS
  - Various augmentation systems
    - WAAS, EGNOS, …