SPACE WEATHER INTRODUCTORY COURSE

Collaboration of

Solar-Terrestrial Centre of Excellence

Koninklijke luchtmacht

Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

The Magnetosphere

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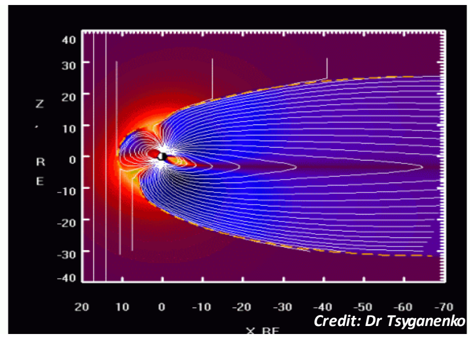
Animation made by Vincent van Leijen: http://fotovins.blogspot.be/2014/03/nl-in-nl.html
Concerns polar light observed on 27 February 2014

The magnetosphere

- ...that area of space, around a planet, that is controlled by the planet's magnetic field.
- Its ... shape is the direct result of being blasted by solar wind.
- Field lines connect the magnetosphere with the ionosphere



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Definition from NASA: https://www.nasa.gov/mission_pages/sunearth/science/magnetosphere2.html

Animation from https://commons.wikimedia.org/wiki/File:Animati3.gif

Created by Dr Tsyganenko (NASA)
More info and animations at http://geo.phys.spbu.ru/~tsyganenko/modeling.html

Note that planets without a (strong) intrinsic magnetic field have an “induced magnetosphere”, for which the above defintion obviously is not applicable. However, this is also not the focus of this lecture, which will consider the earth environment only.

“Induced magnetospheres” by Luhmann et al. (2004)
https://www.sciencedirect.com/science/article/pii/S0273117704000158
Induced magnetospheres occur around planetary bodies that are electrically conducting or have substantial ionospheres, and are exposed to a time-varying external magnetic field. They can also occur where a flowing plasma encounters a mass-loading region in which ions are added to the flow. In this introduction to the subject we examine induced magnetospheres of the former type. The solar wind interaction with Venus is used to illustrate the induced magnetosphere that results from the solar wind interaction with an ionosphere.

The Magnetosphere - Contents

- The geomagnetic field
- Main features
- Geomagnetic (sub)storms
- Measuring magnetic fields
  - Geomagnetic indices
  - Networks
- Miscellaneous

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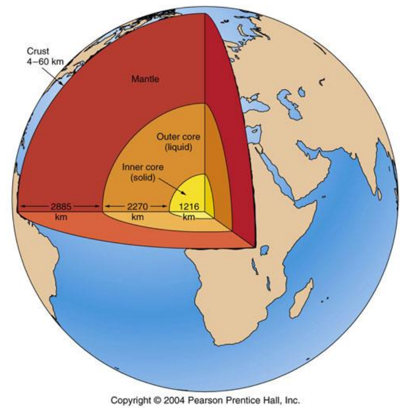
The geomagnetic field

- Created in and by the Earth’s interior



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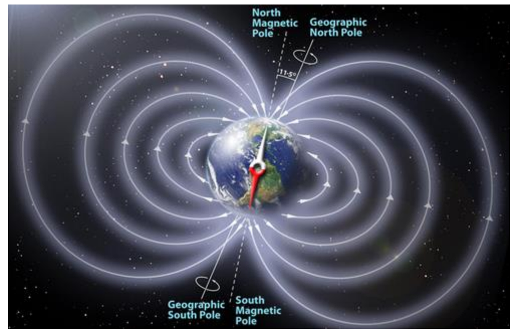
From Wiki: https://en.wikipedia.org/wiki/Earth%27s_magnetic_field#Physical_origin
The Earth's magnetic field is believed to be generated by electric currents in the conductive material of its core, created by convection currents due to heat escaping from the core. However the process is complex, and computer models that reproduce some of its features have only been developed in the last few decades.
The interior **structure of the Earth** is layered in spherical shells: an outer silicate solid crust, a highly viscous mantle, a liquid outer core that is much less viscous than the mantle, and a solid inner core.

The geomagnetic field

- Created in and by the Earth's interior
- Dipole *(not perfect)*
  - In absence of disturbances
  - Enters north pole (-), leaves at south pole (+)
  - Intensity:
    - 25000 – 65000 nT
    - Weakest at equator
    - Strongest at poles



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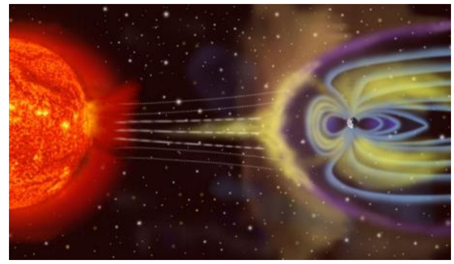
From Wiki: https://en.wikipedia.org/wiki/Earth%27s_magnetic_field#Main_characteristics
The interior **structure of the Earth** is layered in spherical shells: an outer silicate solid crust, a highly viscous mantle, a liquid outer core that is much less viscous than the mantle, and a solid inner core.
By comparison, a strong refrigerator magnet has a field of about 10,000,000 nanoteslas

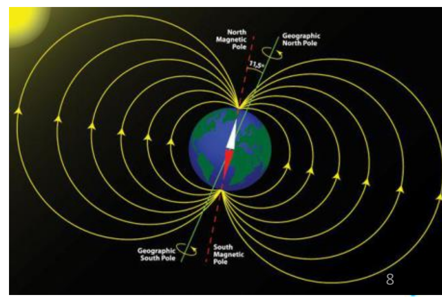
Also at http://www.unc.edu/depts/oceanweb/turtles/geomag.html

Note that the « entering » or « leaving » of magnetic field lines is not a physical reality, but entirely a matter of definition.

The geomagnetic field

- Due to solar wind
  - Drop shape
    - 10 R_E at dayside
    - >200 R_E at nightside
- Magnetic axis
  - 11° tilt wrt Earth's rotational axis
    - Compass does NOT point to true north
  - 500 km offset to north
    - Weakness over Brazil





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From Wiki: https://en.wikipedia.org/wiki/Earth%27s_magnetic_field#Magnetosphere
Earth's magnetic field, predominantly dipolar at its surface, is distorted further out by the solar wind. This is a stream of charged particles leaving the Sun's corona and accelerating to a speed of 200 to 1000 kilometres per second. They carry with them a magnetic field, the interplanetary magnetic field (IMF).

The solar wind exerts a pressure, and if it could reach Earth's atmosphere it would erode it. However, it is kept away by the pressure of the Earth's magnetic field. The magnetopause, the area where the pressures balance, is the boundary of the magnetosphere. Despite its name, the magnetosphere is asymmetric, with the sunward side being about 10 Earth radii out but the other side stretching out in a magnetotail that extends beyond 200 Earth radii.

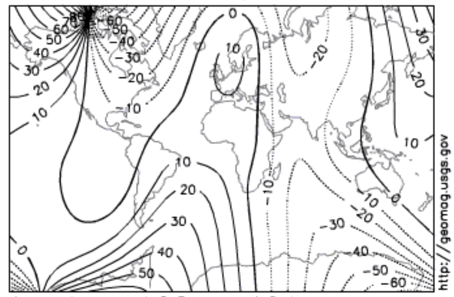
See also at NASA:
https://www.nasa.gov/audience/forstudents/postsecondary/features/29dec_magneticfield.html

From Wiki: https://en.wikipedia.org/wiki/Earth%27s_magnetic_field
Roughly speaking it is the field of a magnetic dipole currently tilted at an angle of about 11 degrees with respect to Earth's rotational axis, as if there were a bar magnet placed at that angle at the center of the Earth. The North geomagnetic pole, located near Greenland in the northern hemisphere, is actually the south pole of the Earth's magnetic field, and the South geomagnetic pole is the north pole.

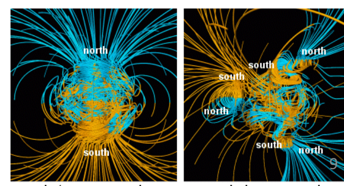
The geomagnetic field

- Continuously changing
  - Short-term
    - Slow enough that compass remains useable
      - Airport runways
  - Long-term
    - Polar field reversals
      - MF does NOT disappear
      - Slow
      - Frequency: +/- 450000 years
        - » 250000 years overdue
      - Compare to Sun: 11^y !!

1590
Declination (degrees east)



Model by A. Jackson, A. R. T. Jonkers, M. R. Walker, Phil. Trans. R. Soc. London A (2000), 358, 957–990.



between reversals during a reversal

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Another good view on Earth’s changing magnetic field is at http://wdc.kugi.kyoto-u.ac.jp/igrf/anime/index.html

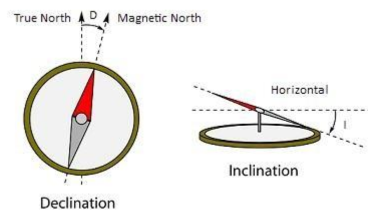
Stassinopoulos et al. (2015) - Forty-Year "Drift" and Change of the SAA
https://ntrs.nasa.gov/search.jsp?R=20160003393
The SAA is really not an “anomaly” at all, but an apparent local depression of the Earth's magnetic field. When first observed, the SAA was considered an “anomaly” of the field, an aberration [1]. Later, the SAA was defined as stemming from the tilt, the eccentricity, and the displacement of the dipole axis from the center of the Earth i.e. the SAA is determined by (a) the tilt of the magnetic dipole axis to the axis of rotation (approximately ~11 degrees), (b) and is considered eccentric because it does not pass through the center of the planet, and (c) is displayed (by about 500 km) away from the center towards the North Pacific, thus producing a weaker magnetic field over Brazil and a stronger field over the North Pacific.

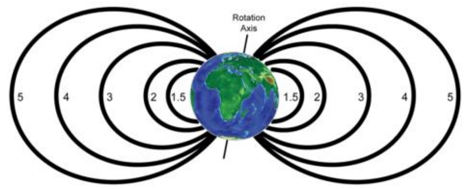
From NASA: https://www.nasa.gov/audience/forstudents/postsecondary/features/29dec_magneticfield.html
The magnetic field waxes and wanes, poles drift and, occasionally, flip. Change is normal, they've learned. And no wonder. The source of the field, the outer core, is itself seething, swirling, turbulent. "It's chaotic down there," notes Glatzmaier. The changes we detect on our planet's surface are a sign of that inner chaos.
They've also learned what happens during a magnetic flip. Reversals take a few thousand years to complete, and during that time--contrary to popular belief--the magnetic field does not vanish. "It just gets more complicated," says Glatzmaier. Magnetic lines of force near Earth's surface become twisted and tangled, and magnetic poles pop up in unaccustomed places. A south magnetic pole might emerge over Africa, for instance, or a north pole over Tahiti. Weird. But it's still a planetary magnetic field, and it still protects us from space radiation and solar storms.

Airports Keep Renaming Runways for a Peculiar Reason: Magnetism
https://www.popularmechanics.com/flight/airlines/a15759858/earth-magnetic-field-airport-runways/

The geomagnetic field

- Parameters
  - Declination
    - BE (2020)
      - +1°40’ (east)
  - Inclination
    - BE (2020)
      - +/- 66°
    - Aka the « dip angle »
  - L-shell
    - Set of MF lines
    - Crossing Earth’s magnetic equator
    - At the number of earth radii (L)
      - L=1: Earth’s surface
      - L ~6.6: GOES orbit





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From Wiki: https://en.wikipedia.org/wiki/Geomagnetic_reversal
The current time scale contains 184 polarity intervals in the last 83 million years.

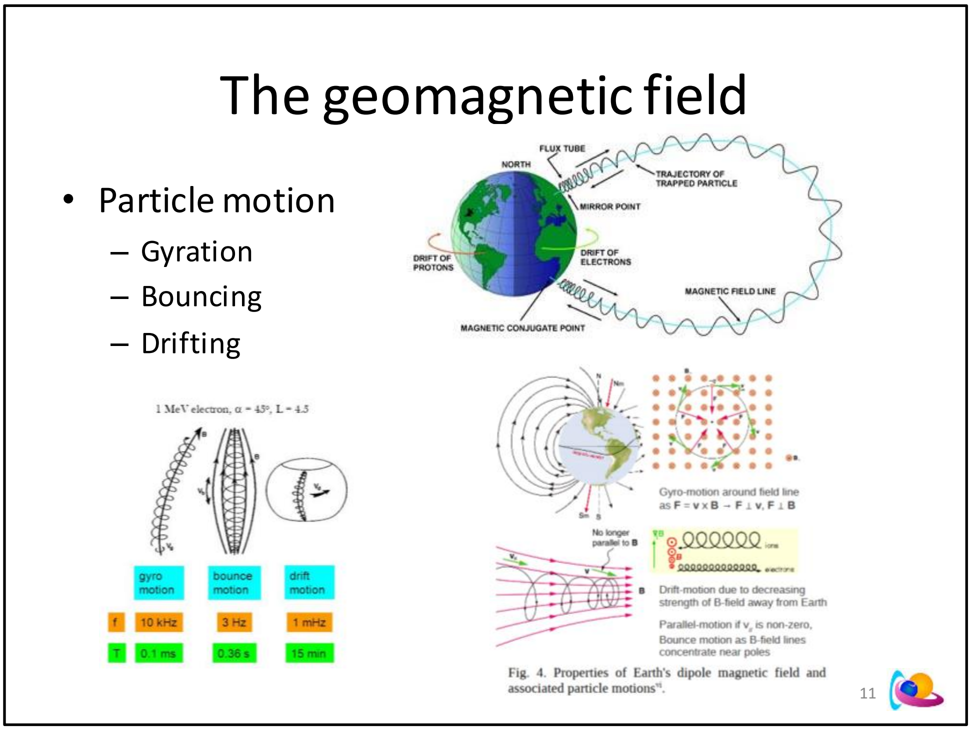
From Wiki: https://en.wikipedia.org/wiki/Brunhes%E2%80%93Matuyama_reversal
The Brunhes–Matuyama reversal, named after Bernard Brunhes and Motonori Matuyama, was a geologic event, approximately 781,000 years ago, when the Earth's magnetic field last underwent reversal. Estimations vary as to the abruptness of the reversal: it might have extended over several thousand years, or much more quickly, perhaps within a human lifetime. The apparent duration at any particular location varied from 1,200 to 10,000 years depending on geomagnetic latitude and local effects of non-dipole components of the Earth's field during the transition.

Values from the US/UK World Magnetic Model (2015-2019).
See https://en.wikipedia.org/wiki/World_Magnetic_Model &
https://en.wikipedia.org/wiki/World_Magnetic_Model

2020 values are at https://www.magnetic-declination.com/

From USGS:: https://www.ngdc.noaa.gov/geomag/faqgeom.shtml#What_are_the_magnetic_elements
Magnetic declination is the angle between magnetic north and true north. D is considered positive when the angle measured is east of true north and negative when west. Magnetic inclination is the angle between the horizontal plane and the total field vector, measured positive into Earth. The parameters describing the direction of the magnetic field are declination (D) and inclination (I). D and I are measured in units of degrees, positive east for D and positive down for I.

From Wiki: https://en.wikipedia.org/wiki/L-shell
L-shell: The L-shell, L-value, or McIlwain L-parameter (after Carl E. McIlwain) is a parameter describing a particular set of planetary magnetic field lines. Colloquially, L-value often describes the set of magnetic field lines which cross the Earth's magnetic equator at a number of Earth-radii equal to the L-value. For example, "L = 2" describes the set of the Earth's magnetic field lines which cross the Earth's magnetic equator two earth radii from the center of the Earth.



http://www.uio.no/studier/emner/matnat/fys/FYS3610/h14/documents/handouts/h01.pdf
https://www.s.u-tokyo.ac.jp/en/utrip/archive/2013/pdf/06NgYuting.pdf
https://www2.mps.mpg.de/solar-system-school/lectures/space_plasma_physics_2007/Lecture_3.pdf

Also very good (and less mathematically):
https://www.plasma-universe.com/Charged_particle_drift
http://slideplayer.com/slide/8028238/

Gyration
The particle moves in a circle, perpendicular to the background magnetic field. It "gyrates". Because of the dependence on q , the direction of the gyromotion of positively charged particles (ions) is opposite that of negatively charged particles (electrons). When considering the gyromotion of electrons and ions, for the same perpendicular energy, the gyrofrequency of electrons is much higher (me << mi) while the gyroradius is much larger.

Bouncing
As particles move along field lines toward the magnetic poles, they experience stronger magnetic fields and are eventually mirrored. As they gyrate they are said to "bounce" between hemispheres; they are trapped in the terrestrial magnetic field. The pitch angle is defined by the ratio between vpara and vperp. From energetic considerations, it can be shown that the particle's movement along the field line (vpara) slows down. Once the field-aligned movement stops, there is still a force on the gyrating particle, pushing it back out of the region of higher B. However, if the pitch angle decreases below a certain critical value, the particle will hit the Earth's surface before it has a chance to mirror, therefore, all particles with the pitch angle < crit val, are lost; this defines the loss cone (for that particular field line at that particular distance).

Drifting
Generally speaking, when there is a force on the particles perpendicular to the magnetic field, then they drift in a direction perpendicular to both the force and the field. The curvature drift is charge dependent, i.e., positively and negatively charged particles drift in opposite directions, creating a current.

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Main features

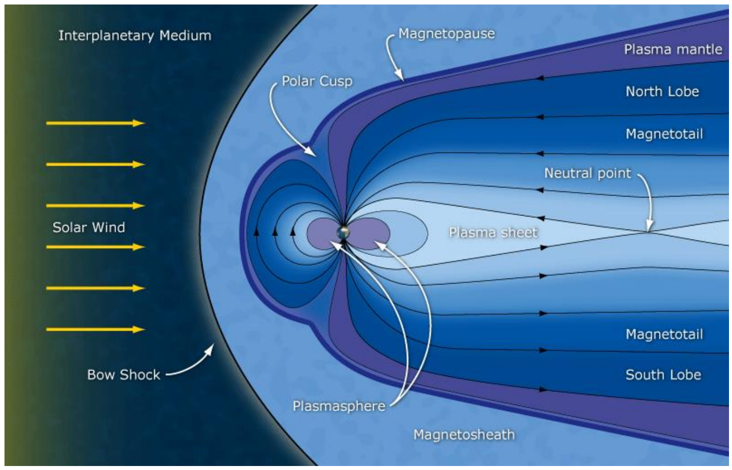

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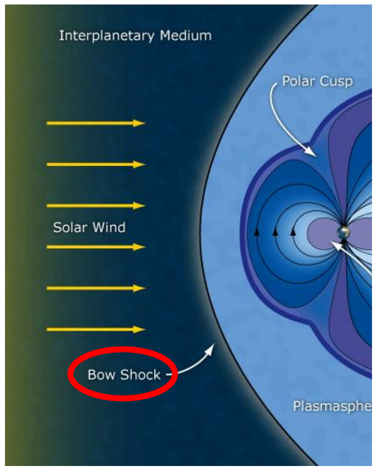
Figure from ESA/ C. Russell
http://sci.esa.int/cluster/50633-cluster-looks-into-waves-in-the-magnetosphere-s-thin-boundaries/

Note that, in the above figure, the placement of "Magnetotail" may be a bit confusing. It seems to suggest that the tail is somehow between plasma sheet and lobes, but this is not the case: The magnetotail is the whole magnetosphere stretching out on the night side.

Main features



- Bow shock
  - First interaction w/ solar wind
    - Speed reduction
    - Increase T, B
    - Shock: very thin
  - Location
    - +/- 90.000 km upstream
      - Variable!

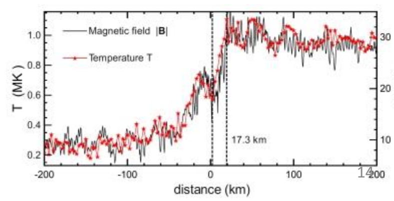


Figure from ESA/ C. Russell
http://sci.esa.int/cluster/50633-cluster-looks-into-waves-in-the-magnetosphere-s-thin-boundaries/

SwRI: http://pluto.space.swri.edu/image/glossary/bow_shock.html

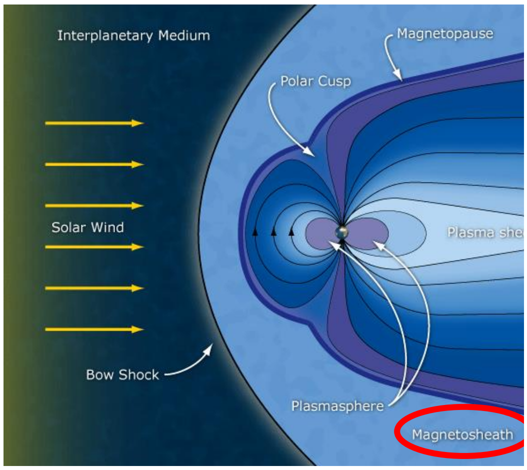
From ESA/Cluster
http://sci.esa.int/cluster/49643-cluster-measures-the-size-of-earth-s-bow-shock/
https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/cluster
The bow shock is a standing shock wave that forms when the solar wind encounters the magnetosphere of our planet.
the bow shock formed by the solar wind as it encounters Earth's magnetic field is remarkably thin: it measures only 17 km across. Thin astrophysical shocks such as this are candidate sites for early phases of particle acceleration.

Also at https://www.astrobio.net/also-in-news/earths-bow-shock-is-remarkably-thin/

Cluster: http://www-ssg.sr.unh.edu/tof/Outreach/music/cluster/index.html#graph
The region around the Earth that is controlled by the Earth’s magnetic field, called the Magnetosphere, acts for the solar wind as an obstacle, like a rock in a flowing river. Since the solar wind with a speed of 250 – 800 km/s is highly supersonic, the situation is more like a supersonic jet plane rushing through the air. As a jet produces the audible supersonic boom, a loud shock wave (to be heard after the jet has passed already the observer’s position), the Earth’s Magnetosphere produces the equivalent structure, the so-called Bow Shock, in the solar wind.
Such shock waves are formed in many places in the universe with violent motion, around planets, at the Sun, around the solar system where the solar wind is stopped, and where supernovae blast into their neighborhood. In all these cases these shock waves slow down the solar wind, compress the flowing gas or plasma and the magnetic field, heat it up, and accelerate some particles to very high energies. The Cluster satellites cross the Earth’s Bow Shock usually several times during orbits that lead into the solar wind. Thus they can study this shock wave at our front doorstep in detail.

More on supersonic/subsonic speeds in interplanetary space:
- http://how.gi.alaska.edu/ao/msp/chapters/chapter6.pdf
- https://en.wikipedia.org/wiki/Alfv%C3%A9n_wave#Alfv%C3%A9n_velocity

Main features



- Magnetosheath
  - Turbulent region between bow shock and magnetopause
  - Solar wind dominated
    - Deflected above and below the magnetopause
  - High particle energy flux
    - « shocked »
    - MF varies erratically
    - Much smaller than geomagnetic field

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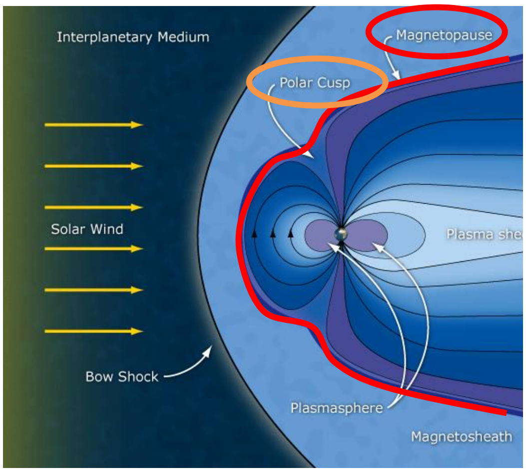
Figure from ESA/ C. Russell
http://sci.esa.int/cluster/50633-cluster-looks-into-waves-in-the-magnetosphere-s-thin-boundaries/

SwRI: http://pluto.space.swri.edu/image/glossary/bow_shock.html

Wiki: https://en.wikipedia.org/wiki/Magnetosphere#Magnetosheath
The magnetosheath is the region of the magnetosphere between the bow shock and the magnetopause. It is formed mainly from shocked solar wind, though it contains a small amount of plasma from the magnetosphere. It is an area exhibiting high particle energy flux, where the direction and magnitude of the magnetic field varies erratically. This is caused by the collection of solar wind gas that has effectively undergone thermalization. It acts as a cushion that transmits the pressure from the flow of the solar wind and the barrier of the magnetic field from the object.

Main features



- Magnetopause
  - Sharp boundary
    - Pressure balance
    - = sum of magnetic + plasma pressure is constant
  - Earth vs. Solar Wind
  - Magnetic reconnection
    - Current sheet
  - Location:
    - 10-12 R_E (6-15 R_E)
  - Cusp
    - Narrow regions of opened/merged MF lines
    - In/outflow of particles

Figure from ESA/ C. Russell
http://sci.esa.int/cluster/50633-cluster-looks-into-waves-in-the-magnetosphere-s-thin-boundaries/

Wiki: https://en.wikipedia.org/wiki/Magnetopause

During high solar activity, i.e. the passing of strong coronal mass ejections, the magnetopause may be pushed much closer to the Earth than usual, sometimes even closer than 6.6RE which is the location of the GOES satellites. At that point, these satellites become entirely exposed to the solar wind particles, which can be seen in erratic measurements of e.g. Hp. This is called a magnetopause crossing. See the course chapter on SWx effects.

Cusp: http://pluto.space.swri.edu/image/glossary/cusp.html
In the "open" model of the magnetosphere, the polar cusps are narrow regions of recently "opened" or merged magnetic field lines mapping to the high-latitude ionosphere just poleward of the last closed field line on the Earth's day side. The open field lines of the cusps are connected with those of the interplanetary magnetic field, which allows the shocked solar wind plasma of the magnetosheath to enter the magnetosphere and to penetrate to the ionosphere. Associated with the cusp is the "cleft ion fountain," from which plasma flows upward from the ionosphere into the magnetosphere, with the peak outflow occurring in the pre-noon sector.

The Earth’s magnetosphere is the area within the red line, so without the magnetosheath and the bow shock.

Magnetopause: As there is pressure balance, this means that the sum of magnetic + plasma pressure is constant. The plasma pressure usually is considerably larger on the magnetosheath side than on the magnetospheric side, and the magnetic field thus is typically smaller on the magnetosheath side.

Main features

- Magnetotail
  - Several 100 R_E long
  - Two lobes
    - Northern: MF points towards Earth
    - Southern: MF points away from Earth
  - Separated by **plasma sheet**
    - Reconnection closer to Earth during strong disturbances
      - Source of aurora

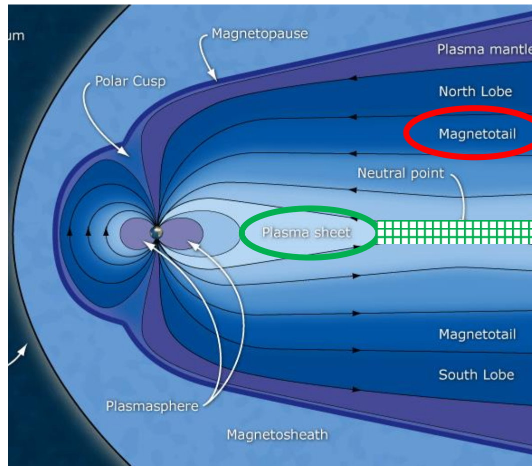


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Figure from ESA/ C. Russell
http://sci.esa.int/cluster/50633-cluster-looks-into-waves-in-the-magnetosphere-s-thin-boundaries/

From Wiki:https://en.wikipedia.org/wiki/Magnetosphere#Magnetotail
Opposite the compressed magnetic field is the magnetotail, where the magnetosphere extends far beyond the astronomical object. It contains two lobes, referred to as the northern and southern tail lobes. Magnetic field lines in the northern tail lobe point towards the object while those in the southern tail lobe point away. The tail lobes are almost empty, with few charged particles opposing the flow of the solar wind. The two lobes are separated by a plasma sheet, an area where the magnetic field is weaker, and the density of charged particles is higher.

http://pluto.space.swri.edu/image/glossary/magnetosphere.html

NASA: The tail of the magnetosphere
https://www-spof.gsfc.nasa.gov/Education/wtail.html

Note that, in the above figure, the placement of "Magnetotail" may be a bit confusing. It seems to suggest that the tail is somehow between plasma sheet and lobes, but this is not the case: The magnetotail is the whole magnetosphere stretching out on the night side.

Also, reconnection tends to occur always. During quiet times, it happens in the distant tail. During disturbed times, you can have reconnection closer to Earth (at ~20 R_E).

Main features

- Plasmasphere
  - Donut shaped region
    - Specific features
  - Cold plasma
    - From ionosphere
  - Strong geomagnetic storms
    - Plasmapause moves closer to inner boundary of outer region
      - « Erosion » of the plasmasphere

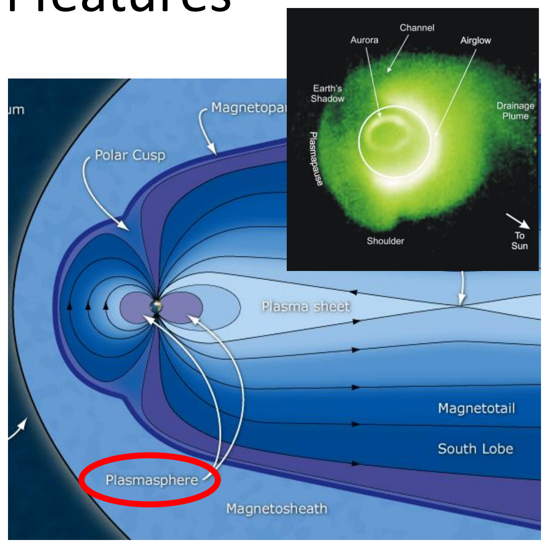

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Figure from ESA/ C. Russell
http://sci.esa.int/cluster/50633-cluster-looks-into-waves-in-the-magnetosphere-s-thin-boundaries/

Stanford: http://vlf.stanford.edu/research/extreme-ultraviolet-imaging-plasmasphere

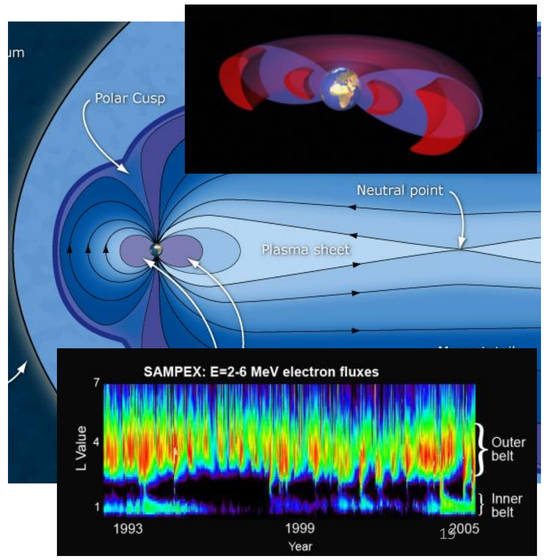
NASA: https://plasmasphere.nasa.gov/
The upper reaches of our planet's atmosphere are exposed to ultraviolet light from the Sun, and they are ionized with electrons that are freed from neutral atmospheric particles. The electrons in plasma gain more energy, and they are very low in mass . They move along Earth's magnetic field lines and their increased energy is enough to escape Earth's gravity. Because electrons are very light, they don't have to gain too much kinetic energy from the Sun's ultraviolet light before gravity loses its grip on them. For a planet like Earth with a strong planetary magnetic field, these outward moving particles remain trapped near the planet unless other processes further draw them away and into interplanetary space. Over only a short time period of hours and days this escaping plasma can, in some places, build up in concentration until an equilibrium is reached where as much plasma flows inward into the ionosphere as flows outward. This "donut shaped" region of cold (about 1 electron volt in energy) plasma encircling the planet is called the plasmasphere.

Generally, that region of space where plasma from the ionosphere has the time to build up to become identified as the plasmasphere rotates or nearly rotates with the Earth. That region shrinks in size with increased space weather activity and expands or refills during times of inactivity. As it shrinks with increasing activity, some of the plasmasphere is drawn away from its main body (plasmaspheric erosion) in the sunward direction toward the boundary in space between that region dominated by Earth's magnetic field and the much larger region dominated by the Sun's magnetic field.

Moldwin et al. (2002): A new model of the location of the plasmapause: CRRES results
https://ui.adsabs.harvard.edu/abs/2002JGRA..107.1339M/abstract

Main features

- Radiation belts
  - Outer belt
    - Mostly e^-
    - 0.1-10 MeV
    - $3 < L < 8$
  - Inner belt
    - Mostly p^+
    - 10-500 MeV
    - $1.2 < L < 2.5$
  - Strong geomagnetic storms
    - Injection of > 15MeV p^+ and > 3MeV e^- which can reach all the way down into the Inner Radiation Belt



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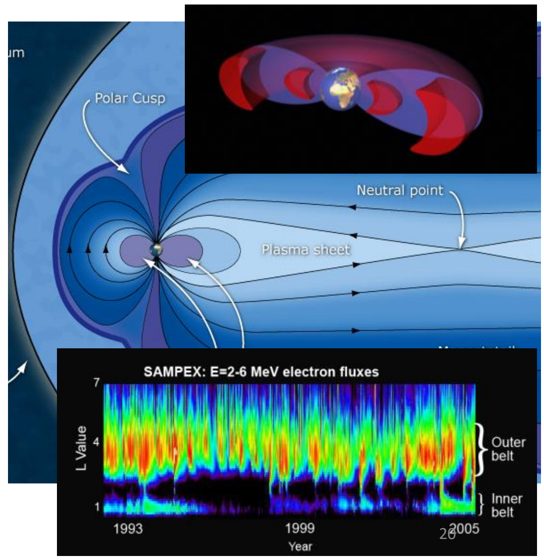
http://sci.esa.int/cluster/50633-cluster-looks-into-waves-in-the-magnetosphere-s-thin-boundaries/

ESA: http://sci.esa.int/cluster/52831-earth-plasmasphere-and-the-van-allen-belts/
The plasmasphere – the innermost part of the Earth's magnetosphere – is a doughnut-shaped region of low energy charged particles (cold plasma) centred around the planet's equator and rotating along with it. Its toroidal shape is determined by the magnetic field of Earth. The plasmasphere begins above the upper ionosphere and extends outwards, with the outer boundary varying (depending on geomagnetic conditions) from 4.5 Earth radii (R_E) to 8 R_E.
The two Van Allen radiation belts are concentric, tyre-shaped belts (shown in blue) of highly energetic (0.1–10 MeV) electrons and protons, which are trapped by the magnetic field and travel around the Earth. These radiation belts partly overlap with the plasmasphere. The inner Van Allen belt is located typically between 6000 and 12 000 km (1 - 2 Earth radii [R_E]) above Earth's surface, although it dips much closer over the South Atlantic Ocean. The outer radiation belt covers altitudes of approximately 25 000 to 45 000 km (4 to 7 R_E).

SAMPEX figure from Spaceflight101: http://www.spaceflight101.net/rbsp-mission-updates.html

Main features

- Radiation belts
  - Outer belt
    - Mostly e^-
    - 0.1-10 MeV
    - $3 < L < 8$
  - Inner belt
    - Mostly p^+
    - 10-500 MeV
    - $1.2 < L < 2.5$
  - Strong geomagnetic storms
    - Injection of > 15MeV p^+ and > 3MeV e^- which can reach all the way down into the Inner Radiation Belt



Main characteristics
Outer Radiation Belt – mostly e- - 0.1 – 10 MeV – 3 < L < 8 (ESA; variable) - the outer belt starts at L= 3.5, especially for electrons with E>1 MeV
Baker et al. (2017): Space Weather Effects in the Earth's Radiation Belts
http://adsabs.harvard.edu/abs/2018SSRv..214...17B

Inner Radiation belt
10 - 500 MeV protons at 1.5 < L < 2
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South Atlantic Anomaly – e- and p+ - 1.03 < L < 1.2 (lower edge Inner Belt) - the SAA is created by electrons and protons of the inner belt. In the SAA and in the inner belt, there are no electrons with E>2 MeV.

Occasionally, during strong geomagnetic storms, there can be an injection of > 15MeV p+ and > 3MeV e- which can reach all the way down into the Inner Radiation Belt and cause even the presence of a third radiation belt during several days.

Main features

- Radiation belts
  - Strong geomagnetic storms
    - .../...
    - Creation of a third radiation belt during several days
  - South Atlantic Anomaly
    - Extension of Inner belt closest to Earth
      - altitude: 200 km
      - Over Brazil
        - » Drift westward at 3°/decade

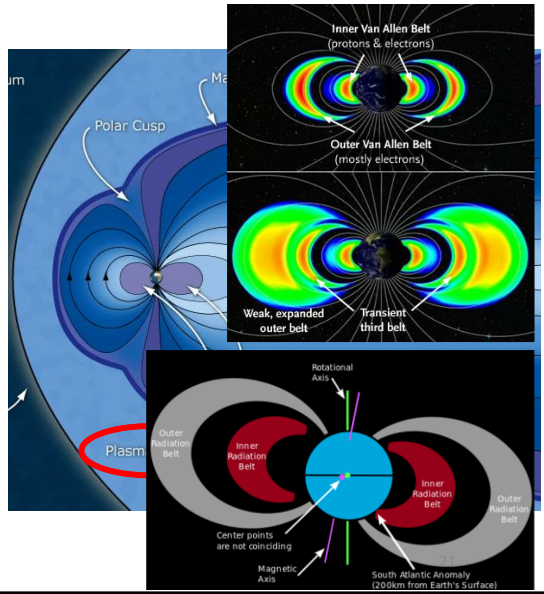

Figure from ESA/ C. Russell
http://sci.esa.int/cluster/50633-cluster-looks-into-waves-in-the-magnetosphere-s-thin-boundaries/

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Figure from Spaceflight101: http://spaceflight101.com/rbsp/science-overview/
Figure from NASA: https://www.nasa.gov/content/goddard/van-allen-probes-mark-first-anniversary/
From SpaceSafety: http://www.spacesafetymagazine.com/media-entertainment/radiation-belt-surprises-rbsp-scientists/

Reminder: the SAA exists due to the fact that the geomagnetic field is not perfectly symmetric; one can approximately say that the bar magnet inside Earth is located slightly off-center. See the inserted figure and slide 8.
Space.com: Van Allen radiation belts: facts and findings - https://www.space.com/33948-van-allen-radiation-belts.html
NASA press conference on 3rd radiation belt: https://www.youtube.com/watch?v=yLw9a5t-sUs
Sky and telescopre: https://skyandtelescope.org/astronomy-news/observing-news/earth-briefly-gains-third-radiation-belt/

Main features

- Radiation belts
  - Strong geomagnetic storms
    - .../...
    - Creation of a third radiation belt during several days
  - South Atlantic Anomaly
    - Extension of Inner belt closest to Earth
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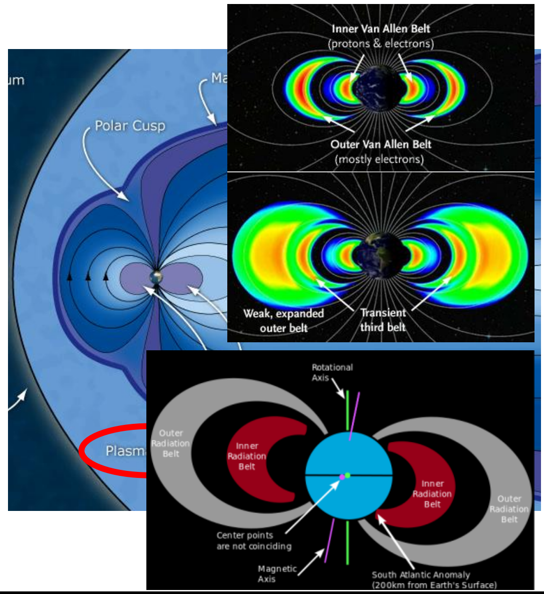

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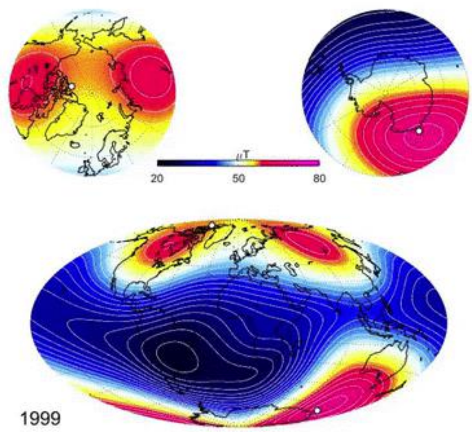
Wiki: https://en.wikipedia.org/wiki/South_Atlantic_Anomaly

https://www.youtube.com/watch?v=3zNmgu6sQXk

Main features

South Atlantic Anomaly (1999-2016) by SWARM



ESA / DTU Space

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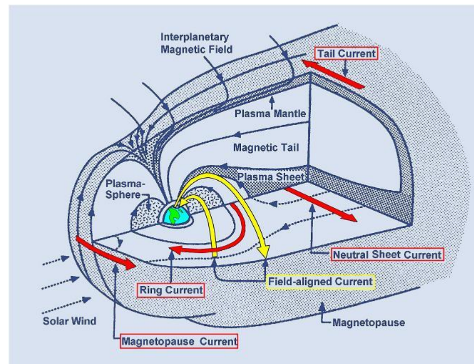
http://www.esa.int/spaceinvideos/Videos/2016/05/Changes_in_strength_of_Earth_s_magnetic_field
http://www.esa.int/Our_Activities/Observing_the_Earth/Swarm/Earth_s_magnetic_heartbeat

Title Changes in strength of Earth's magnetic field
Released: 10/05/2016
Language English
Footage Type Animation
Copyright DTU Space
Description

Based on results from ESA's Swarm mission, the animation shows how the strength of Earth's magnetic field has changed between 1999 and mid-2016. Blue depicts where the field is weak and red shows regions where the field is strong. The field has weakened by about 3.5% at high latitudes over North America, while it has grown about 2% stronger over Asia. The region where the field is at its weakest field – the South Atlantic Anomaly – has moved steadily westward and further weakened by about 2%. In addition, the magnetic north pole is wandering east.

Main features

- Magnetospheric Currents
  - Magnetopause current
  - Ring current
  - Field-Aligned Current (FAC)
  - Neutral sheet current
  - Tail current



Geomag/US: http://geomag.us/info/magnetosphere.html

Note that during times of unusually large solar wind ram pressure the magnetopause may move substantially Earthwards. Indeed, sometimes the magnetopause is observed inside geosynchronous orbit (6.6 RE).
The magnetopause current layer is important in two other ways. First, the magnetic field associated with the current layer is also observable at the surface of the Earth. This is particularly true during times when the magnetopause is compressed Earthwards, leading to an increase in the magnetic field measurable at the surface (since the current layer's field adds to the Earth's field inside the magnetopause). As seen in Lecture 15, this effect can lead to an increase in the geomagnetic activity index at the start of a geomagnetic substorm, while the subsequent increase of the ring current leads to major decrease of the surface field (Section 14.3). Second, and perhaps more importantly, the magnetopause current layer is a global phenomenon that persists wherever the magnetopause does.

Chapman-Ferraro current: https://www.britannica.com/science/Chapman-Ferraro-current-system
http://shadow.eas.gatech.edu/~cpaty/courses/SpacePhysics2013/SpacePhysics2013/Lectures_files/Lecture13_14_15_2013.pdf
A perspective view of the northern portion of the magnetopause current, as seen from above the ecliptic plane. Charged particles in the solar wind are deflected in opposite directions by the Earth's main field, creating a boundary current. This current confines the field inside a finite volume called the magnetosphere (*see* text).

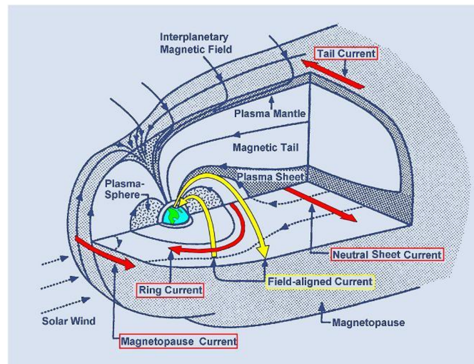
« The Sun, The Earth and Near-Earth space » by John A. Eddy (Fig. pp. 83)
The dayside magnetopause current has a nighttime equivalent (tail current or night-time magnetopause current).

Ring current (pp. 87):
The third obligatory motion is an induced, slower drift in longitude that results from the curvature of the MF lines and the diminished strength of the field with distance above the surface of the planet. The effect is to nudge to gyrating particle a little bit in longitude – an e- in the eastward direction, a p+ or other positive ions westward – each time it bounces. Repeated nudging pushes it bit by bit around the Earth, such that the pole-to-pole motions of the particle sweep over the entire surface of the planet, all in about one hour. … is a ring of current flowing around the magnetic equator of the Earth…

Ring current (Wiki: https://en.wikipedia.org/wiki/Ring_current)
Earth's ring current is responsible for shielding the lower latitudes of the Earth from magnetospheric electric fields. It therefore has a large effect on the electrodynamics of geomagnetic storms. The ring current system consists of a band, at a distance of 3 to 8 Re, which lies in the equatorial plane and circulates clockwise around the Earth (when viewed from the north). The particles of this region produce a magnetic field in opposition to the Earth's magnetic field and so an Earthly observer would observe a decrease in the magnetic field in this area. The negative deflection of the Earth's magnetic field due to the ring current is measured by the Dst index. The ring current energy is mainly carried around by the ions, most of which are protons.

Main features

- Magnetospheric Currents
  - Magnetopause current
  - Ring current
  - Field-Aligned Current (FAC)
  - Neutral sheet current
  - Tail current



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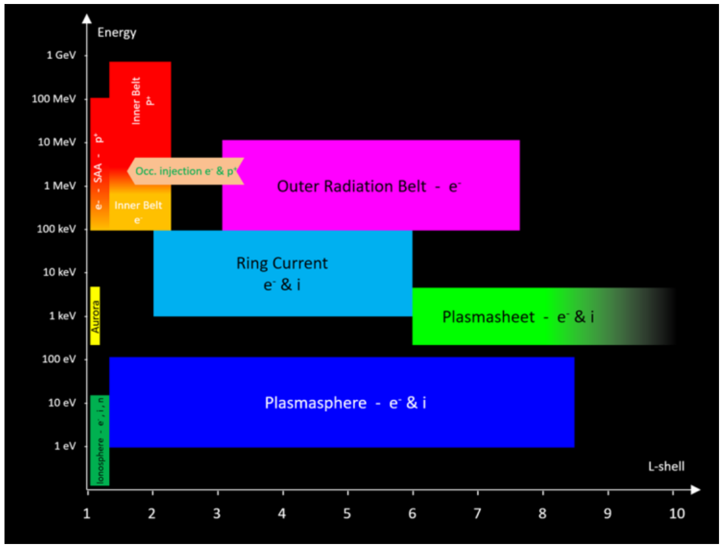
Field-aligned currents: https://wiki.oulu.fi/display/SpaceWiki/Field-aligned+currents
Field-aligned currents (FAC, also called the Birkeland currents) are essential to the coupling between the solar wind - magnetosphere system and the ionosphere. The main large scale FAC systems are the Region 1 and 2 currents.

Plasma universe: https://www.plasma-universe.com/Birkeland_current
A **Birkeland current** usually refers to the electric currents in a planet's ionosphere that follows magnetic field lines (i.e. field-aligned currents), and sometimes used to described any field-aligned electric current in a space plasma. They are caused by the movement of a plasma perpendicular to a magnetic field.

Also at https://en.wikipedia.org/wiki/Birkeland_current
A **Birkeland current** is a set of currents that flow along geomagnetic field lines connecting the Earth's magnetosphere to the Earth's high latitude ionosphere. In the Earth's magnetosphere, the currents are driven by the solar wind and interplanetary magnetic field and by bulk motions of plasma through the magnetosphere (convection indirectly driven by the interplanetary environment). The strength of the Birkeland currents changes with activity in the magnetosphere (e.g. during substorms). Small scale variations in the upward current sheets (downward flowing electrons) accelerate magnetospheric electrons which, when they reach the upper atmosphere, create the Auroras Borealis and Australis. In the high latitude ionosphere (or auroral zones), the Birkeland currents close through the region of the auroral electrojet, which flows perpendicular to the local magnetic field in the ionosphere.

Main features



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This sketch provides a quick overview on the location and energies associated with the features in the magnetopshere. It's certainly not meant as a final scientific model, but rather aims at providing a general idea. Also, the boundaries are not strict and can depend on the energies, on the geomagnetic activity etc... Hence the energies and boundaries of the different regions are just approximations.

The sketch was developed by J. Janssens (STCE) with important contributions by V. Pierrard (BISA).

It shows the main regions of the magnetosphere and ionosphere brought back to the Earth's magnetic equator (L-shell, horizontal axis) and showing the energies of the respective particles (eV to GeV; logaritmic scale; vertical axis).

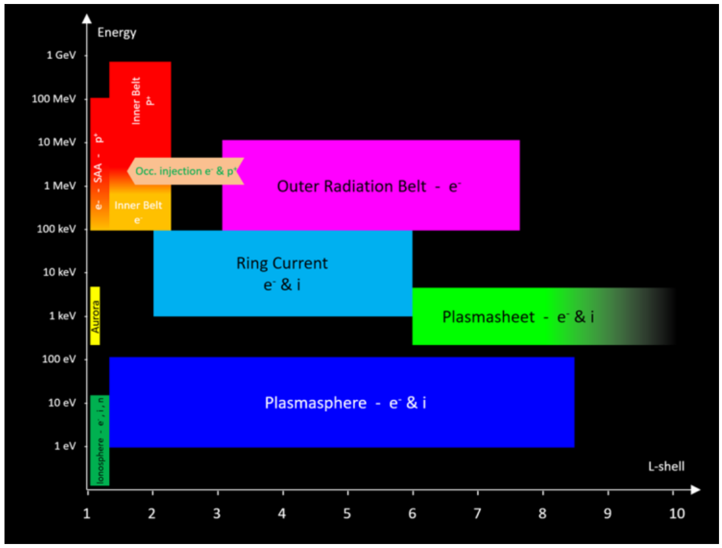
Plasmasheet – e- & ions – hundreds of eV to several keV – 6 < L
Ring Current – e- & i - generally considered from 1 keV up to 200 keV (for 100 keV and for higher energies, one can consider it is electron radiation belts), – 2 < L < 6

Plasmasphere – e- & i – 1 to 100 eV – 1.2 < L < 4.5 to 9 (variable) ; The plasmasphere is the extension of the ionosphere at higher L and indeed the energy is sligthly increasing in the plasmasphere.

Ionosphere – e-, i and neutrals – 0.1 – 10 eV – 1.01 < L < 1.2

Aurora – e- - hundreds of eV to several keV – 1.01 < L < 1.1 (about 400 km) - Aurora are due to injection of plasmasheet electrons in the atmosphere, typically between 90 and 300 km (so the energies of aurora and plasmasheet are similar). Since the auroral particles are accelerated plasmasheet particles, they (yellow box) have somewhat higher energies than the plasmasheet particles (green box), say, up to 20 keV, which are indeed the upper energies observed for auroral precipitating particles.

Main features



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Outer Radiation Belt – mostly e- - 0.1 – 10 MeV – 3.5 < L < 8 (ESA; variable) - the outer belt starts at L= 3.5, especially for electrons with E>1 MeV

Inner Radiation belt

10 - 500 MeV protons at 1.5 < L < 2

100-500 keV e- at 1.2 < L < 2.5 - In the SAA and in the inner belt, there are no electrons with E>2 MeV.

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Occasionally, during strong geomagnetic storms, there can be an injection of > 15MeV p+ and > 3MeV e- which can reach all the way down into the Inner Radiation Belt and cause even the presence of a third radiation belt during several days.

All features rotate with (around) the Earth except the plasmasheet which can be considered as part of the magnetotail.
Also the outer edges of the plasmasphere are not exactly rotating with the Earth in 24h, but more in 27h.

In the Ring current, The ions drift westwards and the electrons drift eastwards, giving rise to a net westward current circulating around the Earth. This current is known as the *ring current*.

Main features

- Satellite Earth orbits

SATELLITE ORBIT DEFINITIONS			
ORBIT NAME	ORBIT INITIALS	ORBIT ALTITUDE (KM ABOVE EARTH'S SURFACE)	DETAILS / COMMENTS
Low Earth Orbit	LEO	200 - 1200	
Medium Earth Orbit	MEO	1200 - 35790	
Geosynchronous Orbit	GSO	35790	Orbits once a day, but not necessarily in the same direction as the rotation of the Earth - not necessarily stationary
Geostationary Orbit	GEO	35790	Orbits once a day and moves in the same direction as the Earth and therefore appears stationary above the same point on the Earth's surface. Can only be above the Equator.
High Earth Orbit	HEO	Above 35790	

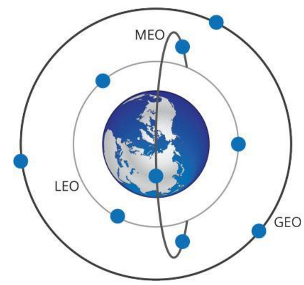

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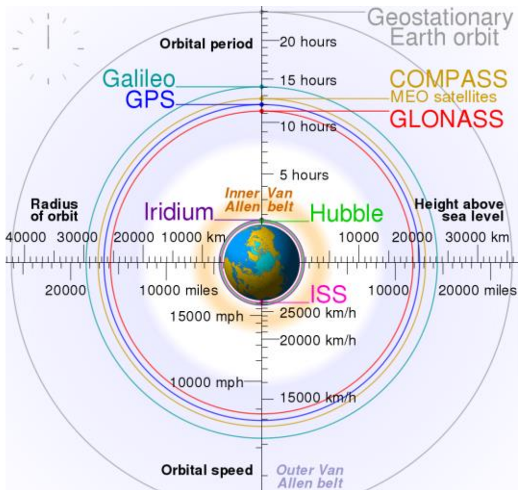
Table from radio-electronics
http://www.radio-electronics.com/info/satellite/satellite-orbits/satellites-orbit-definitions.php

Figure from ESOA
https://www.esoa.net/technology/satellite-orbits.asp

Main features

- Satellite Earth orbits



https://upload.wikimedia.org/wikipedia/commons/b/b4/Comparison_satellite_navigation_orbits.svg

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https://upload.wikimedia.org/wikipedia/commons/b/b4/Comparison_satellite_navigation_orbits.svg

From Wiki: https://en.wikipedia.org/wiki/Medium_Earth_orbit
Medium Earth orbit (MEO), sometimes called intermediate circular orbit (ICO), is the region of space around the Earth above low Earth orbit (altitude of 2,000 km) and below geostationary orbit (altitude of 35,786 km).

The most common use for satellites in this region is for navigation, communication, and geodetic/space environment science. The most common altitude is approximately 20,200 kilometres, which yields an orbital period of 12 hours, as used, for example, by the Global Positioning System (GPS). Other satellites in medium Earth orbit include Glonass (with an altitude of 19,100 kilometres and Galileo (with an altitude of 23,222 kilometres) constellations. Communications satellites that cover the North and South Pole are also put in MEO.

The orbital periods of MEO satellites range from about 2 to nearly 24 hours.[1] Telstar 1, an experimental satellite launched in 1962, orbited in MEO.

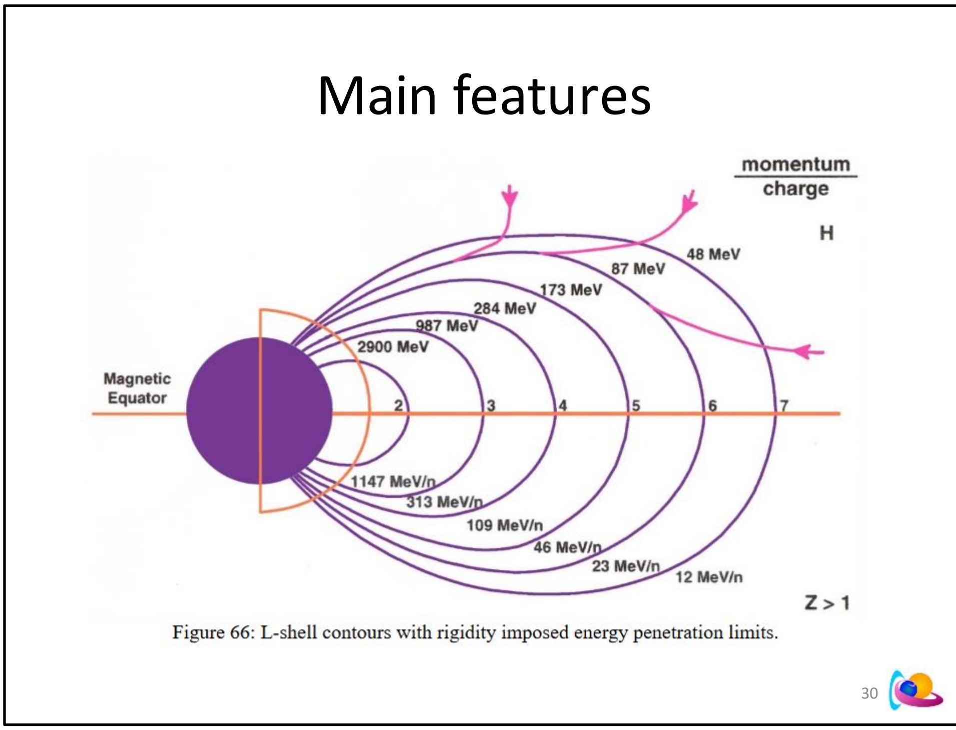


Figure 66: L-shell contours with rigidity imposed energy penetration limits.

From NASA: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160003393.pdf
https://ntrs.nasa.gov/search.jsp?R=20160003393

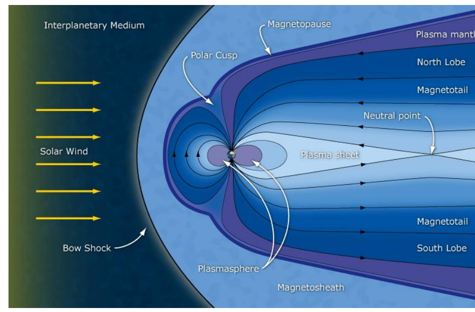
The question of energetic proton penetration into the inner zone of the Van Allen belts, and hence the SAA, is of particular importance because it is frequently mentioned in several publications, which claim that these particles affected their measurements in the SAA and had an impact on the SAA's evolution. However, the "rigidity principle" applies to the inner zone of the radiation belts, and consequently the SAA; protons must have energies greater than 2.9 GeV (as mentioned above) at least, to be able to reach the low altitude range of the anomaly.

Cosmic Rays. A few papers mentioned concern about the penetration of cosmic rays into the SAA region. Solar and galactic cosmic rays are high-energy heavy ions: 90% hydrogen, 9% alpha particles, and 1% nuclei of heavier elements. In order for these particles to reach the inner zone of the Van Allen belts, and hence the SAA, they must have energies in excess of 1.15 GeV per nucleon. All cosmic rays with lower energies are deflected by the Earth's magnetic field (rigidity cutoff). Most workers consider the galactic cosmic rays reaching the vicinity of the Earth (about 1 AU) as fully ionized, which means maximum deflection. As a consequence, very few of these particles reach the SAA. A solar cycle variation has been observed in the cosmic ray flux levels between solar minimum and solar maximum. During the active phase of the solar cycle, the cosmic ray intensities are about a factor of two or so lower than during solar minimum. It is obvious, considering Figure66, that more cosmic rays have access to the higher latitude regions than near the equator, with a free unimpeded penetration over the poles, where open field lines connect directly to the interplanetary medium.

Interesting reading: the STARFISH prime project
https://en.wikipedia.org/wiki/Starfish_Prime

Exercise: Magnetosphere

- The magnetosphere
  a. Stretches all the way to the bow shock
  b. Stretches all the way to the magnetopause
  c. Contains only specific areas such as the radiation belts

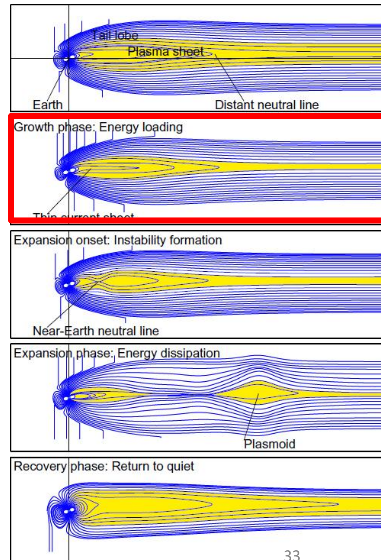


The Magnetosphere - Contents

- The geomagnetic field
- Main features
- Geomagnetic (sub)storms
- Measuring magnetic fields
  - Geomagnetic indices
  - Networks
- Miscellaneous

Geomagnetic (sub)storm

- Growth phase
  - Reconnection at magnetopause
    - Magnetic erosion
  - Open field lines are swept back into magnetotail
    - Some particles get access via cusps
    - Building of magnetic flux in magnetotail



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Pulkkinen 2007 (Figure 5)

Figure from Pulkkinen 2007: https://link.springer.com/article/10.12942%2Flrsp-2007-1

A full description of the evolution of a geomagnetic (sub)storm can be found in the SIDC SWx Forecast Guide: http://www.sidc.be/PRODEX_SIDEx/docs/Space_Weather_Forecasting_Guide_latest.pdf

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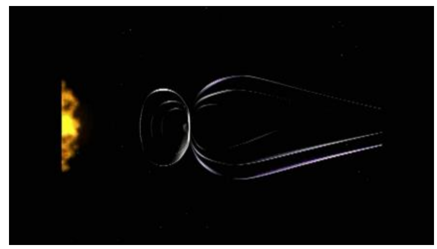

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See http://sci.esa.int/cluster/51744-magnetic-reconnection-in-earth-s-magnetosphere/ for another animation

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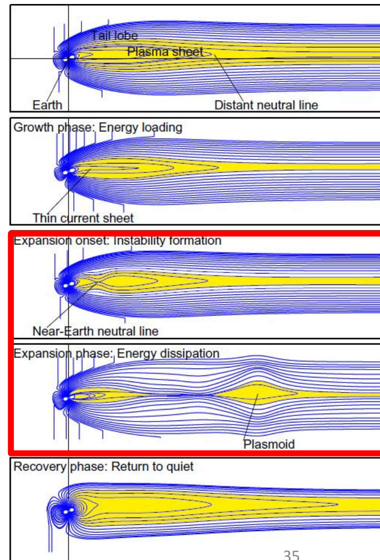
Geomagnetic (sub)storm

- Expansion phase
  - Explosive release of built-up energy in magnetotail
    - Particles get accelerated to Earth
      - Aurora, Ring current enhancement,…
    - A plasmoid gets ejected tailward back into solar wind



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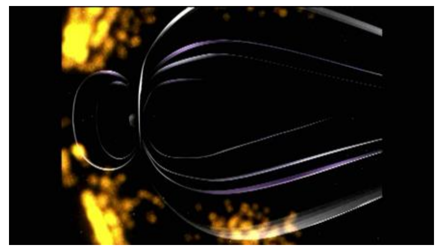

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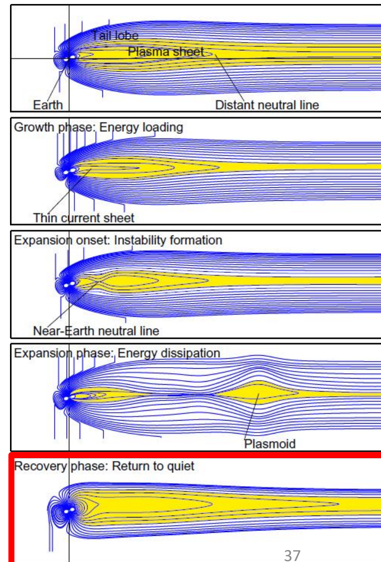
Geomagnetic (sub)storm

- Recovery phase
  - Neutral line retreats from Earth and propagates down the tail
  - New distant neutral line



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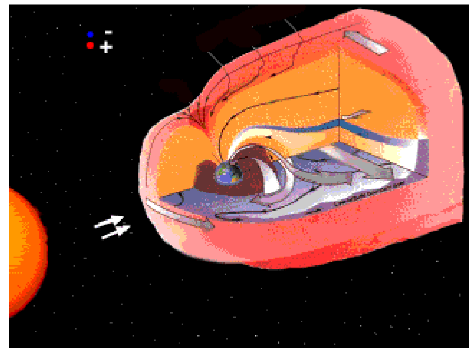
Geomagnetic (sub)storm

- In summary
  - Growth phase
    - Reconnection at magnetopause
  - Expansion phase
    - Reconnection in near-tail
    - Particle acceleration
  - Recovery phase
- 4 to 5 substorms / day
  - Energy input of 30-60’
  - 2-3 hours each
- If energy input > 3 hrs
  - Development of geomagnetic storm



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From; Windows to the Universe
https://www.windows2universe.org/glossary/plasmaspheric_gain.html&edu=high

Movie with substorm: NASA: https://svs.gsfc.nasa.gov/20097

Magnetosphere from ESA: http://sci.esa.int/cluster/54025-model-of-changing-magnetosphere/

A full description of the evolution of a geomagnetic (sub)storm can be found in the SIDC SWx Forecast Guide: http://www.sidc.be/PRODEX_SIDEx/docs/Space_Weather_Forecasting_Guide_latest.pdf

Exercise: Geomagnetic (sub)storms

- In the magnetosphere, magnetic reconnection can take place:
  a. Near the magnetopause
  b. In the plasmasheet
  c. In the plasmasphere
  d. In the Van Allen radiation belts

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See also at http://sci.esa.int/cluster/51744-magnetic-reconnection-in-earth-s-magnetosphere/

A full description of the evolution of a geomagnetic (sub)storm can be found in the SIDC SWx Forecast Guide: http://www.sidc.be/PRODEX_SIDEx/docs/Space_Weather_Forecasting_Guide_latest.pdf

The Magnetosphere - Contents

- The geomagnetic field
- Main features
- Geomagnetic (sub)storms
- Measuring magnetic fields
  - Geomagnetic indices
  - Networks
- Miscellaneous

Geomagnetic indices

- Measure for geomagnetic unrest
- Ground-based magnetometer networks
  - Intensity and changes in intensity of the geomagnetic field
  - Corrected for diurnal and seasonal variations (quiet Sun)

The K index is derived from the amplitude of the variations of the field's horizontal components (the H and D pair, or alternatively, the X and Y components) after subtracting the daily solar regular (S_R) variation for the particular component (cf. **Fig.2**).

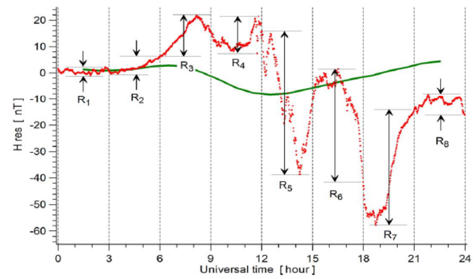

Fig.2. Calculation of the 3-hour K index over a 24 hour period. A daily record of 1-min measurements of the H component is presented here to illustrate the elimination of the solar regular variation, the S_R curve (the solid line), and the consequent determination of the 8 ranges (R_i, i=1,8). The difference between the upper (maximum) and lower (minimum) envelopes that are parallel to the S_R curve, determines the disturbance range within every 3-hour interval.

Figure from Stankov et al. (2010): Local Operational Geomagnetic Index K Calculation (K-LOGIC) from digital ground-based magnetic measurements
http://swans.meteo.be/sites/default/files/documentation/TN-RMI-2010-01_K-LOGIC.pdf

Geomagnetic indices

K index

- Kennziffer
- Local
  - E.g. Dourbes
- Quasi-logaritmic scale
- Expressed in full units
  - 0, 1, … , 9
- 3hrs interval
  - 0-3UT, … , 21-24UT
  - 1hrs possible (Dourbes)

Kp index

- Planetarische Kennziffer
- From network
  - 13 observatories
- Quasi-logaritmic scale
- Expressed in 1/3
  - 0o, 0+, … => … , 9-, 9o
- 3hrs interval
  - 0-3UT, … , 21-24UT
- Used in NOAA scales (G)
  - Auroral visibility maps
- Estimated Kp
- Going back to 1932

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On the K and Kp index: SWPC: https://www.swpc.noaa.gov/sites/default/files/images/u2/TheK-index.pdf
Potsdam: https://www.gfz-potsdam.de/en/kp-index/

The reported values, be they updated every hour or every 3 hours, always cover the recordings of the last 3 hours.
E.g. the 10UT value reported by Dourbes covers the interval 07-10UT.

The estimated Kp values are the ones that can be found at NOAA/SWPC:
https://www.swpc.noaa.gov/products/planetary-k-index

The final Kp values are determined by GFZ Potsdam and can be downloaded at Kyoto WDC:
http://wdc.kugi.kyoto-u.ac.jp/kp/index.html
The geomagnetic three-hourly Kp index was introduced by J. Bartels in 1949 and is derived from the standardized K index (Ks) of 13 magnetic observatories. It is designed to measure solar particle radiation by its magnetic effects and today it is considered a proxy for the energy input from the solar wind to Earth.

The maps for auroral visibility can be found at https://www.swpc.noaa.gov/content/tips-viewing-aurora

Geomagnetic indices

- NOAA-scales: G-scale

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme		Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe		Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong		Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate		Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor		Kp = 5	1700 per cycle (900 days per cycle)

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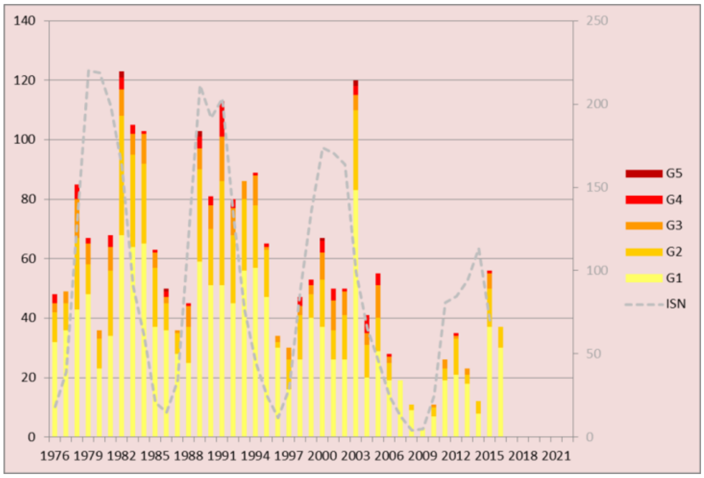
From the SWPC webpage:
NOAA Space Weather Scales
The NOAA Space Weather Scales were introduced as a way to communicate to the general public the current and future space weather conditions and their possible effects on people and systems. Many of the SWPC products describe the space environment, but few have described the effects that can be experienced as the result of environmental disturbances. These scales are useful to users of our products and those who are interested in space weather effects. The scales describe the environmental disturbances for three event types: geomagnetic storms, solar radiation storms, and radio blackouts. The scales have numbered levels, analogous to hurricanes, tornadoes, and earthquakes that convey severity. They list possible effects at each level. They also show how often such events happen, and give a measure of the intensity of the physical causes.

The « G » stands for Geomagnetic storms. Note it starts only from Kp =5 or higher.

More at http://www.stce.be/news/366/welcome.html

Geomagnetic indices

- NOAA-scales: G-scale



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More on the NOAA-scales at at http://www.stce.be/news/366/welcome.html

Each graph shows the yearly accumulation of the events, with the yearly International Sunspot Number (SILSO) superposed on it as the gray dashed line.
The plot of the geomagnetic storm days bears much less resemblance with the evolution of the sunspot number than in the previous two charts. This is because minor to strong geomagnetic disturbances can also be caused by the high speed solar wind streams (HSS) from coronal holes, hence distorting the familiar outlook of the sunspot cycle. Nonetheless, even then it is very clear that SC24 has been quite disappointing when it comes to the number and intensity of geomagnetic storms, with no extreme storms (G5) so far and precious few severe events (G4). Worse, the numbers even get depressingly low when one compares to other years such as e.g. the 120 storming days in 2003. Interestingly, the number of geomagnetic storm days is peaking in 2015-2016, so after the SC24 maximum in 2014. This is particularly due to the HSS from numerous coronal holes, and is a well-known aspect of this stage of a solar cycle.

More on SC24 geomagnetic performance at http://www.stce.be/news/243/welcome.html

A quick analysis of the final Kp indices as archived at the Kyoto World Data Centre (WDC) for geomagnetism reveals that the current solar cycle (SC24) is really underperforming so far. Not only has there not been any day with extreme geomagnetic storming, SC24 also has a lot more "quiet" days compared to the average of the previous 7 solar cycles (SC17-23). Of course, most of those cycles had already passed their maximum for 1-2 years, whereas SC24 is peaking only now and at a much lower solar activity level.

Geomagnetic indices

- From K to Kp (1/2)
  - Measurement of local H-components
  - Removal of diurnal variations (quiet days)
  - Range (Min-to-Max) during 3-hours interval
  - Conversion to quasi-logaritmic integer K
    - Local K index (0, … , 9)
    - Scale is location specific + normalization of occurrence frequency

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Source: Love J.J., Remick K.J. (2007) Magnetic Indices. In: Gubbins D., Herrero-Bervera E. (eds) Encyclopedia of Geomagnetism and Paleomagnetism. Springer, Dordrecht
https://doi.org/10.1007/978-1-4020-4423-6_178
https://geomag.usgs.gov/downloads/publications/Magnetic_Indices.pdf

H-component: the horizontal intensity of the magnetic field vector
http://geomag.nrcan.gc.ca/mag_fld/comp-en.php

Geomagnetic indices

- From K to Kp (1/2)

The K index is derived from the amplitude of the variations of the field's horizontal components (the H and D pair, or alternatively, the X and Y components) after subtracting the daily solar regular (S_R) variation for the particular component (cf. **Fig.2**).

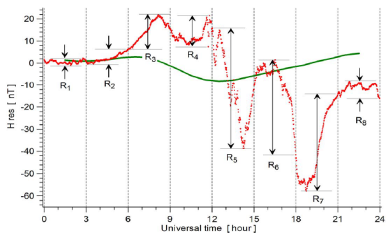

Fig.2. Calculation of the 3-hour K index over a 24 hour period. A daily record of 1-min measurements of the H component is presented here to illustrate the elimination of the solar regular variation, the S_R curve (the solid line), and the consequent determination of the 8 ranges (R_i, i=1,8). The difference between the upper (maximum) and lower (minimum) envelopes that are parallel to the S_R curve, determines the disturbance range within every 3-hour interval.

K-index value	Limits of Range Classes, nT (Niemegk)	Limits of Range Classes, nT (Dourbes)
0	0 - 5	0 – 4.9
1	5 - 10	4.9 – 9.7
2	10 - 20	9.7 – 19.4
3	20 - 40	19.4 – 38.9
4	40 - 70	38.9 – 68.0
5	70 - 120	68.0 – 116.6
6	120 - 200	116.6 – 194.4
7	200 - 330	194.4 – 320.8
8	330 - 500	320.8 – 483.0
9	500 +	483 +

Geomagnetic indices

- From K to Kp (2/2)
  - Correction for local, diurnal and seasonal differences between the stations
    - Conversion tables (different for each station)
  - Result is a standardized K index « Ks » for each of the 13 stations
    - In thirds (0o, 0+, … , 9-, 9o)
  - The Kp index is the average of the 13 stations Ks
    - Estimated Kp is average of 8 stations

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From GFZ Potsdam: https://www.gfz-potsdam.de/en/kp-index/

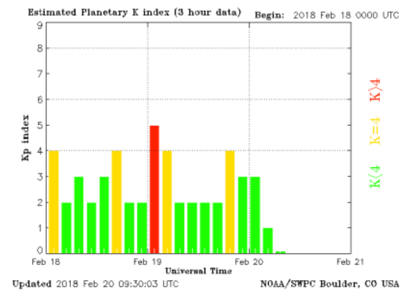
F. De Meyer (2006): The geomagnetic aa index as precursor of solar activity
www.meteo.be/meteo/download/de/520427/pdf/
The Kp index forms the basis for several other indices. Although the Kp index is very useful as an indicator of geomagnetic activity in the sub-auroral region, it has to be realized that it is not truly a planetary index since the network of stations is not uniformly distributed in longitude over the globe. The Soviet sector between 100° and 250° E and the Atlantic Ocean between 350° to 80° E are not covered. The southern hemisphere is represented by only two stations. An ideal network should have equal representation of observatories in both hemispheres. Moreover, the standardization procedure for evaluation of the index is largely empirical, which effectively cancels out some true features of geomagnetic activity such as summer/winter difference and Universal Time variations (Mayaud, 1980).

Geomagnetic indices

- From K to Kp (2/2)

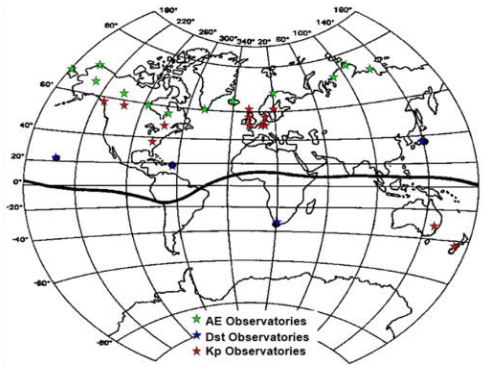
	JFND								MASO								MJJA							
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	3	3	4	3	2	2	2	2	3	4	4	3	3	2	2	2	3	3	4	3	2	2	2	3
2	6	7	8	7	6	5	4	5	6	8	8	7	6	6	5	5	6	6	7	6	5	4	5	6
3	9	11	12	11	9	8	7	8	10	11	12	11	10	9	8	8	9	10	11	9	8	8	8	9
4	13	14	15	14	12	11	10	11	13	15	16	15	13	12	11	11	13	13	15	14	12	11	12	12
5	16	17	19	17	16	14	13	14	16	19	19	19	17	15	15	15	16	18	19	17	16	15	16	16
6	20	21	23	21	20	17	17	17	21	22	23	22	21	18	19	19	21	22	21	21	21	19	20	20
7	23	24	25	24	24	20	20	21	24	25	25	25	24	23	23	24	24	25	24	24	24	24	24	24
8	25	26	26	26	26	24	25	25	26	26	26	26	26	25	25	25	26	26	26	26	26	26	26	26
9	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27

K to Ks conversion table for Niemegk

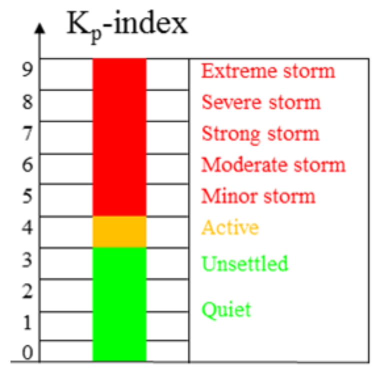


Geomagnetic indices

- Observatories



- Nomenclature



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Left figure taken from HAO/UCAR SW103 Lecture 4: Geomagnetic indices and space weather models.
https://www2.hao.ucar.edu/sites/default/files/users/whawkins/SW102_4_Indices.pdf

The nomenclature is the one mentioned in NOAA/SWPC' User guide.
https://www.swpc.noaa.gov/sites/default/files/images/u2/Usr_guide.pdf

The 13 observatories for Kp are (currently operational: https://www.gfz-potsdam.de/en/kp-index/): Sitka, Alaska, USA; Meanook, Canada; Ottawa, Canada; Fredericksburg, Virginia, USA; Hartland, UK; Wingst, Germany; Niemegk, Germany; Canberra, Australia; Brorfelde, Denmark; Eyerewell, New Zealand; Uppsala, Sweden; Eskdalemuir, UK; Lerwick, UK.

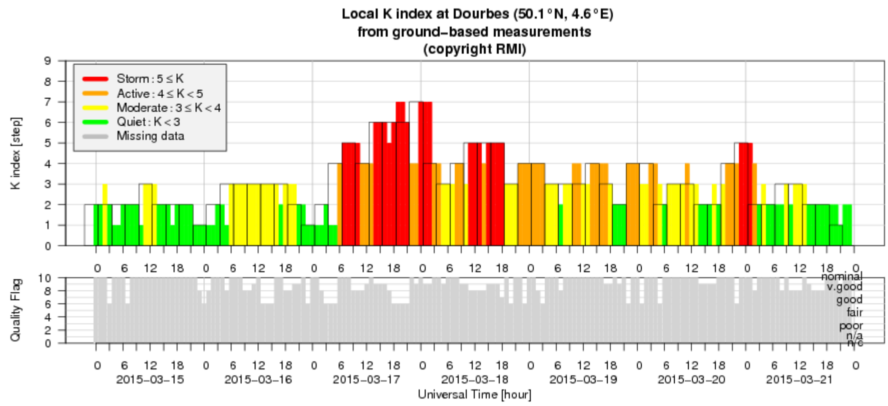
All these stations have geomagnetic latitudes between 35° and 60°. This zone is called the subauroral zone.

The main purpose of the standardized index Ks is to provide a basis for the global geomagnetic index Kp which is the average of a number of "Kp stations", originally 11. The Ks data for the two stations Brorfelde and Lovö/Uppsala, as well as for Eyerewell and Canberra, are combined so that their average enters into the final calculation, the divisor thus remaining 11.

The Estimated 3-hour Planetary Kp-index is derived at the NOAA Space Weather Prediction Center using data from the following ground-based magnetometers: Sitka, Alaska; Meanook, Canada; Ottawa, Canada; Fredericksburg, Virginia; Hartland, UK; Wingst, Germany; Niemegk, Germany; and Canberra, Australia.

Geomagnetic indices

- RMI Geophysical Centre of Dourbes



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Dourbes: http://ionosphere.meteo.be/geomagnetism/ground_K_dourbes

An important network of geomagnetic observatories is « Intermagnet »
http://www.intermagnet.org/data-donnee/dataplot-eng.php

INTERMAGNET has its roots in discussions held at the Workshop on Magnetic Observatory Instruments in Ottawa, Canada, in August 1986 and at the Nordic Comparison Meeting in Chambon La Foret, France, in May 1987. A pilot scheme between the United States and British Geological Surveys was described in the sessions of Division V of the International Association of Geomagnetism and Aeronomy at the 19th General Assembly of the International Union of Geodesy and Geophysics in Vancouver, Canada, in August 1987. This scheme used the GOES East satellite to successfully transfer geomagnetic data between the two organisations. INTERMAGNET was founded soon after in order to extend the network of observatories communicating in this way. In order to direct the work and oversee the operations of INTERMAGNET, an Executive Council and an Operations Committee were set up. The first Geomagnetic Information Node (GIN) was established in 1991, the first CD-ROM/DVD was also published in 1991.

Other important networks of geomagnetic observatories are « USGS » (USA; U.S. Geological Survey: https://geomag.usgs.gov/plots/) and “Izmiran” (Russia; http://forecast.izmiran.ru/en/index.php). An overview of smaller networks is at http://flux.phys.uit.no/Last24/, allowing also for real-time monitoring of selected stations with the tool “Stackplot” at http://flux.phys.uit.no/stackplot/

Geomagnetic indices

- Ap, ap
  - Derived from Kp
  - Required for daily averaging
  - « ap » value per interval (Kp)
    - Ap is the average of the 8 ap values for that day
  - Unit: nT
- aa
  - Derived (weighted average) from K indices from 2 antipodal , subauroral stations
    - Canberra
    - Hartland
  - Unit: nT
  - Going back to 1868
    - One of the oldest indices

Kp	0o	0+	1-	1o	1+	2-	2o	2+	3-	3o	3+	4-	4o	4+
ap	0	2	3	4	5	6	7	9	12	15	18	22	27	32

Kp	5-	5o	5+	6-	6o	6+	7-	7o	7+	8-	8o	8+	9-	9o
ap	39	48	56	67	80	94	111	132	154	179	207	236	300	400

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From GFZ/Potsdam: https://www.gfz-potsdam.de/en/kp-index/
The three-hour index ap and the daily indices *Ap*, ... are directly related to the *Kp* index. In order to obtain a linear scale from *Kp*, J. Bartels gave the [above] table to derive a three-hour equivalent range, named ap index. This table is made in such a way that at a station at about dipole latitude 50 degrees, *ap* may be regarded as the range of the most disturbed of the two horizontal field components, expressed in the unit of 2nT.

On the aa-index: F. De Meyer (2006): The geomagnetic aa index as precursor of solar activity
www.meteo.be/meteo/download/de/520427/pdf/
The availability of magnetic records from two old observatories, Greenwich (51.5° N,0.0° E) and Melbourne (37.8° S,145.0° E), which are almost antipodal, gave the possibility of obtaining a reliable long series if K scalings were made on their records (Mayaud, 1972). The two stations are nearly at the same geomagnetic latitude (one in the northern hemisphere, Greenwich: 50.1°, and one in the southern hemisphere, Melbourne: {48.9°) and about 10 h apart in longitude. The K indices from these two observatories at sub-auroral latitudes were first standardized for the corrected geomagnetic latitude of 50° in order to obtain a value identical with the one that would be obtained at a distance of 19° from the auroral zone. The converted equivalent amplitudes ak of the two stations were then averaged to provide the three-hourly index aa (expressed in units of nanotesla), which aims at monitoring the average intensity of the transient magnetic variations at sub-auroral latitudes.

More information on the aa-index also at BGS:
http://www.geomag.bgs.ac.uk/data_service/data/magnetic_indices/aaindex.html

Exercise: Calculation of Ap

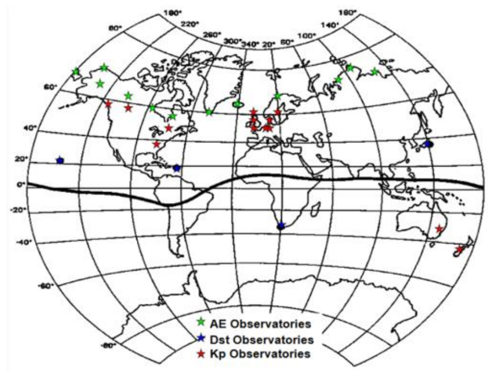
- On 8 September 2017, the 8 Kp values for that day were 8 5-4+5 8+7+6+5- (Kyoto, WDC). What is the Ap value for that day?
  - ✗ 6.3
  - ✗ 48.7
  - ✓ 106 nT
  - ✗ 236 nT

```
YYYYMMDD Kp[8]            Sum ap[8]                 Ap
20170901 3+3+2 4 4-2 2 4-24   18 18  7 27 22  7  7 22 16
20170902 4-5-5-3 2-3-3-3 26   22 39 39 15  6 12 12 15 20
20170903 2+2+1-2-3-2 1-2 14+   9  9  3  6 12  7  3  7  7
20170904 4-3+2-2 2-3-4-5-23+ 22 18  6  7  6 12 22 39 16
20170905 4 3 2+2-2 2+3-1+19+ 27 15  9  6  7  9 12  5 11
20170906 1+1+1+3-3 2-0+3+15    5  5  5 12 15  6  2 18  8
20170907 3-4-4-4-3-2 3-8-29- 12 22 22 22 12  7 12179 36
20170908 8 5-4+5 8+7+6+5-49-207 39 32 48236154 94 39106
20170909 2+2-0+0+1-0+0 0  6-   9  6  2  2  3  2  0  0  3
20170910 0 0 0 0 0+3-2 3  8    0  0  0  0  2 12  7 15  4
20170911 3+3-2+2 3-2 3-3-20+ 18 12  9  7 12  7 12 12 11
20170912 2 2-2+2 3-2+4 5+22+   7  6  9  7 12  9 27 56 17
```


20170908 8 5-4+5 8+7+6+5-49-207 39 32 48236154 94 39106

Geomagnetic indices

- Dst
  - Storm-time Disturbance index
    - Severity of magnetic storms
  - Depression of the intensity of the H-component
    - Westward current
      - Related to changes in the ring current
  - Measured by 4 stations close to magnetic equator
    - But not too close…



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Source: Love J.J., Remick K.J. (2007) Magnetic Indices. In: Gubbins D., Herrero-Bervera E. (eds) Encyclopedia of Geomagnetism and Paleomagnetism. Springer, Dordrecht
https://doi.org/10.1007/978-1-4020-4423-6_178
https://geomag.usgs.gov/downloads/publications/Magnetic_Indices.pdf

One of the most systematic effects seen in ground-based magnetometer data is a general depression of the horizontal magnetic field as recorded at near-equatorial observatories (Moos, 1910). This is often interpreted as an enhancement of a westward magnetospheric equatorial ring current, whose magnetic field at the Earth's surface partially cancels the predominantly northerly component of the main field. The storm-time disturbance index Dst (Sugiura, 1964) is designed to measure this phenomenon. Dst is one of the most widely used indices in academic research on the magnetosphere, in part because it is well
motivated by a specific physical theory. The calculation of Dst is generally similar to that of AE, but it is more refined, since the magnetic signal of interest is quite a bit smaller. One-min resolution horizontal intensity data from low-latitude observatories are used, and diurnal and secular variation baselines are subtracted. A geometric adjustment is made to the resulting data from each observatory so that they are all normalized to the magnetic equator.
The average, then, is the Dst index. It is worth noting that, unlike the other indices summarized here, Dst is not a range index.

The 4 stations are Kakioka (Japan), Hermanus (South Africa), Honolulu (Hawaii, USA), San Juan (USA).

Geomagnetic indices

- Dst
  - Storm-time Disturbance index
    - Severity of magnetic storms
  - Depression of the intensity of the H-component
    - Westward current
      - Related to changes in the ring current
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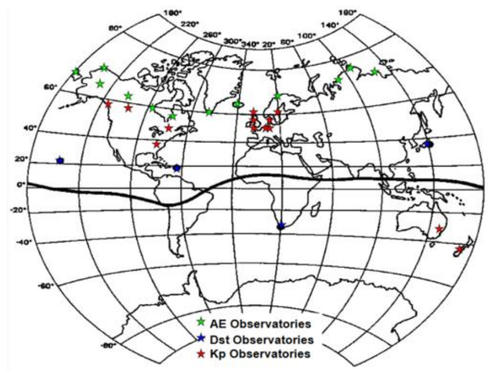

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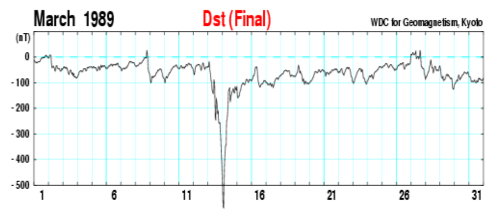
From the SIDC SWx Forecast Guide:
http://www.sidc.be/PRODEX_SIDEx/docs/Space_Weather_Forecasting_Guide_latest.pdf
The Dst or disturbance storm time index is a measure of geomagnetic activity used to assess the severity of magnetic storms. It is often considered to reflect variations in the intensity of the symmetric part of the ring current that circles Earth at altitudes ranging from about 3 to 8 Earth radii (RE), and is proportional to the total energy in the drifting particles that form the ring current (Wanliss et al. 2006, and references therein). It is calculated as an hourly index from the horizontal magnetic field component (H) at four observatories located close enough to the magnetic equator that they are not strongly influenced by auroral current systems. At the same time, these stations are far enough away from the magnetic equator so that they are not significantly influenced by the equatorial electrojet current that flows in the ionosphere. They are also relatively evenly spaced in longitude.... The convolution of their magnetic variations forms the Dst index, measured in nT, which is thought to provide a reasonable global estimate of the variation of the horizontal field near the equator.

So: Dst represents an induced magnetic field caused by the ring current particles, which are plasmasheet particles that are accelerated towards Earth during (sub)storms, where electrons rotate around Earth in one sense, and the ions in the other sense (as in the radiation belts) thus creating a current.

Geomagnetic indices

- Dst
  - Hourly measurements
  - Unit: nT
    - NOT a range index
  - Nomenclature
    - > -30 nT: Quiet
    - -30 - -50 nT: Weak storm
    - -50 - -100 nT: Moderate storm
    - -100 - -250 nT: Intense storm
    - < -250 nT: Extreme storm

- Real-time monitoring at Kyoto, WDC
  - http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/presentmonth/index.html



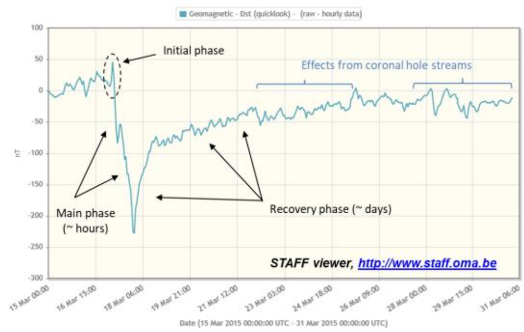
Real time monitoring at http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/presentmonth/index.html

A description on how the Dst index is determined can be found at http://wdc.kugi.kyoto-u.ac.jp/dstdir/dst2/onDstindex.html
3. INTERPRETATION OF THE Dst INDEX
The Dst index represents the axially symmetric disturbance magnetic field at the dipole equator on the Earth's surface. Major disturbances in Dst are negative, namely decreases in the geomagnetic field. These field decreases are produced mainly by the equatorial current system in the magnetosphere, usually referred to as the ring current. The neutral sheet current flowing across the magnetospheric tail makes a small contribution to the field decreases near the Earth. Positive variations in Dst are mostly caused by the compression of the magnetosphere from solar wind pressure increases.

Reminder: Dst represents an induced magnetic field caused by the ring current particles, which are plasmasheet particles that are accelerated towards Earth during (sub)storms, where electrons rotate around Earth in one sense, and the ions in the other sense (as in the radiation belts) thus creating a current.

Geomagnetic indices

- Dst
  - Phases of a geomagnetic storm
    - Initial phase
    - Main phase
    - Recovery phase
  - Most intense storms of SC24
    - 17 March 2015 (-223 nT)
    - 23 Jun 2015 (-204 nT)
  - Extreme storms
    - 30 Oct 2003: -383 nT
    - 14 Mar 1989: -589 nT



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Real time monitoring at http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/presentmonth/index.html

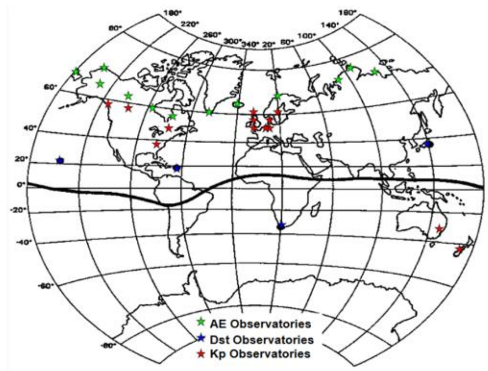
From the SIDC SWx Forecast Guide:
http://www.sidc.be/PRODEX_SIDEx/docs/Space_Weather_Forecasting_Guide_latest.pdf
Magnetic storms occur when the number and energy of positive ions and electrons drifting in the outer radiation belts increase significantly. Since electrons and protons drift in opposite directions they produce a ring current around the Earth. The direction of this current is westward causing a decrease in the surface field. The Dst index is a measure of the total energy of these drifting particles. A magnetic storm typically consists of three phases (Figure above). The initial phase is a result of an increase in solar wind dynamic pressure. This increase presses the magnetopause current closer to the Earth causing a positive perturbation in H. The main phase is a consequence of a southward turning of the interplanetary magnetic field (IMF). When the IMF turns southward, magnetic reconnection occurs on the dayside allowing a fraction of the solar wind electric field to penetrate the magnetosphere. This field transports ions from the tail to the inner magnetosphere where they are trapped in the ring current, causing the Dst index to become more negative. The recovery phase is a consequence of the IMF turning northward shutting off the magnetospheric electric field. Particle injection decreases while the drifting ions charge exchange with atmospheric neutral particles losing their energy and thereby decreasing the strength of the ring current (McPherron et al. 2001)

From the SWPC glossary: https://www.swpc.noaa.gov/content/space-weather-glossary#suddenimpulse
Sudden Impulse (SI): A sudden perturbation, positive or negative, of several nanotesla in the northward component (X component of the horizontal component) of the low-latitude geomagnetic field, *not* associated with a following geomagnetic storm. An SI becomes a Storm Sudden Commencement (SSC) if a storm follows.

SWPC sends alerts for these SI: https://www.swpc.noaa.gov/content/subscription-services
A Geomagnetic Sudden Impulse (SI) Expected Warning is issued when a shock has been observed in the upstream, in situ solar wind data. Based on the post-shock velocity, space weather forecasters generate a warning period indicative of when this disturbance is expected at Earth. The Geomagnetic Sudden Impulse Summary product is issued when the shock is actually observed at Earth, as indicated by the response of ground-based magnetic observatories. These products are useful in that they can confirm the actual arrival of anticipated coronal mass ejection (CME).

Geomagnetic indices

- AE index
  - Auroral Electrojet
  - Ionospheric closure current
  - 12 auroral stations
    - Northern hem.
      - +60° to +71°
      - Quite evenly spaced
  - Unit: nT
  - Best to determine aurora visibility



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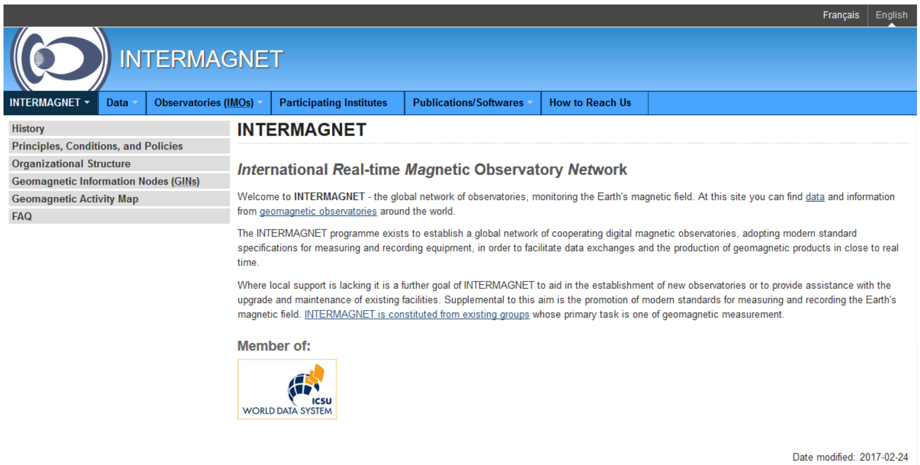
From the SIDC SWx Forecast Guide:
http://www.sidc.be/PRODEX_SIDEx/docs/Space_Weather_Forecasting_Guide_latest.pdf
During geomagnetic storms, magnetospheric electric currents are often diverted along field lines, with current closure through the ionosphere. The Auroral Electrojet (AE) index was originally introduced by Davis and Sugiura in 1966 as a measure of this global electrojet activity in the auroral zone. The configuration of the auroral ovals, roughly centred around the north and south magnetic poles where bright, active aurorae and strong magnetic disturbances are observed, is approximately a circle. The ovals contract during quite intervals, and expand equatorwards during enhanced geomagnetic activity (Perrone et al. 1998).
Ideally, the index should be derived from data collected from an equally spread series of stations forming a string situated underneath the northern and southern auroral ovals, but in practice the number of stations on the southern hemisphere is too sparse for reasonable utility in calculating AE (Love et al. 2007). Hence, the AE index is derived from 12 ground stations on the northern hemisphere between latitudes +60° and +71°.
The calculation of AE is relatively straightforward. One-minute resolution data from auroral observatories are used, and the average horizontal intensity during the five magnetically quietest days is subtracted. The total range of the data from among the various AE observatories for each minute is measured, with AU being the highest value and AL being the lowest value (Love 2007). The symbols AU and AL, derive from the fact that these values form the upper and lower envelopes of the superposed plots of all the data from these stations as functions of UT. The difference is defined as AE = AU - AL, which are indicators of the strength of the eastward and westward electrojet respectively. For completeness, the average is also defined as AO = 1/2 (AU + AL) (Perrone et al. 1998). Figure 50 shows the evolution of the AE index during the St-Patrick's day event on 17 March 2015.

Geomagnetic networks



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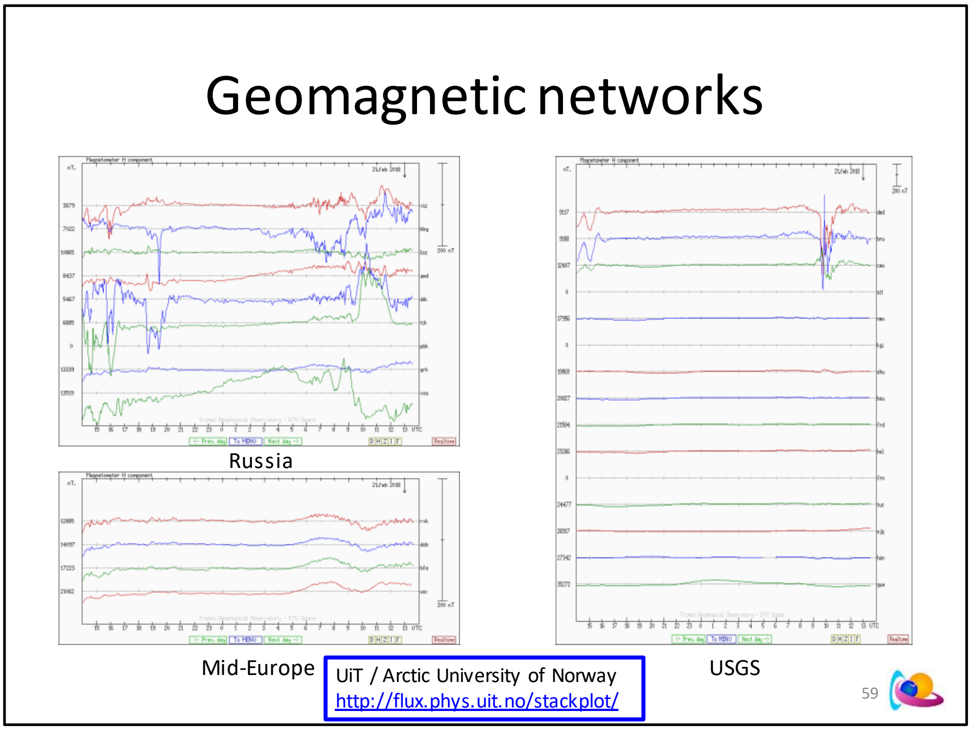
Dourbes: http://ionosphere.meteo.be/geomagnetism/ground_K_dourbes

An important network of geomagnetic observatories is « Intermagnet »
http://www.intermagnet.org/data-donnee/dataplot-eng.php

INTERMAGNET has its roots in discussions held at the Workshop on Magnetic Observatory Instruments in Ottawa, Canada, in August 1986 and at the Nordic Comparison Meeting in Chambon La Foret, France, in May 1987. A pilot scheme between the United States and British Geological Surveys was described in the sessions of Division V of the International Association of Geomagnetism and Aeronomy at the 19th General Assembly of the International Union of Geodesy and Geophysics in Vancouver, Canada, in August 1987. This scheme used the GOES East satellite to successfully transfer geomagnetic data between the two organisations. INTERMAGNET was founded soon after in order to extend the network of observatories communicating in this way. In order to direct the work and oversee the operations of INTERMAGNET, an Executive Council and an Operations Committee were set up. The first Geomagnetic Information Node (GIN) was established in 1991, the first CD-ROM/DVD was also published in 1991.

Other important networks of geomagnetic observatories are « USGS » (USA; U.S. Geological Survey: https://geomag.usgs.gov/plots/) and “Izmiran” (Russia; http://forecast.izmiran.ru/en/index.php). An overview of smaller networks is at http://flux.phys.uit.no/Last24/, allowing also for real-time monitoring of selected stations with the tool “Stackplot” at http://flux.phys.uit.no/stackplot/



Dourbes: http://ionosphere.meteo.be/geomagnetism/ground_K_dourbes

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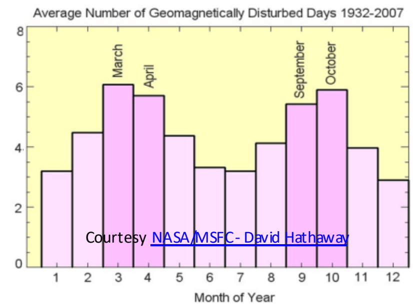
The Magnetosphere - Contents

- The geomagnetic field
- Main features
- Geomagnetic (sub)storms
- Measuring magnetic fields
  - Geomagnetic indices
  - Networks
- Miscellaneous

Miscellaneous

- Seasonal variation
  - More geomagnetic storms during equinoxes than during solstices
  - Probable explanation by Russell & McPherron (1973)



Courtesy NASA/MSFC- David Hathaway

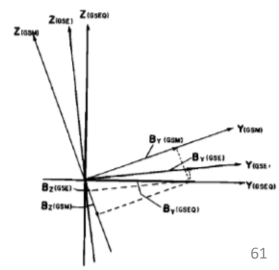


Fig. 4. One of the possible orientations of the Y-Z planes of the solar equatorial (GSEQ), solar ecliptic (GSE), and solar magnetospheric (GSM) coordinates, showing how a vector in the solar equatorial plane can have a southward (along the $-Z$ axis) GSE and GSM component.

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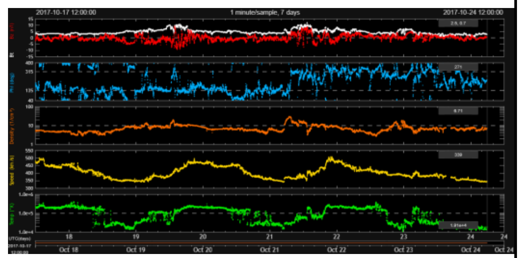
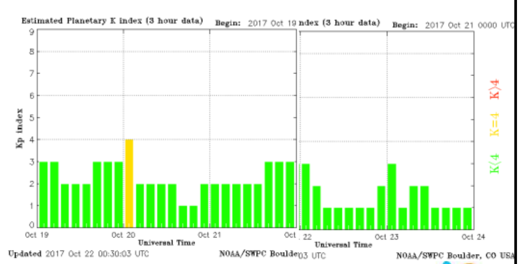
From the SIDC SWx Forecast Guide:
http://www.sidc.be/PRODEX_SIDEx/docs/Space_Weather_Forecasting_Guide_latest.pdf
Another element is the seasonal variation of the geomagnetic disturbances (Figure 52). Already in 1856, Edward Sabine showed from magnetic recordings that "… January and June are the months of minimum disturbance, September and April the months of maximum disturbance. The aggregate value of the disturbances in the equinoctial months is about three times as great as in the solstitial months." (Sabine 1856). This finding has been assessed and confirmed on numerous occasions and for various geomagnetic indices (e.g. Cliver et al. 2001, Svalgaard et al. 2002, Balan et al. 2017). The semiannual variation has been interpreted in terms of the (1) axial hypothesis based on the variation of the heliospheric latitude of the Earth with time of year (e.g., Cortie 1912), (2) equinoctial hypothesis based on the variation of the angle between the Earth–Sun line and Earth's dipole axis (e.g., Bartels 1932) and (3) Russell–McPherron (RM) effect based on the varying angle between the GSM (geocentric solar magnetospheric) Z-axis and GSE (geocentric solar ecliptic) Y-axis (Russell and McPherron 1973). From a review of subsequent papers, Bothmer et al. 2007 concluded that hypothesis (1) does not seem to play a key role in the origin of the semiannual variation.

Russell, C. T., McPherron, R. L. (1973): Semiannual variation of geomagnetic activity
http://adsabs.harvard.edu/abs/1973JGR....78...92R
*** … geomagnetic activity is caused by substorms, and, whereas the magnitude of the southward component has been shown to control substorm activity, the solar wind velocity, which controls the Kelvin-Helmholtz instability, has not. … The semiannual variation of geomagnetic activity is a manifestation of the varying probability of a southward component occurring in solar magnetospheric coordinates due to the changing orientation of the solar magnetospheric coordinate system relative to the solar equatorial system. This theory is both an axial theory, because the solar equatorial system depends on the heliographic latitude of the earth, and an equinoctial hypothesis, because the orientation of the solar magnetospheric coordinate system depends on the orientation of the earth's rotation axis relative to the solar wind. … We can further test the models, though, by examining auxiliary predictions of the models.
In particular, the southward component model predicts that the spring maximum in activity is associated on the average with fields toward the sun and the fall maximum with fields away from the sun.***

Miscellaneous

- **SNAP** effect
  - Concerns CHs
  - More intense storms
    - In **S**pring
      - From **N**egative pol. CHs
        - » Phi-angle towards the Sun (~315°)
    - In **A**utumn
      - From **P**ositive pol. CHs
        - » Phi-angle away from Sun (~135°)
  - Results from Russell-McPherron effect





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From the SIDC SWx Forecast Guide:
http://www.sidc.be/PRODEX_SIDEx/docs/Space_Weather_Forecasting_Guide_latest.pdf

The hypothesis proposed by Russell and McPherron (1973) has also another effect to be considered, i.e. that the high speed streams associated with coronal holes have different effects pending the season of the year they occur. Indeed, as the authors write from their analysis "…the prediction of the model using the southward component in solar magnetospheric coordinates that geomagnetic activity is stronger in the spring for inward interplanetary fields and stronger in the fall for outward interplanetary fields is supported." This has generally become known as the SNAP-principle, i.e. during spring months negative magnetic fields (directed towards the Sun) are more geo-effective, whereas during the fall months the positive magnetic fields (directed away from the Sun) are more geo-effective.

Summary

- The magnetosphere
  - Has a drop-shape
    - Compressed at sunside, stretched at nightside
  - Contains several zones w/ particles of varying E
    - Van Allen radiation belts,...
  - Protects us against high-energetic particles
- Geomagnetic storm
- The most often used geomagnetic indices are:
  - Kp, Ap, Dst

SPACE WEATHER INTRODUCTORY COURSE

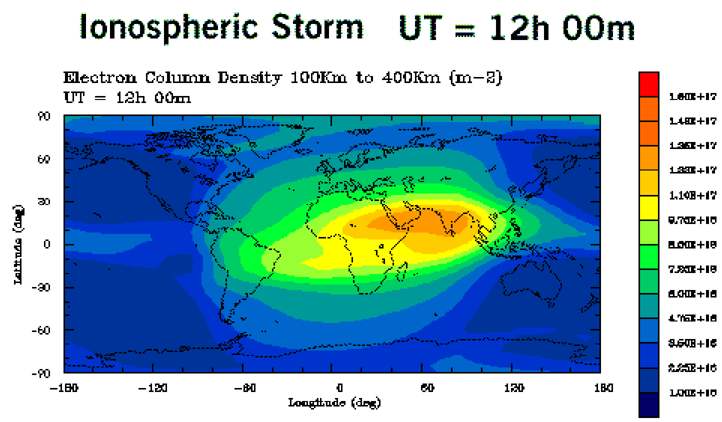
SWIC

Collaboration of

Solar-Terrestrial Centre of Excellence

Koninklijke luchtmacht

Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu



A. Burns, T. Killeen and W. Wang

The Ionosphere

Jan Janssens, Dr Nicolas Bergeot, Dr Jean-Marie Chevalier

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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

- 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

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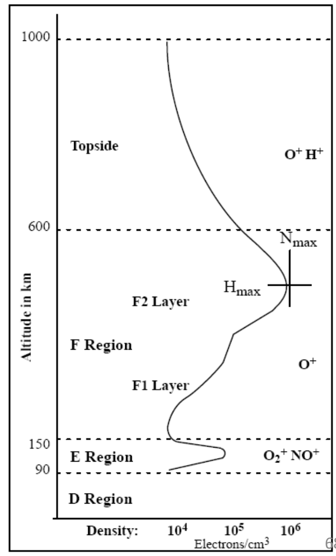
The ionosphere

- 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.

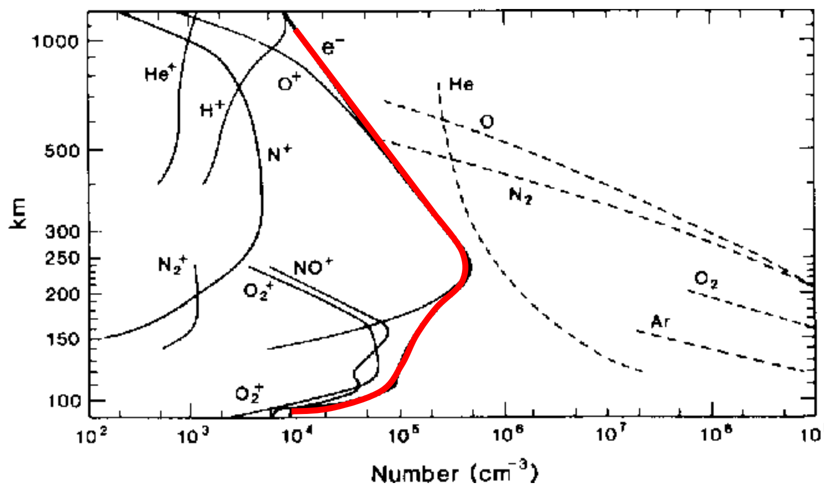
Definition from NASA: https://www.hq.nasa.gov/iwgsdi/Ionosphere.html
A shell of partially ionized atmosphere surrounding the Earth from approximately 60-1000 km. Absorption of short wavelength radiation from the Sun photo-ionizes gases in the atmosphere to produce the ionosphere. Gas dynamics and electromagnetic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



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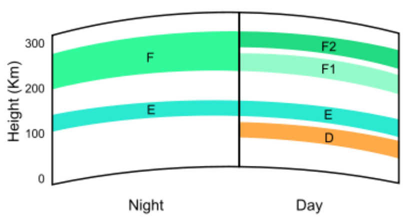
From: Earth’s atmosphere (Iver Cairns, 1999)
http://www.physics.usyd.edu.au/~cairns/teaching/lecture16/node2.html

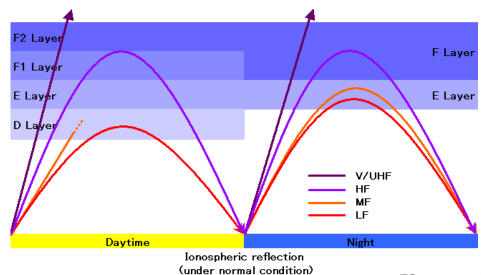
International Quiet Solar Year daytime ionospheric and atmospheric composition based on mass spectrometer measurements (Johnson, 1969; Luhmann, 1995).

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_reflection Day_and_Night.PNG
Alternative: https://radiojove.gsfc.nasa.gov/education/educ/radio/tran-rec/exerc/iono.htm

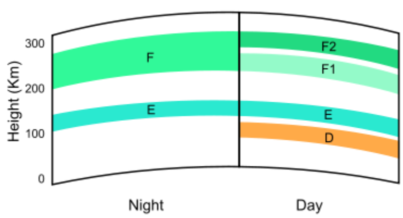
Ly-α (Lyman alpha): the Lyman-alpha line … is a spectral line of hydrogen … its wavelength of 1215.67 angstroms (121.567 nm …), … , places the Lyman-alpha line in the vacuum ultraviolet part of the electromagnetic spectrum, which is absorbed by air.

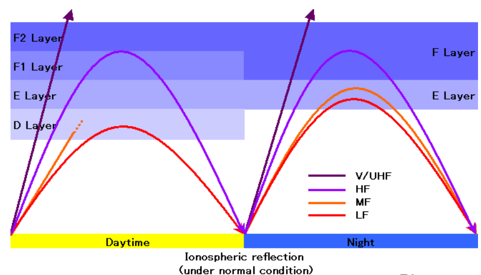
From Electronics notes (https://www.electronics-notes.com/articles/antennas-propagation/ionospheric/ionospheric-layers-regions-d-e-f1-f2.php) and Kenneth Davies (1990) Ionospheric Radio (*https://books.google.be/books?isbn=086341186X*)
There is a C-layer at about 55 km caused by galactic Cosmic Rays (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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- GNSS
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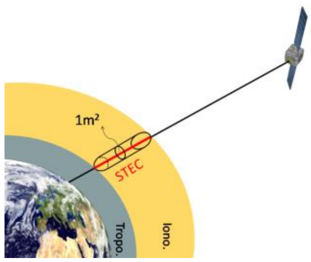
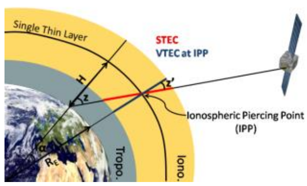
  - Error remedies
- ROB/RMI GNSS products

Ionosphere – Units and terminology 1





- **TEC**
  - Total Electron Content
  - = total # e⁻ along line-of-sight from spacecraft to ground receiver
  - = STEC
    - Slant TEC
  - Unit: TECu
    - TEC unit
    - 1 TECu = 10^{16} e^- per m^2
- **VTEC** *(Vertical TEC)*
  - *Typical* max. daily values BE (medium SC)
    - SC min: 10 TECu ; SC max: 30 TECu
- **ROTI**
  - Rate of TEC index (ROT index)
    - TEC/min
    - Info on temporal ionospheric irregularities

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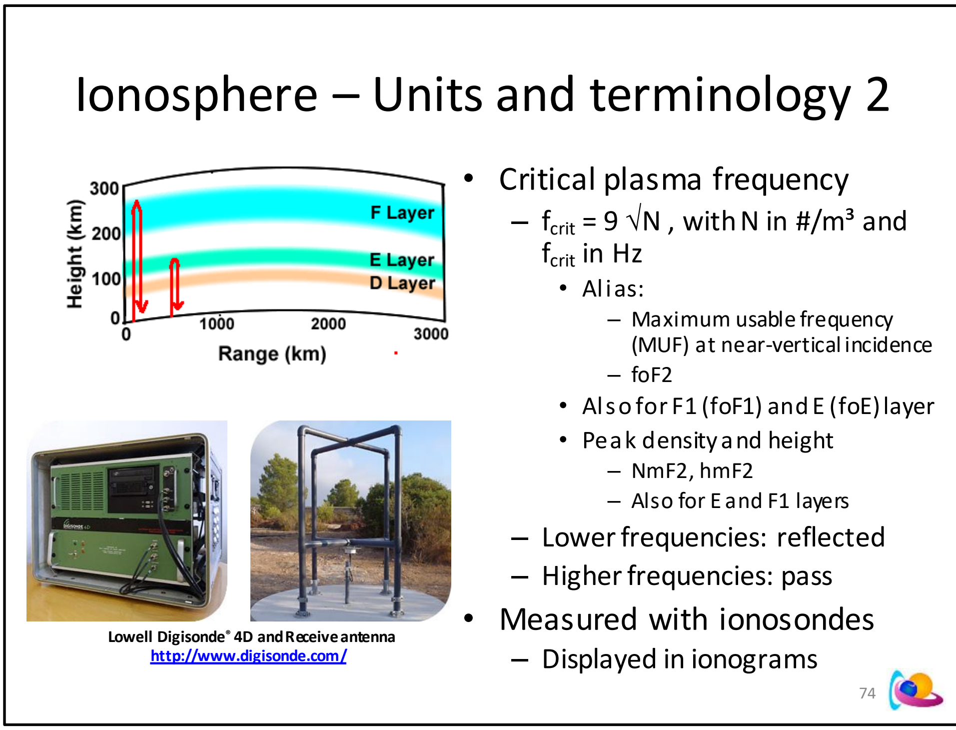
Oryema et al. (2015): Investigation of TEC variations over the magnetic equatorial and equatorial anomaly regions of the African sector
https://www.sciencedirect.com/science/article/pii/S0273117715003774
… TEC is defined as a measure of the total number of electrons in a unit area along the line of sight 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).

The IPP is usually taken at an altitude of 350 km , but may vary between 250 and 750+ km pending e.g. the elevation angle of the satellite.

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.

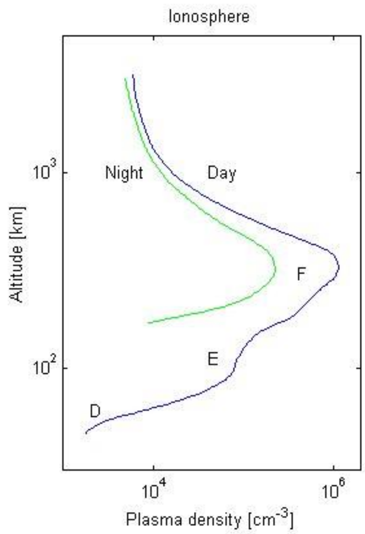
Norsuzila et al. (2008): Leveling Process of Total Electron Content (TEC) Using Malaysian Global Positioning System (GPS) Data
http://thescipub.com/pdf/10.3844/ajeassp.2008.223.229
ROTI maps can be found at the ESA page http://swe.ssa.esa.int/web/guest/swaci-federated (SWACI/DLR)



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

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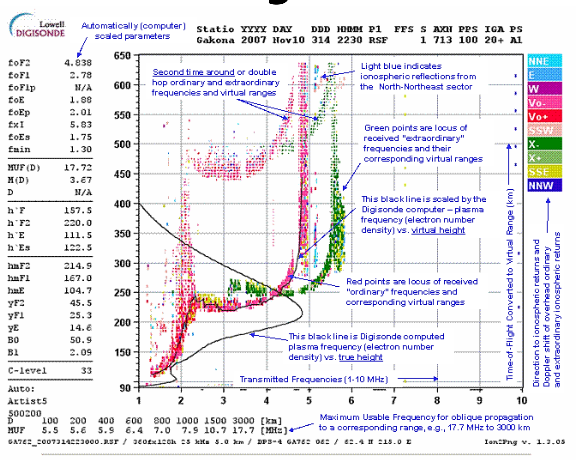
Figure from University of Oulu at Wikipedia: https://wiki.oulu.fi/display/SpaceWiki/Ionosphere

Ionosphere – Units and terminology 3

Ionogram



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

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

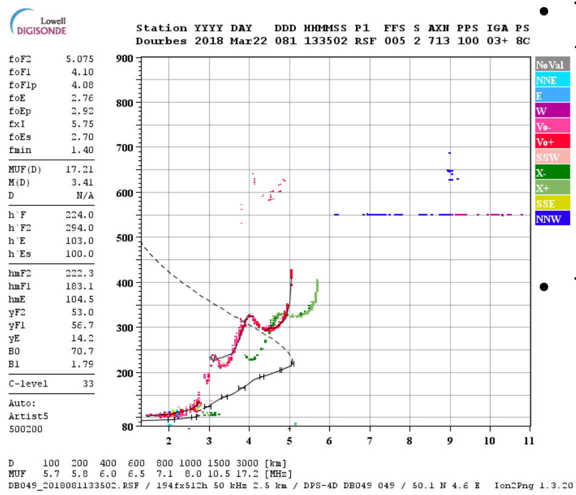
Text from World Data Center A for Solar-Terrestrial Physics – URSI Handbook of Ionogram Interpretation and Reduction (1972)
ftp://ftp.ngdc.noaa.gov/ionosonde/documentation/UAG_23A_Searchable.pdf (Chapter 1)

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.

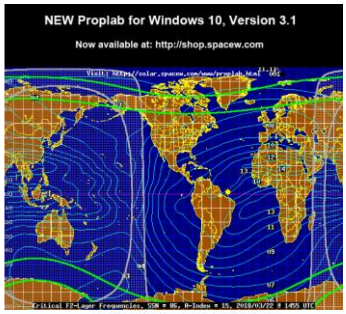
Exercise – Ionogram

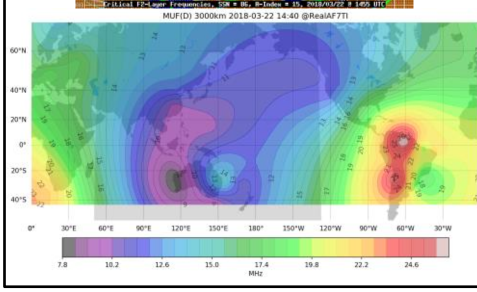


Credits: Dourbes GC - http://digisonde.oma.be/

- 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

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

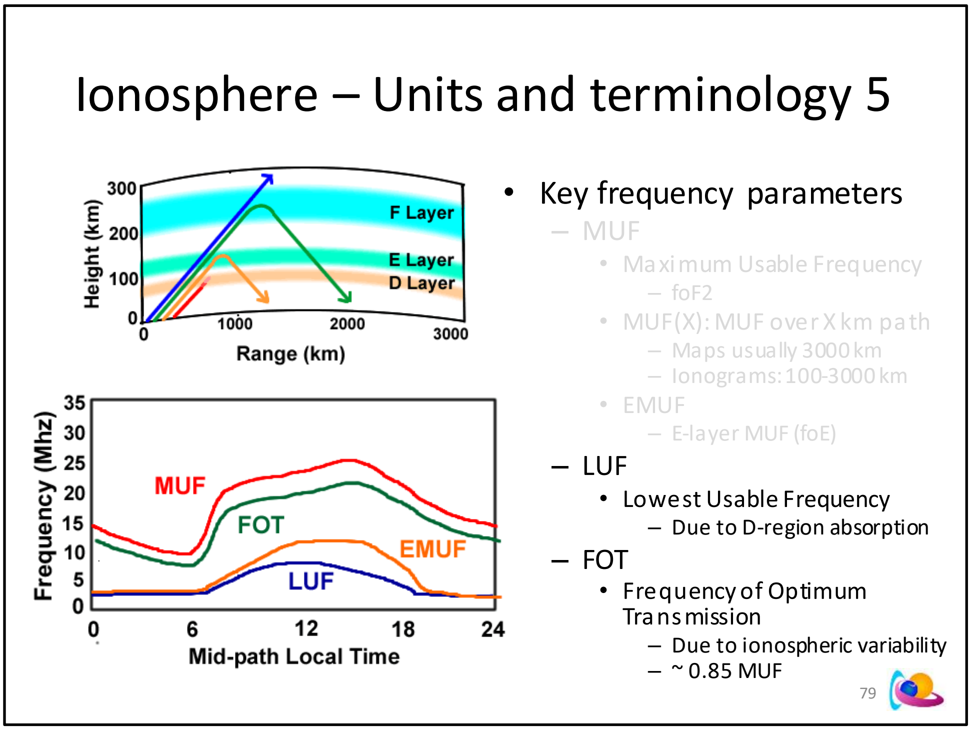
Info on critical frequencies from Naval Post-graduate School:
http://www.met.nps.edu/~psguest/EMEO_online/module3/module_3_2b.html

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/



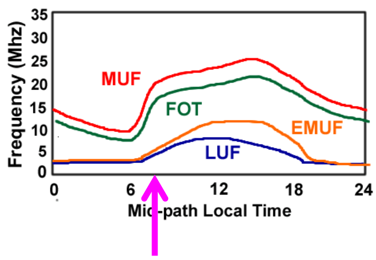
Near-real time graphs available at DXZone: https://www.dxzone.com/catalog/Propagation/
MUF: vertical incidence: http://www.spacew.com/www/realtime.php

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

Exercise – Solar flare & HF comms

- What happens to HF radio communication when a strong solar flare occurs (e.g. at 07UT)?



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 radiowave
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).

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

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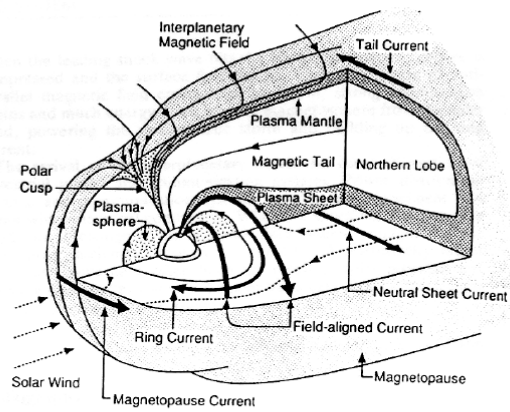
Ionosphere – Main features

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

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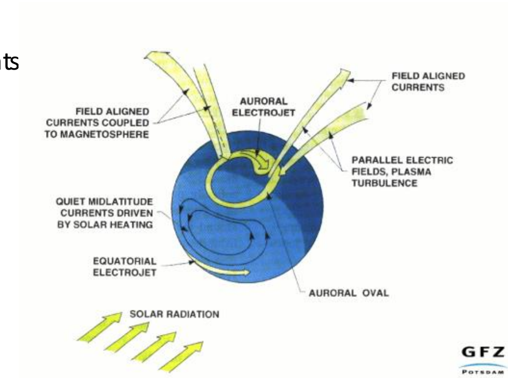
Potzdam figure taken from http://www-app2.gfz-potsdam.de/pb1/op/champ/science/magnetic_SCIENCE.html

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.

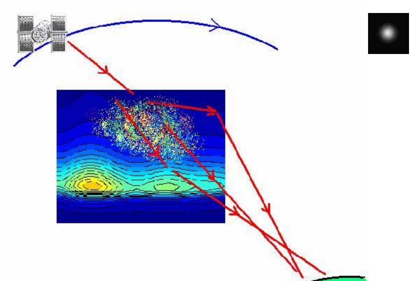
Ionosphere – Main features

- Equatorial anomaly
- Plasma bubbles
- Traveling Ionospheric Disturbances

Sources of ionospheric scintillation

Ionospheric scintillation

- Rapid fluctuations radio signal
  - Phase and intensity
    - May result in signal loss
- Source
  - Small scale irregularities in e⁻ density
  - Quantification *(e.g. PECASUS)*
    - Amplitude: S4 index
      - *Low (<0.5) to High (>0.8)*
    - Phase: σ_Φ index (radians)
      - *Low (<0.4) to High (>0.7)*
- Locations
  - Equatorial anomaly
  - Polar regions
- Difficult to predict



Credits: INGV

The scintillation of the satellite signals is due to the random fluctuations of the refractive index which distort the original wave front, giving rise to a random phase modulation of a wave. If the satellite and/or the ionosphere move relative to the receiver, temporal variations of amplitude and phase are recorded on the ground. The fluctuations in the refractive index are due to the irregularities in the ionosphere!

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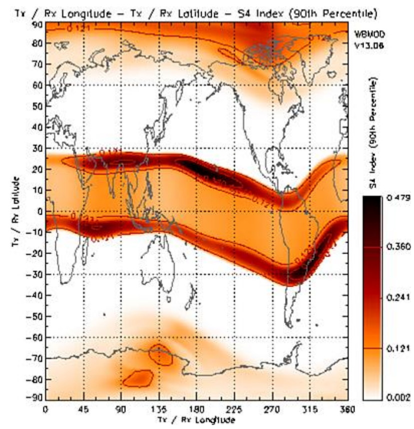
Ionospheric scintillation to radio signals is very similar as atmospheric scintillation to visible light
Atmospheric scintillation: http://www.islandnet.com/~see/weather/elements/twinkle.htm
The technical term for twinkling is scintillation, the rapid variation in apparent position, colour or brightness 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 *(e.g. PECASUS)*
    - Amplitude: S4 index
      - *Low (<0.5) to High (>0.8)*
    - Phase: σ_Φ index (radians)
      - *Low (<0.4) to High (>0.7)*
- 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

Equatorial (Ionization) Anomaly

- Solar-driven winds + eastward electric field
  - Charged particles move up and along northward oriented magnetic field
    - Equatorial fountain
      - Daytime phenomeon
      - Magnetic equator
        - » 15° N & S

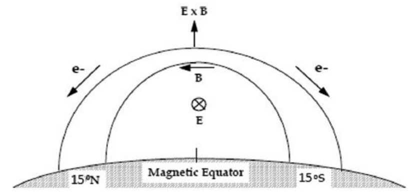
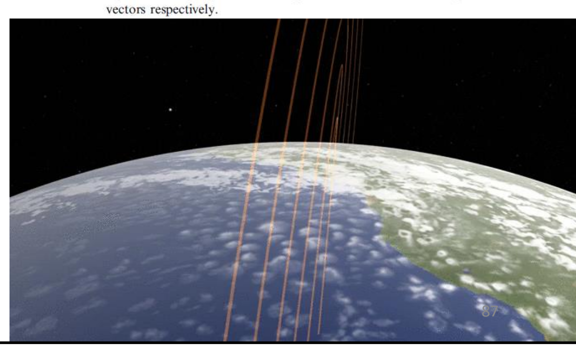


Fig. 1. Illustration of the equatorial fountain effect which gives rise to the equatorial anomaly. E and B represent the electric and magnetic field vectors respectively.



Credits: NASA / GSFC

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.

Equatorial (Ionization) Anomaly

- Solar-driven winds + eastward electric field
  - Charged particles move up and along northward oriented magnetic field
    - Equatorial fountain
      - Daytime phenomeon
      - Magnetic equator
        - » 15° N & S

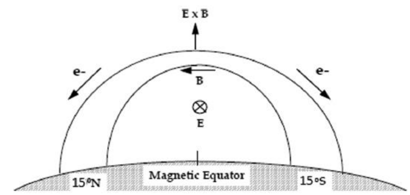
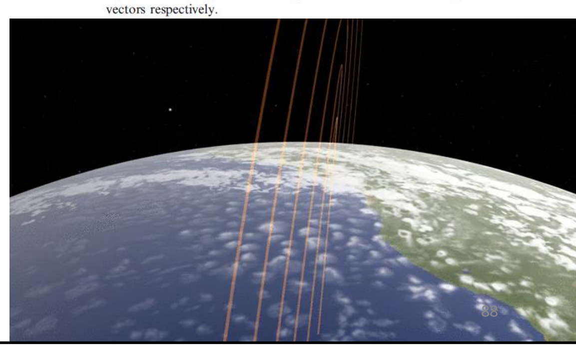


Fig. 1. Illustration of the equatorial fountain effect which gives rise to the equatorial anomaly. E and B represent the electric and magnetic field vectors respectively.



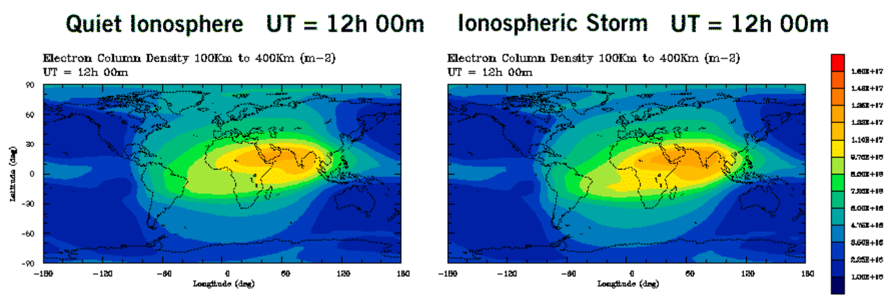
Credits: NASA / GSFC

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).

A more complete story can be found in Balan et al. (2018) at
https://agupubs.onlinelibrary.wiley.com/doi/full/10.26464/epp2018025

Equatorial (Ionization) Anomaly

- Effect on EIA from geomagnetic storm



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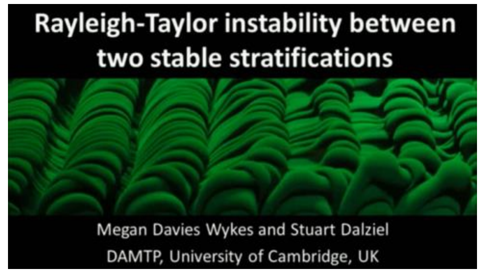
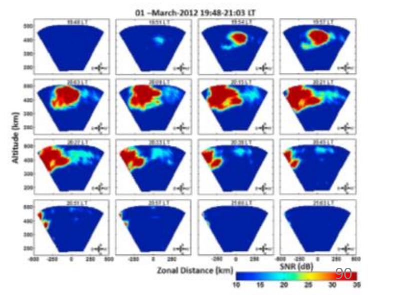
Equatorial anomaly
Animation from Radio Jove: https://radiojove.gsfc.nasa.gov/education/educ/radio/tran-rec/exerc/iono.htm
Below is an animation comparing the ionospheric conditions during a typical day with that of a day containing an ionospheric storm. An ionospheric storm is caused by a coronal mass 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





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.

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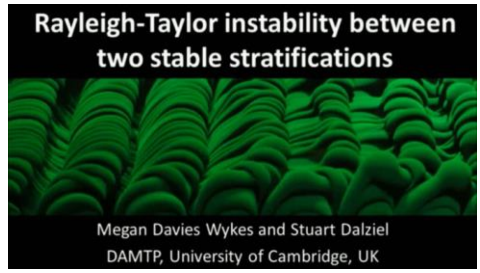
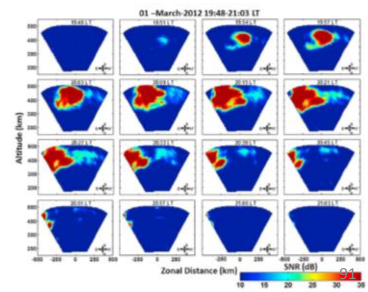




Bottom Picture taken from
Ajith et al. (2015): Explicit characteristics of evolutionary-type plasma bubbles observed from Equatorial Atmosphere Radar during the low to moderate solar activity years 2010-2012
http://adsabs.harvard.edu/abs/2015JGRA..120.1371A
The equatorial plasma bubbles (EPBs)/equatorial 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.

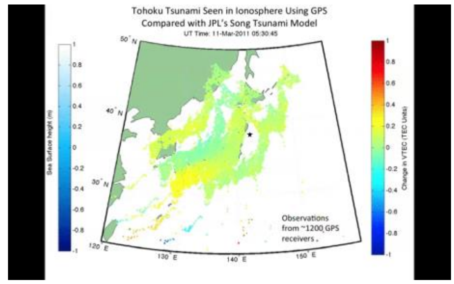
From the STCE Newsitem:
http://www.stce.be/news/420/welcome.html
The main cause of the ionospheric unrest is the presence of equatorial plasma bubbles, i.e. depletions of electron density inthe ionosphere. Their number correlates with the solar activity level, and they also are more numerous during the 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

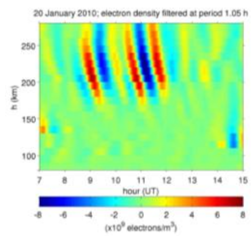
More on (equatorial) spread F: https://www.hsu.edu/academicforum/1998-1999/1998-9AFA%20Review%20of%20Equatorial%20Spread%20F.pdf (McDaniel, 1998)

Travelling Ionospheric Disturbances

- TID
  - Ionospheric manifestations of atmospheric gravity waves
  - 2 classes
    - Large Scale
      - Size: > 1000 km
      - Period: 1-3 hours
      - Can travel from Pole to Eq.
      - Source: Geomagnetic storms
    - Medium scale
      - Size: 100s km
      - Period: < 1 hour
      - Sources
        - » Solar eclipses
        - » Earthquakes
        - » Jet streams
        - » …



Credits: NASA / JPL



Credits: Van de Kamp et al. (2014) 92

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).

The ionosphere - Contents

- Introduction
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  - Coupling magnetosphere
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- Ionospheric variability
- GNSS
  - What & How
  - Error sources
  - Error remedies
- ROB/RMI GNSS products

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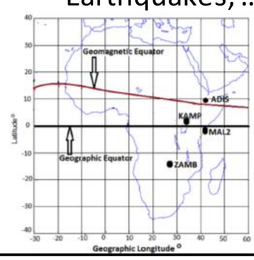
Ionospheric variability

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



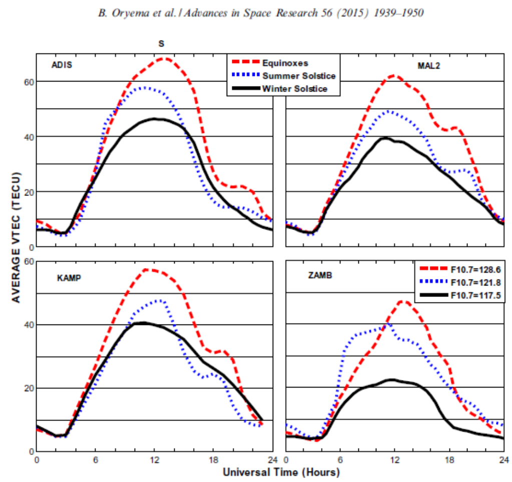


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Figure from Oryema (2015): Investigation of TEC variations over the magnetic equatorial and equatorial anomaly regions of the African sector
https://www.sciencedirect.com/science/article/pii/S0273117715003774

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,…

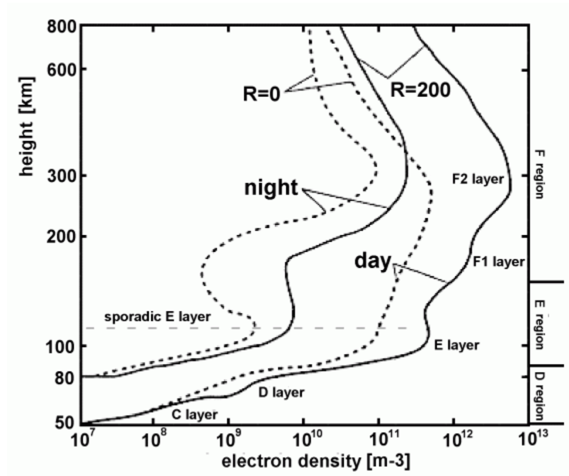

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Figure from INGV: http://roma2.rm.ingv.it/en/research_areas/4/ionosphere showing the day-to-night and the solar cycle variation (their Figure 1)

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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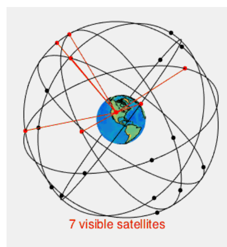
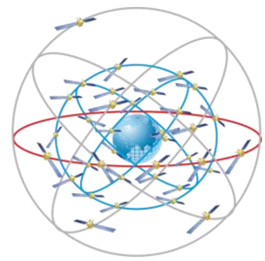
GNSS - Global Navigation Satellite System

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

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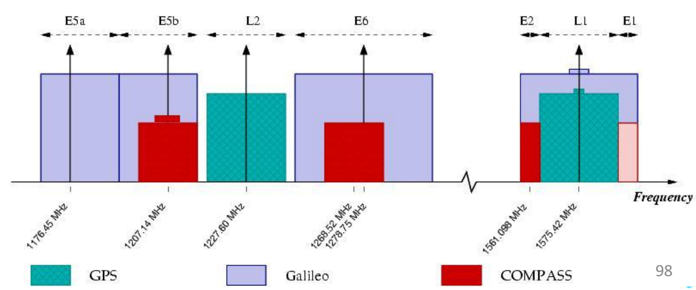

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Situation in February 2018

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

https://en.wikipedia.org/wiki/Satellite_navigation#/
Global coverage for each system is generally achieved by a satellite constellation of 18–30 medium Earth orbit (MEO) satellites spread between several orbital planes. The actual systems vary, but use orbital inclinations of >50° and orbital periods of roughly twelve hours (at an altitude of about 20,000 kilometres or 12,000 miles).

How does GNSS work?

- 4 satellites needed
  - Trilateration with 3 S/C
    - = measure distances
  - 3 is not enough
    - Gives only coarse location
      - Earth is not a perfect sphere
      - Receiver has no atomic clock
        - » Position of the satellites is never « precisely » known
  - 4 or more satellites
    - Time diff. S/C & Rec clocks
      - Least squares
        - » Most likely position
    - 24 sats needed for worldwide coverage
  - Still needs further correction
    - Ionospheric delays
    - Tropospheric delays

Credits: Techtitude
http://techtitude.blogspot.be/2010/10/triangulationtrilateration-in-gps.html

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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

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Credits: Techtitude
http://techtitude.blogspot.be/2010/10/triangulationtrilateration-in-gps.html

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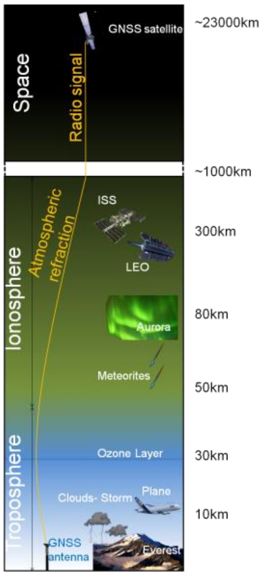
Wikipedia: https://en.wikipedia.org/wiki/Global_Positioning_System#Basic_concept_of_GPS

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.

GNSS – Error sources



- Atmospheric refraction
  - Signal delays
    - Inaccuracies (x, y, z, t)
  - Troposphere
    - Delays between 2 to 10 m
    - Water vapour & (N_2, O_2, Ar)
  - Ionosphere
    - Delays between 10 to 30 m
      - Loss-of-signal possible
    - Function of
      - Number of electrons
      - Inversely proportional to f^2
- Local environment
  - Multipathing,…

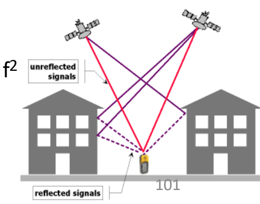


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Figure from ROB/GNSS: http://gnss.be/atmosphere_tutorial.php
Figure from http://psychology.wikia.com/wiki/Light_refraction

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.

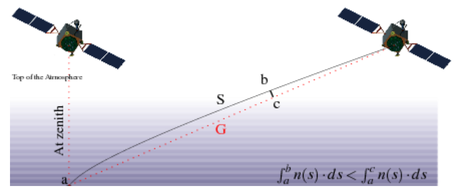
More info on multipathing at Wikipedia: https://en.wikipedia.org/wiki/Multipath_propagation

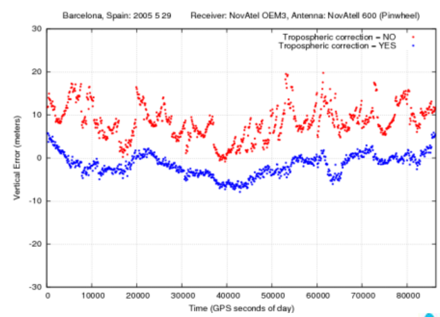
Figure from http://www.jocosarblog.org/jocosarblog/2011/10/gps-multipath-errors-what-they-are-and-why-the-confuse-your-gps.html

GNSS – Error remedies

Tropospheric 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

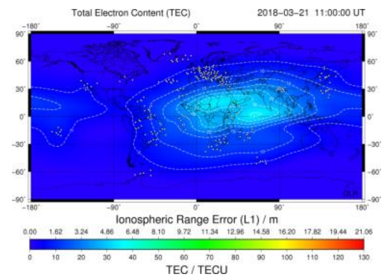
Troposphere is the atmospheric layer placed between earth's surface and an altitude of about 60 kilometres. The effect of the troposphere on the GNSS signals appears as an extra delay in the measurement of the signal traveling from the satellite to receiver. This delay depends on the temperature, pressure, 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.

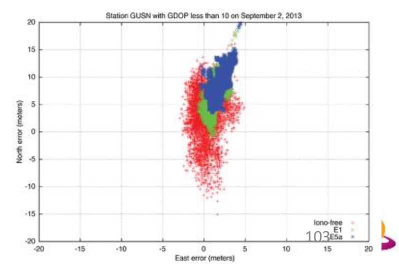
GNSS – Error remedies

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…

… / …

GNSS – Error remedies

Ionospheric corrections

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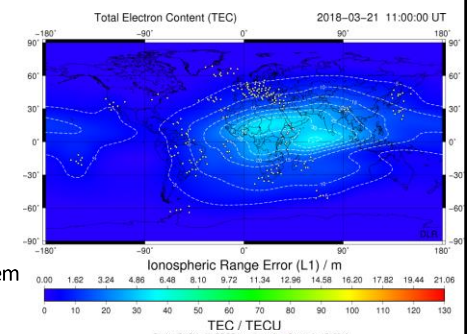

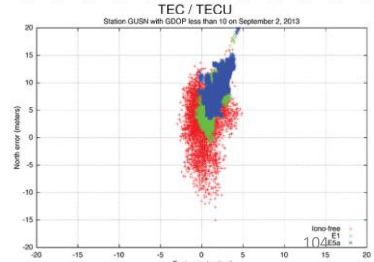

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… / …

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
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    - Removes most of errors
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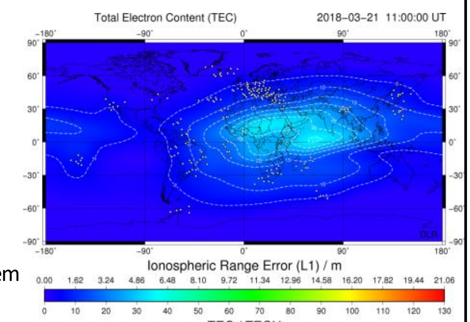

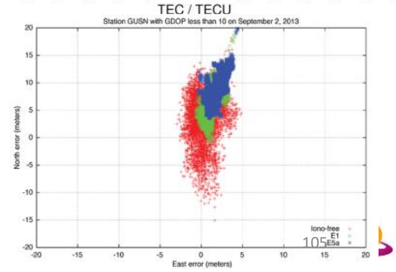

… / …

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

GNSS – Error remedies

Ionospheric corrections

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    - Removes most of errors
  - Single frequency receivers
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      - DGPS: RTK, PPP
    - External ionospheric models
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        - » GPS
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      - Nequick model
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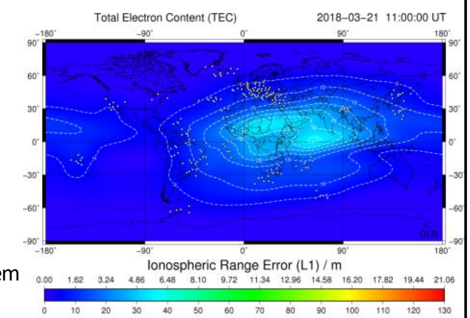

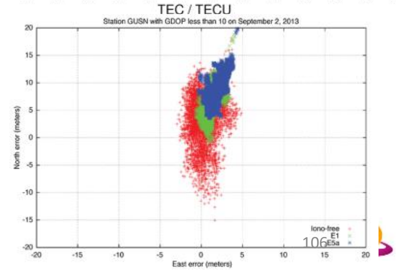

Single frequency users

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.

… / …

GNSS – Error remedies

Ionospheric corrections

- Errors <u>ARE</u> f-dependent
  - Dual frequency receivers
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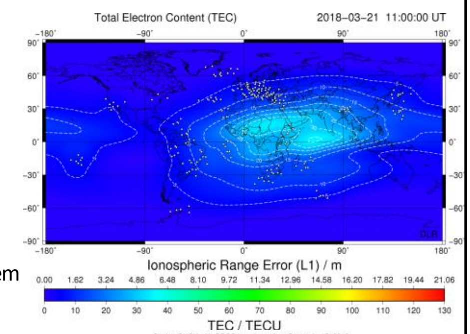
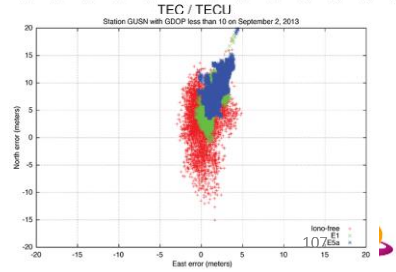




Single frequency users
Concerning single frequency receivers, the user need an external information to correct the signal delay. For that, different methods can be used: …
B. … / …

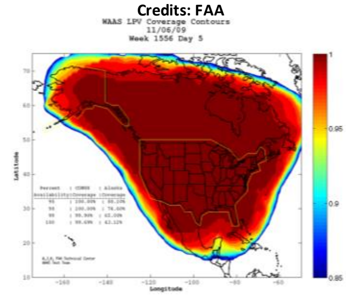
<u>IRI 2007 model</u>: The International Reference Ionosphere (IRI) (http://ccmc.gsfc.nasa.gov/modelweb/models/iri_vitmo.php) This model [e.g. Bilitza and Reinisch, 2008] is an empirical model based on a wide range of ground and space data. It gives monthly averages of electron density, ion composition (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

- Satellite Based Augmentation Systems (SBAS)
  - Based on corrections from ground-based stations
  - Sent to two master stations
    - Calculate and send corrections to GEO satellites
  - Use of GEO sats to distribute corrections
  - Regional

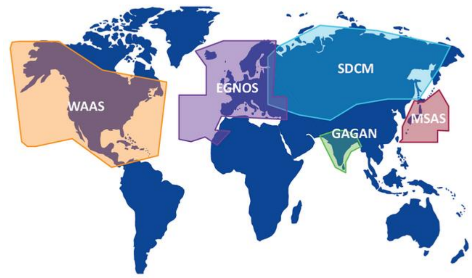
Credits: FAA

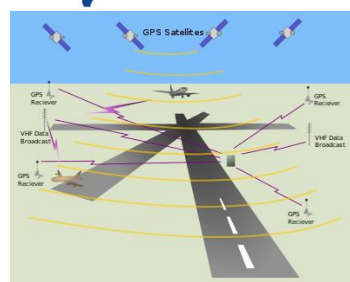


Info from and full movie at FAA: https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas/howitworks/

GNSS – Augmentation systems

- Satellite 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 (old terminology)
    - Local^2
  - RTK (local) & PPP (global)





Figures from https://www.gsa.europa.eu/european-gnss/what-gnss/what-sbas and from https://en.wikipedia.org/wiki/Local-area_augmentation_system

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

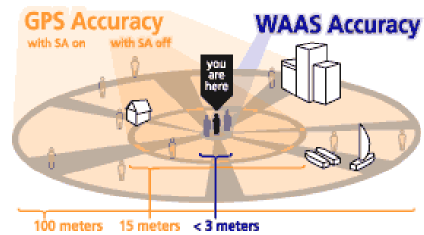
EGNOS: **European Geostationary Navigation Overlay Service**
Wikipedia: https://en.wikipedia.org/wiki/European_Geostationary_Navigation_Overlay_Service
ESA: http://www.egnos-pro.esa.int/
ESA: http://www.esa.int/Our_Activities/Navigation/EGNOS/What_is_EGNOS

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

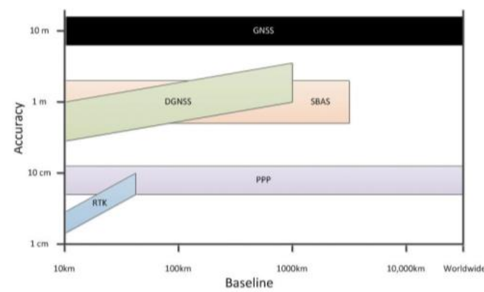
Avionics: http://www.aviationtoday.com/2011/11/01/precision-approaches/
In very broad terms, the basic concepts of the two systems are similar — each uses a dedicated network of precision GPS monitor receivers dispersed at separate, accurately surveyed locations. In both cases each individual monitor's 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).

GNSS – Augmentation systems

- Accuracies
  - Augmentation systems have significantly higher accuracy
    - Typical GPS: 15 metres
    - Typical DGPS: 3-5 metres
    - Typical WAAS: < 3 metres
  - Further improved by LAAS
    - RTK & PPP
  - Carrier phase PPP gives cm-dm accuracies over a global scale



Credits: FAA



Figures from FAA and https://www.novatel.com/an-introduction-to-gnss/chapter-5-resolving-errors/gnss-data-post-processing/
Further info at https://www.novatel.com/an-introduction-to-gnss/chapter-5-resolving-errors/gnss-measurements/ ; https://www.gsa.europa.eu/european-gnss/what-gnss/what-sbas ;

Accuracies:
Springer Handbook of Global Navigation Satellite Systems edited by Peter Teunissen, Oliver Montenbruck pp. 854

Comparison of systems:
Hugues D : https://www.youtube.com/watch?v=BGkohw9xGyk

PPP: https://en.wikipedia.org/wiki/Precise_Point_Positioning
“Precise Point Positioning (PPP) is a global navigation satellite system (GNSS) positioning method that calculates very precise positions, with errors as small as a few centimeters under good conditions. PPP is a combination of several relatively sophisticated GNSS position refinement techniques that can be used with near-consumer-grade hardware to yield near-survey-grade results. PPP uses a single GNSS receiver, unlike standard RTK methods, which use a temporarily fixed base receiver in the field as well as a relatively nearby mobile receiver. PPP methods overlap somewhat with DGNSS positioning methods, which use permanent reference stations to quantify systemic errors. … PPP relies on two general sources of information: direct observables and ephemerides. … One direct observable for PPP is **carrier phase**, i.e., not only the timing message encoded in the GNSS signal, but also whether the wave of that signal is going "up" or "down" at a given moment. … Ephemerides are precise measurements of the GNSS satellites' orbits, made by the geodetic community (the International GNSS Service and other public and private organizations) with global networks of ground stations. … The ephemerides that the satellites broadcast are earlier forecasts, up to a few hours old, and are less accurate (by up to a few meters) than carefully processed observations of where the satellites actually were. Therefore, if a GNSS receiver system stores raw observations, they can be processed later against a more accurate ephemeris than what was in the GNSS messages, yielding more accurate position estimates than what would be possible with standard realtime calculations. This post-processing technique has long been standard for GNSS applications that need high accuracy.”

GNSS – Augmentation systems

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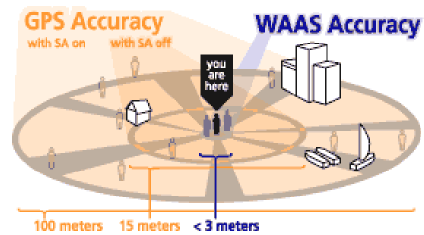
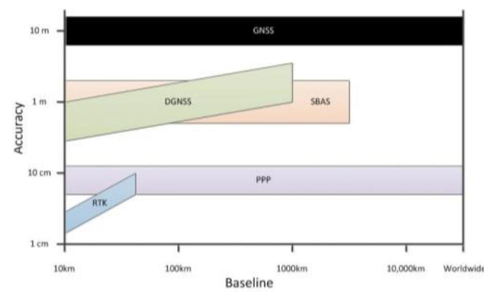


Credits: FAA



Figures from FAA and https://www.novatel.com/an-introduction-to-gnss/chapter-5-resolving-errors/gnss-data-post-processing/
Further info at https://www.novatel.com/an-introduction-to-gnss/chapter-5-resolving-errors/gnss-measurements/ ; https://www.gsa.europa.eu/european-gnss/what-gnss/what-sbas ;

Accuracies:
Springer Handbook of Global Navigation Satellite Systems edited by Peter Teunissen, Oliver Montenbruck pp. 854

Comparison of systems:
Hugues D : https://www.youtube.com/watch?v=BGkohw9xGyk

… / …

RTK: https://en.wikipedia.org/wiki/Real-time_kinematic
"Real-time kinematic (RTK) positioning is a satellite navigation technique used to enhance the precision of position data derived from satellite-based positioning systems (global navigation satellite systems, GNSS) such as GPS, GLONASS, Galileo, NavIC and BeiDou. It uses measurements of the phase of the signal's carrier wave in addition to the information content of the signal and relies on a single reference station or interpolated virtual station to provide real-time corrections, providing up to centimetre-level accuracy."

RTK requires a base-station (PPP not), requires a link with the user (PPP not), has a more complex hardware and set-up than PPP, and is for local use (PPP global). Note PPP has a long convergence time (several 10s of minutes; RTK is real time) and is not free (RTK is).

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

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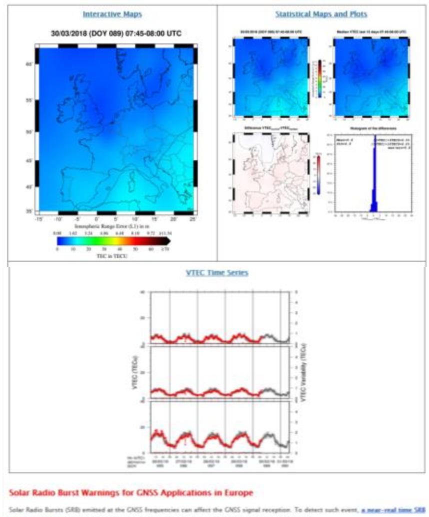
Technical details on the ROB GNSS station
http://epncb.oma.be/_networkdata/siteinfo4onestation.php?station=BRUX00BEL

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.

ROB – GNSS products

http://gnss.be/Atmospheric_Maps/ionospheric_maps.php



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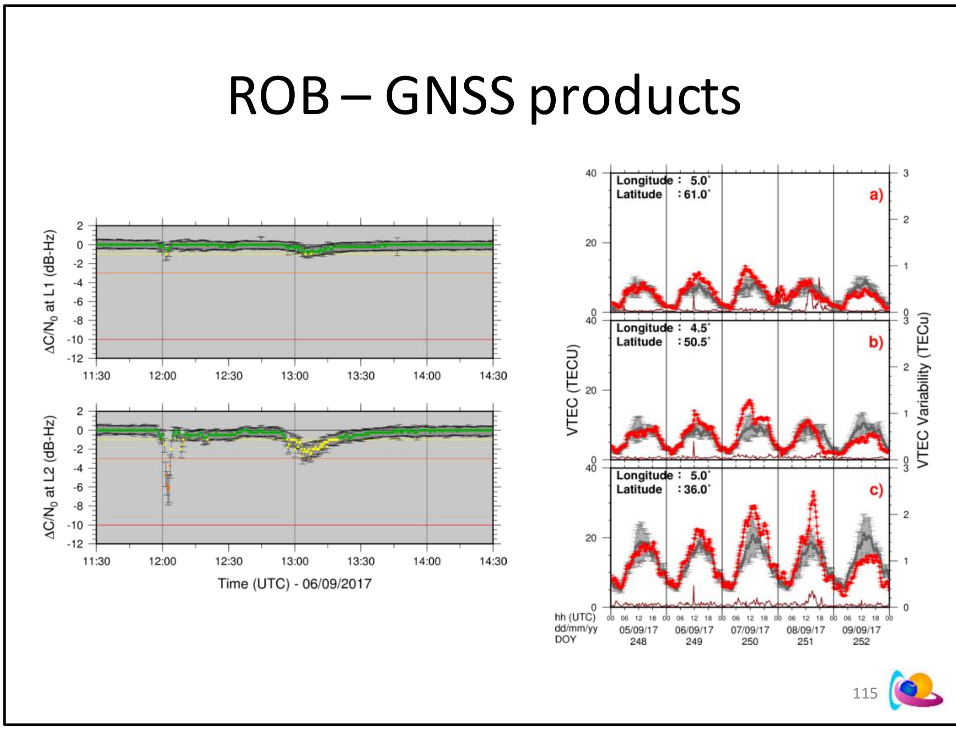
NRT and GNSS products and descriptions can be found at http://gnss.be/Atmospheric_Maps/ionospheric_maps.php

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.

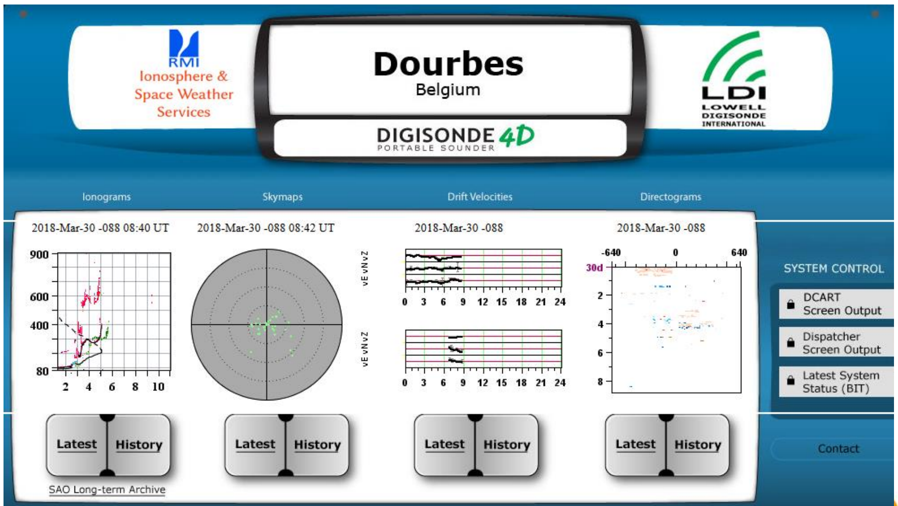
Ionospheric Event 2017-09-07
http://gnss.be/Atmospheric_Maps/ionospheric_event.php?date=2017-09-07

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/



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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, …