Summer School Alpbach 2002

Space Weather
-
Effects on Navigation and Communication Systems

B. Arbesser-Rastburg
ESA-ESTEC / TOS-EEP
Keplerlaan 1
NL-2200 AG Noordwijk
The Netherlands
E-Mail(1): bertram@xe.estec.esa.nl
E-Mail(2): bertram.arbesser-rastburg@esa.int

esa

OUTLINE

- Overview of effects
- Satellite Communications
- Satellite Navigation
- Observations needed
- Summary

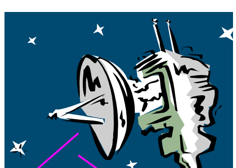
Special marks: To remember {Typical values}

Overview of the Effects

	Solar Radiation Hazards	Geomagnetic Activity
Terrestrial Communications Short wave (HF) communications Long-line telephone communications		☼ ☼
Satellite Communications Satellite command and control anomalies Communication link disturbance	☼	☼
Terrestrial Navigation Signal disturbance at VLF		☼
Satellite Navigation Orbit variation Ionospheric gradients and scintillations	☼	☼ ☼

Space weather effects on SatComs

ORBIT Variation
due to drag (especially on LEO sats)



RADIATION
•Spacecraft electronics (especially on HEO sats)

Fixed links
f > 4 GHz

no effect

Mobile links
f < 3 GHz

IONOSPHERE
•Scintillations
•Faraday rotation

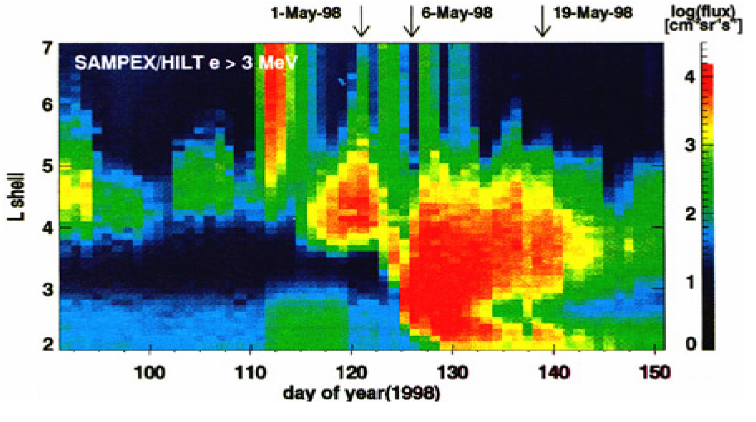
Ionospheric effects on Sat Navigation

RADIATION
- Spacecraft electronics

IONOSPHERE
- **TEC variations** affect position for single frequency receivers (UERE budget)
- **TEC gradients and irregularities** can affect the integrity

IONOSPHERE
- **Scintillations** affect continuity/availability

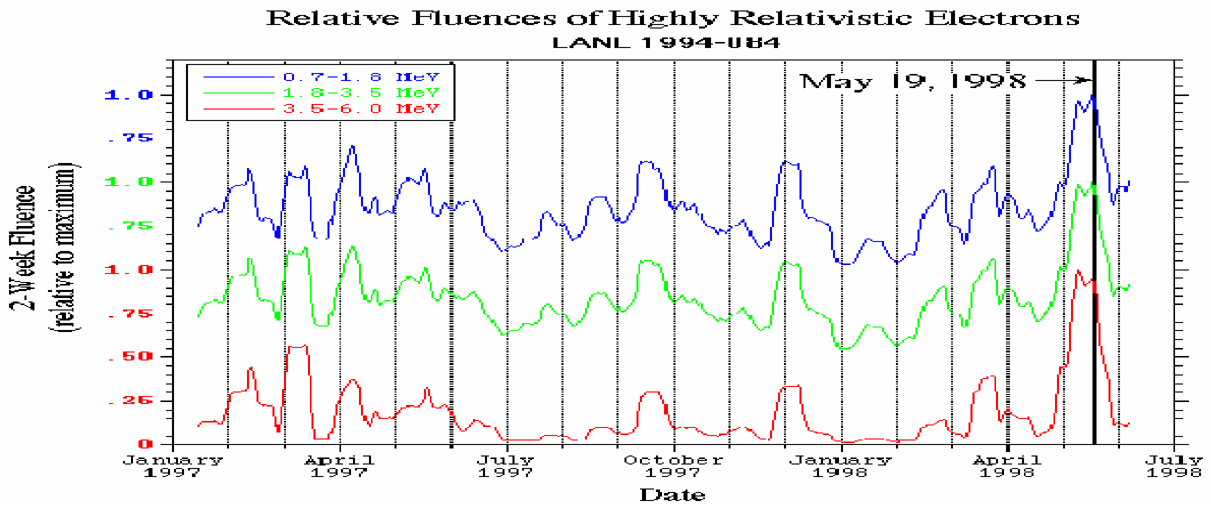
Solar Radiation Hazards



Solar ionising radiation consists of low level X-rays and a small particle component - the "solar wind". During flares and coronal mass ejections, the flux of X-rays may increase several orders of magnitude and the energy of this radiation increases.

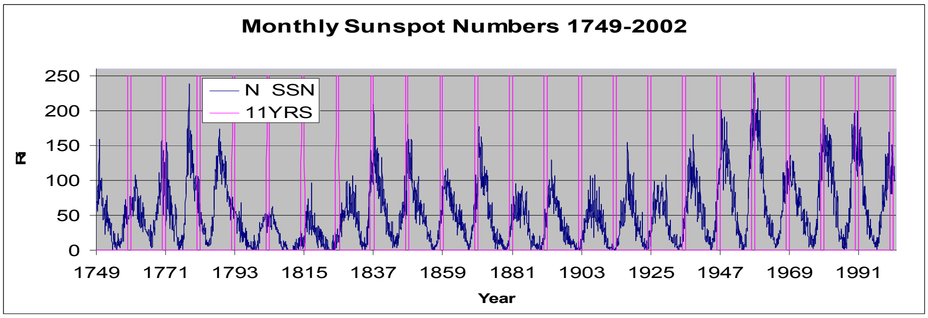
In rare events some particles, called **solar energetic particles** (SEP's) may be accelerated to very high energies (even in excess of 1 GeV). SEP's may cause direct radiation damage to spacecraft components. Some spacecraft have had the efficiency of their solar cells reduced by over 30% in a single large solar particle event. This effectively reduces the lifetime of the spacecraft. Even large numbers of lower energy electrons have caused damage to satellites, in one case resulting in a total spacecraft loss.

Some Satellite Anomalies



1994-01-20: “Anik E1” (Telesat), GEO, short disruption of AOCS [ESD ?]
1994-01-20: “Anik E2” (Telesat), GEO, loss of AOCS [ESD by **MeV-electrons**]
1997-01-10: “Telstar 401” (AT&T) GEO, complete failure [ESD ?]
1998-05-01: “Equator-S” (DLR/MPI) 500 x 67300km, CPU memory latch-up (?)
1998-05-19: “Galaxy 4” (Panamsat), GEO, loss of attitude control system [ESD]

Sunspot Numbers -Solar Cycle



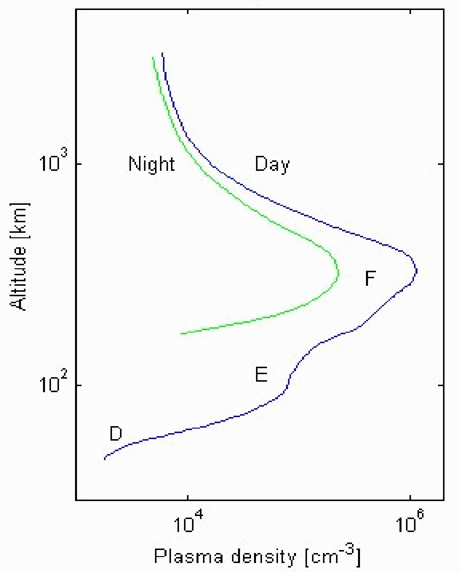
The solar cycle is ~11 years

R = k (10g+s)
where
R= Sunspot number
g= # groups
s = # indiv.spots

Sunspots are dark spots on the surface of the sun, first noticed by Theophrastus around 325 BC. In 1848 Rudolph Wolf (Zurich) devised a daily method of estimating solar activity by counting the number of individual spots and groups of spots on the sun. Wolf chose to compute his sunspot number by adding 10 times the number of groups to the total count of individual spots, because neither quantity alone completely captured the level of activity. Today, sunspot counts continue, since no other index of the sun's activity reaches so far into the past. Today, the international sunspot number *Ri* is computed as a weighted average of measurements from a network of cooperating observatories.

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

What is the ionosphere?



The ionosphere is the upper part of the atmosphere where sufficient ionization can exist to influence radiowave propagation. The ionosphere is usually divided into two main layers: a lower layer, designated the **E layer** (sometimes called Kennelly-Heaviside layer), which is between about 80 and 113 km above the earth's surface and which reflects radio waves of low frequency; and a higher layer, the **F layer** (also called the Appleton layer), which reflects higher-frequency radio waves. The latter is further divided into an F_1 layer, which begins at about 180 km above the earth; and an F_2 layer, which begins at about 300 km from the surface. The F layer rises during the night and therefore changes its reflecting characteristics.

The ionization is mainly caused by solar radiation. It is therefore dependant on location and time of the day as well as season and on the 11-year sunspot cycle.

Indices for Ionospheric Models

For studies of the main component of the solar cycle, the 12-month running mean sunspot number R_{12} is used because the resultant smoothing considerably reduces complicated rapidly-varying components, but does not obscure the slowly-varying component.

The definition of R_{12} is:

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

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

{0-160}

The radio emission from the sun at a wavelength of 10.7 centimetres (often called "the 10 cm flux") has been found to correlate well with the sunspot number.

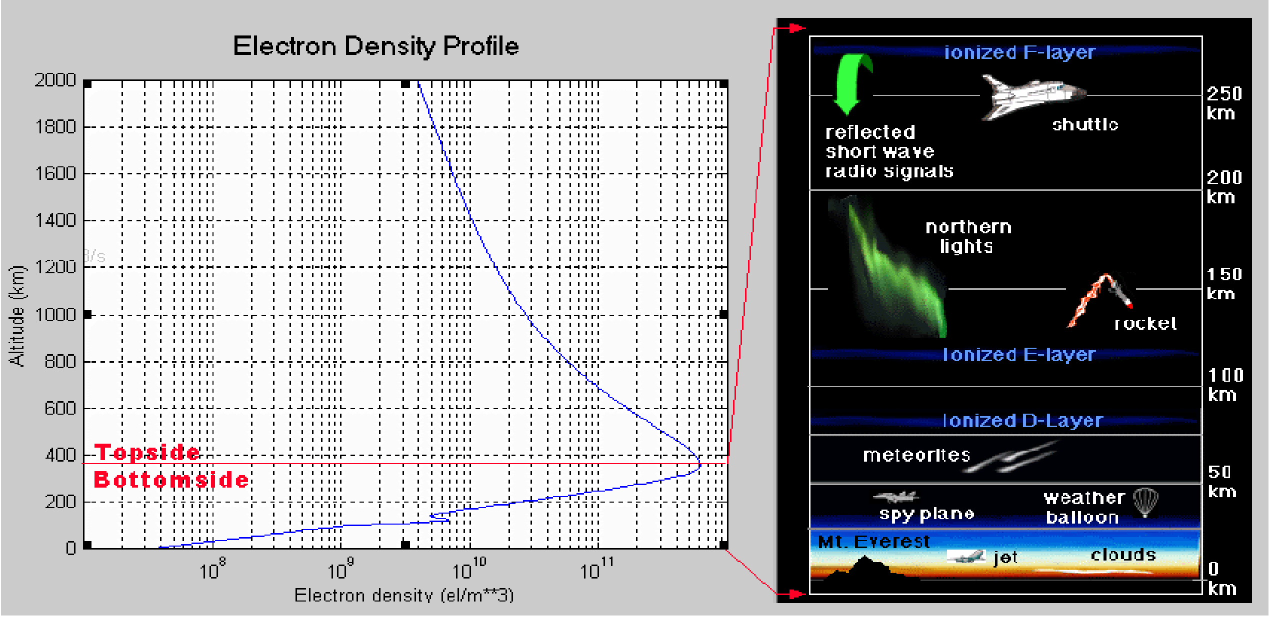
Φ_{12} … (also $F_{10.7}$) the 2 800 MHz (10.7 cm) solar radio noise flux $[10^{-22}\ \mathrm{Wm^{-2}\ Hz^{-1}}]$

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

{67-200}

Sources: Kenneth Davies, “Ionospheric Radio”, Peter Peregrinus Ltd.; ITU-R Rec P.371-8

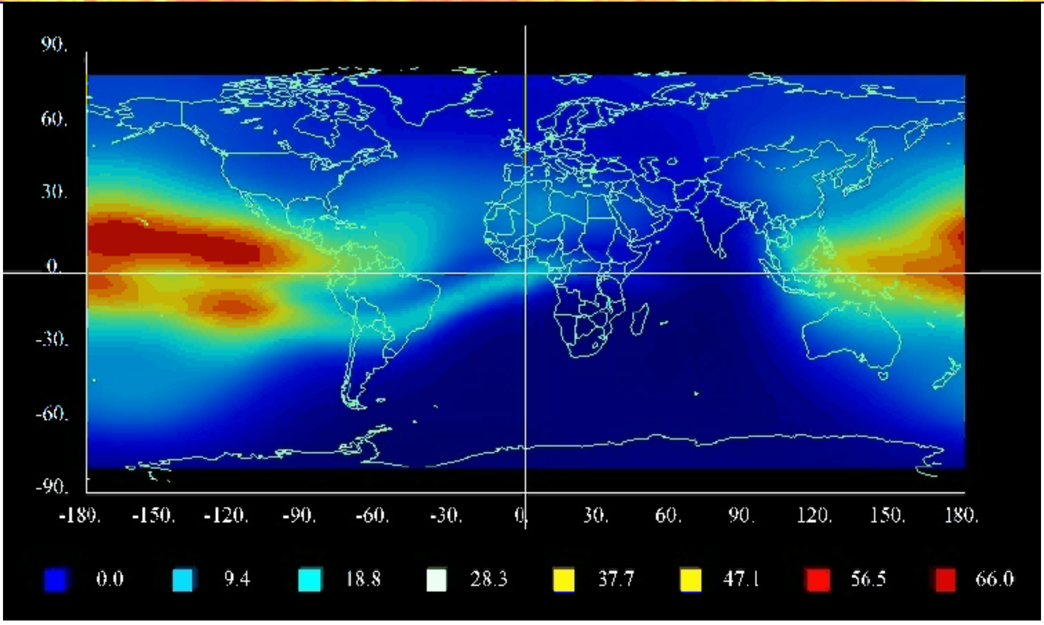
Profile of Ionospheric Electron Density



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

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

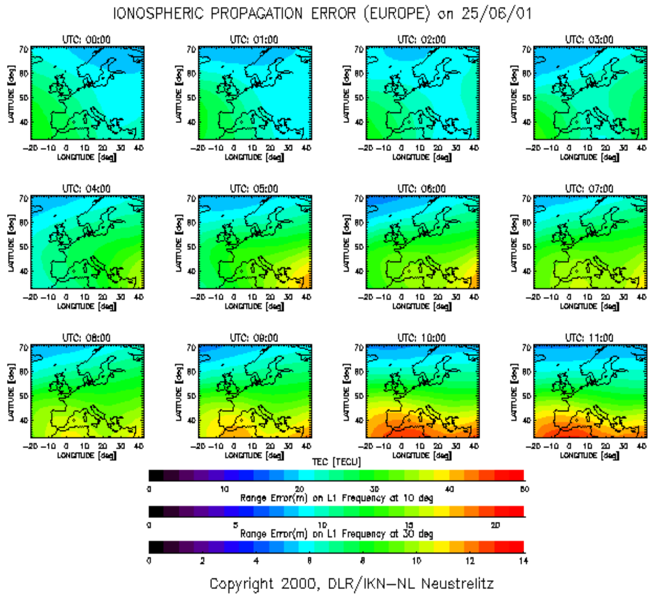
Global Map of Vertical TEC



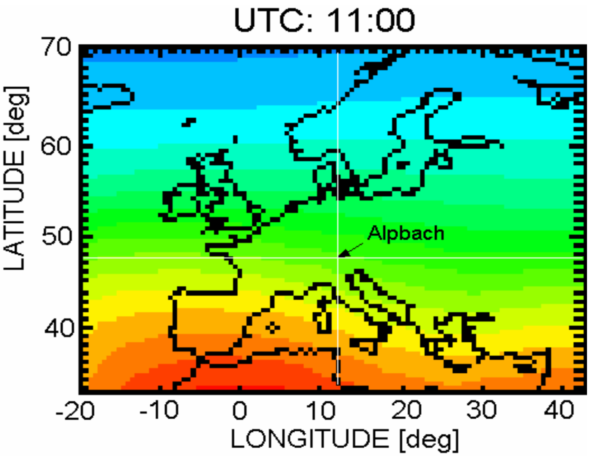
Vertical TEC plotted in TECU (calculated using NeQuick)
F10.7 = 150, 1999-07-15 00, 03, 06, 09, 12, 15, 18, 21 UTC

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

12-hour variation of TEC over Europe



TEC maps presented here are derived from GPS ground stations of the global IGS network and processed by DLR Neustrelitz (see link below)



The vertical Total Electron Content in Alpbach on 2001-06-25 at 11:00 UTC was 30 TECU

Source: http://www.kn.nz.dlr.de/WWW_nv_nz/ionos/index.htm

What is refraction?

Refraction, bending of waves that occurs when a wavefront passes obliquely from one medium to another. Passing from a less dense medium to a denser one, the wavefront is refracted towards the normal (an imaginary line perpendicular to the surface). On passing from a denser medium into a less dense one, it is refracted away from the normal.

There are two **laws of refraction**:

1)The incident ray, the refracted ray, and the normal all lie in the same plane.

2)For light rays passing from one medium (n_1) to another (n_2), the sine of the angle of incidence, i, and the sine of the angle of refraction, r, bear a constant ratio to one another.

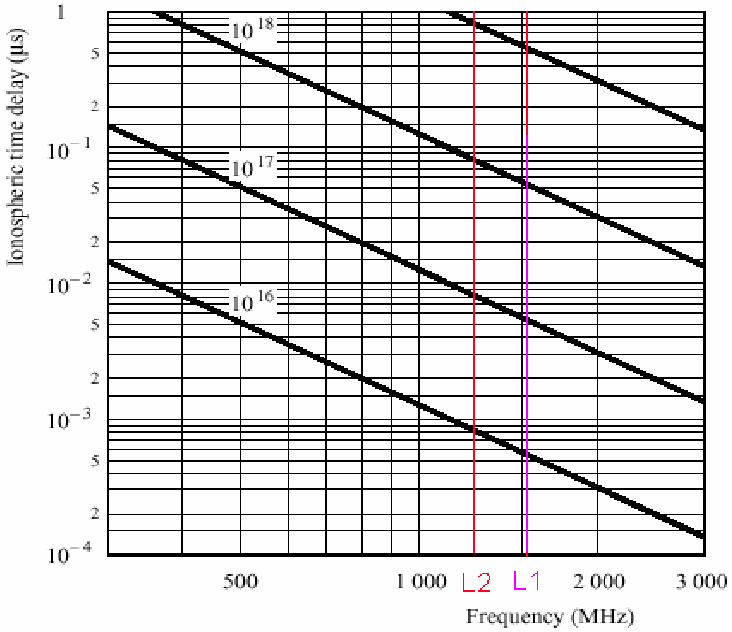
$\sin i / \sin r = n_2 / n_1$

where n is the refractive index of the material. The higher the refractive index, the greater will be the extent of the refraction. (Snell's law).

The propagation velocity $v = c/n$ where c = speed of light $\approx 3\times10^8$ ms $^{-1}$

Trans-ionospheric delay

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



Source: ITU-R Rec P.531-5

Where:

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

f : frequency of propagation [Hz]

N_T : total electron content along the slant propagation path.

Ranging error: (s = c.t)

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

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

at L1, 1 TECU means 0.16 m

1 μs delay means 300 m range error

Trans-ionospheric delay correction

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

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

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

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

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

where

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

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

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

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

all α_i and β_i are transmitted

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

t_{UT} is UTC, IP is Iono Point

λ_{IP} is longitude of IP

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

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

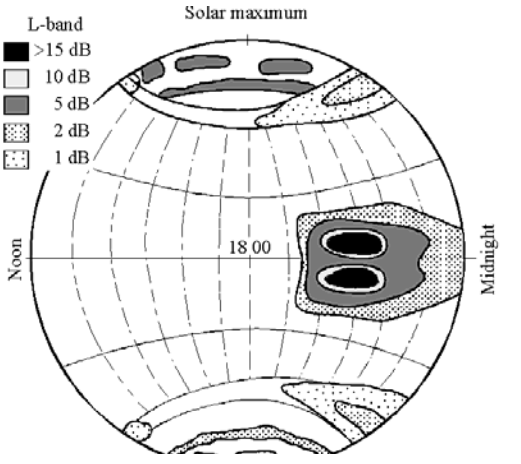
Ionospheric Scintillations (1)

One of the most severe disruptions along a trans-ionospheric propagation path for signals below 3 GHz is caused by ionospheric scintillation. Principally through the mechanisms of forward scattering and diffraction, small-scale irregular structures in the ionization density cause scintillation phenomena in which the steady signal at the receiver is replaced by one which is fluctuating in amplitude, phase and apparent direction of arrival.

Depending on the modulation of the system, various aspects of scintillation affect the system performance differently. The most commonly used parameter characterizing the intensity fluctuations is the scintillation index S_4:

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

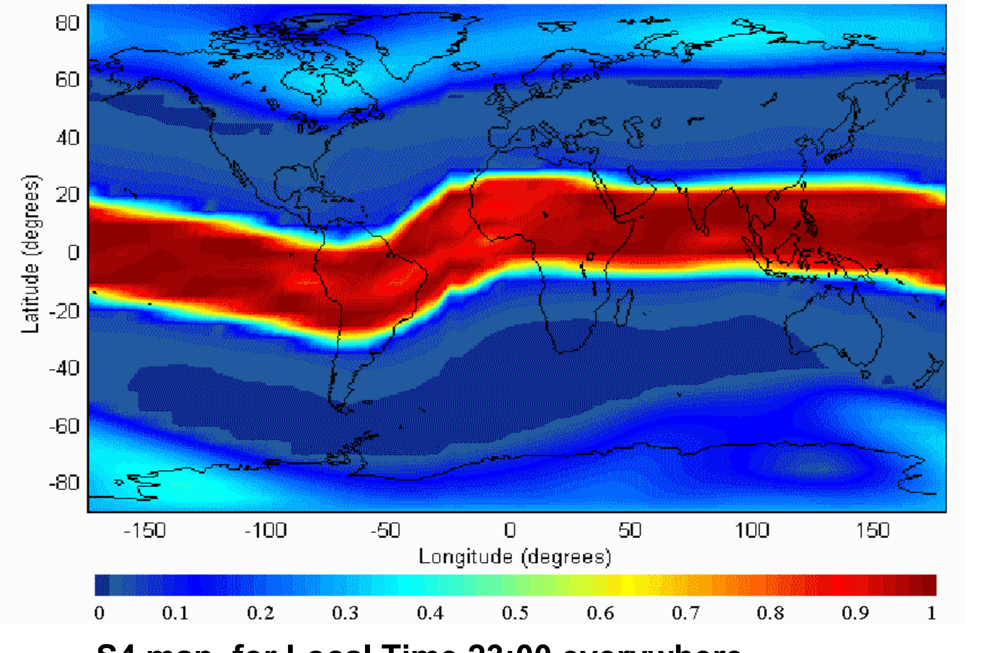
where I is the intensity of the signal and $\langle \; \rangle$ denotes averaging..



Ionospheric Scintillations (2)

At Scintillation Index values of S4 > 0.7 navigation receivers tend to lose lock, leading to interruptions in the navigation solution.

Besides amplitude scintillations, also phase scintillations need to be considered in system design.



S4 map for Local Time 23:00 everywhere
Month = April, Ri = 150, Kp =1 as modelled by GISM

Faraday Rotation (1)

When propagating through the ionosphere, a linearly polarized wave will suffer a gradual rotation of its plane of polarization due to the presence of the geomagnetic field and the anisotropy of the plasma medium. The magnitude of Faraday rotation, q, will depend on the frequency of the radiowave, the magnetic field strength, and the electron density of the plasma as:

$$\theta = 2.36 \times 10^2 \quad B_{av} \ N_T \ f^{-2}$$

where:

- θ: angle of rotation (rad)
- $\boldsymbol{B_{av}}$: avg. Earth magnetic field (Wb/m²)
- $\boldsymbol{f}$: frequency (GHz)
- N_T: TEC (el/m²).

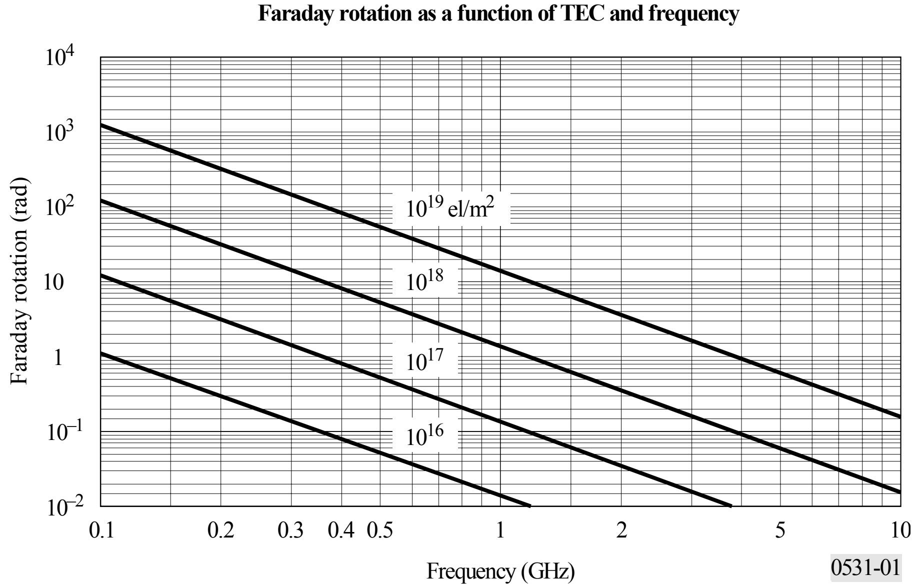
The Faraday rotation is thus inversely proportional to the square of frequency and directly proportional to the integrated product of the electron density and the component of the Earth's magnetic field along the propagation path.

Source: ITU-R Rec P. 531-6

Faraday Rotation (2)

FIGURE 1

Faraday rotation as a function of TEC and frequency



SatComs and SatNav systems at f < 6 GHz are normally using circular polarization in order to avoid the effects of Faraday rotation. For remote sensing systems, the Faraday rotation can constitute severe limitations

The cross-polarization discrimination for aligned antennas, XPD (dB), is related to the Faraday rotation angle, q, by:

$$XPD = -20 \log (\tan \theta)$$

Some models of the ionosphere

F2 peak parameters

•ITU-R (was: CCIR) [1978-1999] Rec P.1239, http://www.itu.int/brsg/sg3/databanks/wom_hrm/

Electron Density & TEC:

•IRI (Int. Reference Ionosphere) [1995] http://nssdc.gsfc.nasa.gov/space/model/ionos/iri.html

•Bent [1972] http://nssdc.gsfc.nasa.gov/space/model/ionos/bent.html

•Chiu [1975] http://nssdc.gsfc.nasa.gov/space/model/ionos/chiu.html

•PIM [1996] http://www-vsbs.plh.af.mil/projects/geospace/pim.html

•SLIM [1985] http://nssdc.gsfc.nasa.gov/space/model/ionos/slim.html

•COSTprof [1997] http://www-cost251.rcru.rl.ac.uk/

•NeQuick [2000] http://www.itu.int/ITU-R/software/study-groups/rsg3/databanks/ionosph/index.html

Scintillations

•Wbmod [1997] http://www.nwra-az.com/ionoscint/wbmod.html

•GISM [2002] (was called GIM before 2002)

Observations needed

•**Total Electron Content**: [GNSS Receivers]
Sat-Nav aeronautical single frequency receivers (SBAS)
Measurement one minute, update rate to user: 5 minutes

•**Kp- Index, Geomagnetic Storm**:
Sat-Navigation, HF Communications (3 hours -> 24 hours)

•**foF2** [Ionosonde]: HF-Communication links (5 minutes)

•**Sunspot Number** or **F10.7:** at-Nav single frequency receiver (24 hours)

•**Atmospheric scale height**:
LEO Satellites (drag), (3 hours -> 24 hours)

•**Ionospheric Scintillations**:
Sat-Navigation, HF Communications (3 hours -> 24 hours)

•**Relativistic Electrons** (>0.3 MeV): Satellites (1 hour)

Note that in many cases to warning to the user is only necessary when the value deviates significantly for the model value. The times provided are normally the update rate to the user.

References

K. Davies, "Ionospheric Radio", Peter Peregrinus Ltd, 1990, ISBN 0 86341 186X

R. Leitinger, S. Radicella, B. Nava, G. Hochegger and J. Hafner, "NeQuick- COSTprof –NEUOG-Plas, a family of 3D electron density models" Proceedings of the 4th COST 251 Workshop 'The impact of the Upper Atmosphere on Terrestrial & Earth-Space Communications", Funchal, Madeira, Portugal, 1999, 75.

ITU-R Rec. P.371-8 "Choice of Indices for Long-term Ionospheric Predictions", Geneva 1999

ITU-R Rec. P.531-6 "Ionospheric propagation data and prediction methods required for the design of satellite services and systems", Geneva 2001

ITU-R Rec. P.1239 "ITU-R Reference ionospheric characteristics", Geneva 1997

D. N. Baker, J. H. Allen, S. G. Kanekal, and G. D. Reeves, "Pager Satellite Failure May Have Been Related to Disturbed Space Environment", EOS, October 1998, p. 477.

ESTEC Final Report Co 14069, "European Space Weather Programme System Requirements Definition", DERA, April 2001

Glossary – Acronyms - Abbreviations

Coronal mass ejection --large clouds of material expelled from the Sun. These often travel away from the Sun at very high speeds (one to two million miles per hour), especially near sunspot activity maximum. They can contain 10^{15} grams (or more) of solar material;

Fluence --the number of particles that hit a given area (say a square centimeter) of a spacecraft over a given unit of time. For example, we are often interested in how many 1 million electron Volt particles hit a cm^2 of spacecraft each day in space: this would be the "daily fluence" of >1MeV electrons;

GEO (GEOstationary orbit)--the special orbit above the Earth's equator that is at an altitude of 35,600 km. A GEO satellite appears to move at the same angular speed as the Earth turns - it stays above the same spot on the Earth;

GPS -- Global Positioning System

HEO (Highly Elliptical Orbit) -- an elliptical orbit with perigee < 3000 km and apogee > 30000 km

LEO (Low Earth Orbit) -- a circular orbit with an altitude of 200 to 1500 km

Magnetosphere--the uppermost part of the Earth's atmosphere. This region is populated by a very tenuous gas (1 to 1000 particles per cubic centimeter) made up mostly of electrons, protons, and atomic nuclei (such as charged oxygen that has moved up from the lower atmosphere), all controlled by the Earth's magnetic field;

SBAS – Satellite Based Augmentation Systems such as WAAS or EGNOS are providing GPS receivers with wide area differential correction plus integrity by means of a network of reference stations and geostationary satellites which broadcast the message.

Solar flares--the occasional, powerful energy bursts that occur on the Sun's surface. These often occur in the form of X rays, radio emissions, and powerful bursts of very high energy particles;

Solar wind--the hot, expanding gas of charged particles that flow away from the Sun toward the cold void of interstellar space. The solar wind contains ions, electrons, and magnetic fields.

UERE – User Equivalent Range Error