Space Weather Impact on Radio Systems

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- Mitigation of space weather impact
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- Summary
Space weather refers to the conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health. (Definition NSWP, USA, 1996)
Das ionospheric weather is strongly coupled with processes in the magnetosphere.
The ionosphere is part of the complex dynamics of the near Earth space. The understanding of interdisciplinary coupling processes of the Geo-Plasma is important to forecast space weather effects and their impact on radio systems.

\[ TEC = \int n_e(h)dh \]

Electron density

0.5 1.0 1.5 \( \times 10^{12} \, \text{m}^{-3} \)
Radio wave propagation in the ionosphere

**Ionosphere causes**

- Regular effects due to the presence of plasma
  - signal delay
  - rotation of polarisation
- Irregular effects due to plasma distortions, turbulences
  - misinterpretation of data due to horizontal gradients (HMI)
  - Radio scintillations

Electron density $n_e$ & Total Electron Content (TEC) are closely related to the solar irradiance

$$T E C_V = \int n_e(h) \, dh$$

**Ionospheric Range Error**

- Solar Flux Index $F_{10.7}$
- Total Electron Content (TEC)
- Electron density $n_e$

Night
Day

Height / km

100 200 300
TEC – monitoring -  Navigation errors

GNSS*-Data obtained from geodetic networks for TEC Monitoring in streaming mode (IGS, EUREF)

Empirical modelling of the ionosphere (in DLR: Europe, polar regions, global)

Near real time monitoring possible

Ionospheric first order range error \( d_1 \) is proportional to TEC

\[
 d_1^{(1)} = \frac{K}{f^2} \int n_0 ds = \frac{K}{f^2} \cdot TEC
\]

At high solar activity level errors up to 35 m possible!

Sample:16 GPS stations  Time: 01:04:00 UT

*GNSS- Global Navigation Satellite System
Ionospheric perturbation regions where radio wave propagation may seriously be affected

Source: AFRL
Performance degradation of the GPS reference network of ascos on 25 July 2004

Performance of the GPS reference network of Allsat GmbH, Hannover degrades during the ionospheric storm on 25 July 2004

Different effects in different network areas over Germany

- Propagation of perturbation from high to mid-latitudes
- Provision of ionospheric now- and forecast information valuable for users
- Perturbation degree should be quantified by a perturbation index that can directly be used by customers
• Degradation of accuracy, integrity, availability and continuity of signals
• HF Communication disturbed or interrupted
  
  Operational detection and modelling of ionospheric perturbations needed
  
  Ionospheric “Threat-Model” required

HMI: Hazardous Misleading Information
Solar flare induced storm on 28 October 2003

- Strong Solar Flare was observed on 28 October 2003 at 11:05 UT
- Total solar irradiation enhances within a few minutes by 267 ppm
- Rapid and strong increase of TEC at all GPS measurements (range error up to 3.5 m)
- Number of usable GPS measurements dropped down from 30 to 7
Impact of Solar Radio Bursts on GPS signal reception

December 6, 2006

Source: P. Doherty
Ionospheric impact on transionospheric radio waves

Plasma instabilities in the ionosphere

AGC fluctuations affecting all four CLUSTER spacecrafts at different ground stations
(Source: ESOC Report CL-COM-RP-1001-TOS)

Communication

Plasma instabilities cause rapid signal strength fluctuations
Loss of lock possible

Navigation
Radio waves at frequencies below 10 MHz are mostly reflected by the ionosphere.

This results in a long distant propagation of waves.

Solar flares and particle precipitation can prevent the ionosphere from reflecting or refracting radio waves.

Short wave radio waves may be absorbed by enhanced plasma density in the lower ionosphere leading to a blackout in radio communications (Short wave fading).

Ionospheric disturbance may enhance long wave radio propagation (measurements of Sudden Ionospheric Disturbances - SIDs).
Remote sensing - Radar measurements

The ionospheric plasma impacts the phase and polarisation angle of transionospheric radio waves in C-, L- und P- bands, i.e. numerous radar systems.

<table>
<thead>
<tr>
<th>Band</th>
<th>f (GHz)</th>
<th>$\Omega_F [^\circ]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>5.0</td>
<td>2</td>
</tr>
<tr>
<td>L</td>
<td>1.2</td>
<td>25</td>
</tr>
<tr>
<td>P</td>
<td>0.4</td>
<td>200</td>
</tr>
</tbody>
</table>

Plasma turbulences cause defocussing effects in particular in L- and P- band radars.

Planned ESA Biomass Explorer will use P-band radar.

Development of methods and algorithms for correction and mitigation of ionospheric propagation errors needed.
**Ground and space based ionosphere service products**

**Topside reconstructions**
28 / 29 October 2003

Ionospheric services help **study** the ionosphere and relationships between ionosphere and space weather, to **correct/mitigate** propagation errors, to **detect** ionospheric perturbation, to **warn** and **forecast** users.

- Services: ISES, Space Weather Prediction Center Boulder, Int. GNSS Service (IGS), SWACI

![Ground and space based ionosphere service products](image)
Sun & Ionosphere MOnitoring NEtwork - SIMONE

**Antenna**
EMAG Bergen

**Receiver**

**Diagram**
- Solar flare
- Ionosphere
- 24 kHz
- NAA Cutler
- ca. 6000 km
- Schools in Germany
- Signal strength
  - 1 June 2007
- Solar flare
- EMAG Bergen
- DLR Neustrelitz
- Time / hrs
Summary

Radio wave propagation is strongly affected by space weather effects via their interaction with the non-isotropic ionospheric plasma.

Impacted are technical systems related to:
- Terrestrial radio wave propagation
  - Telecommunication
  - Radar systems
- Transionospheric radio wave propagation
  - Telecommunication
  - Satellite navigation /positioning
  - Remote sensing, altimetry
  - Research facilities

Space weather / ionospheric monitoring and provision of actual and forecasted information helps to mitigate the space weather impact.

A number of ionospheric data and information services exist (e.g. ISES, SWPC, SWACI), data products with higher temporal and spatial resolution are required to improve the Space Situational Awareness (SSA).

The International Space Weather Initiative (ISWI) is a unique opportunity to improve our understanding of space weather effects.
Thank you for your attention
Dual frequency GNSS measurements

Total Electron Content

\[ TEC_v = \int n_e(h) \, dh \]

\[ \Delta P = P_2 - P_1 = K \frac{f_2^2 - f_1^2}{f_1 f_2} \cdot TEC + \epsilon_{off} \]

TEC can be derived from dual frequency GNSS measurements.

- Ionospheric range error up to about 100 m
- Estimation of ionospheric perturbation degree is a practical need
- Statistics and case studies required

GPS based TEC measurements and mapping in DLR Neustrelitz

**Europe**
- post proc. (1 day) since 1995
  - http://www.kn.nz.dlr.de/daily/tec-eu
- operational (5 min) since 2005
  - http://swaciweb.dlr.de

**North Pole**
- post proc. (1 day) since 2002
  - http://www.kn.nz.dlr.de/daily/tec-np
Impact of Ionospheric perturbations on navigation and positioning

Impact of Ionospheric perturbations on navigation and positioning

Ionospheric irregularities

Ionospheric irregularities

Corrupted Signal (Scintillations)

Ionospheric irregularities

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Differential GNSS Integrity

Risk of undetected failures resulting in the violation of the protection level

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GPS Signal amplitude

Bandung

GPS Signal amplitude

Bandung

05.04.2006
Ionospheric perturbations on 29 / 30 October 2003

Numerous perturbations in Com/Nav Systems in Europe and in the USA

Close correlation of TEC behaviour with the southward component of the IMF
Higher-order refraction effects

Ionosphere phase refractive index

\[ n = 1 - \frac{f_p^2}{2 f^2} \pm \frac{f_p^2 f_g \cos \Theta}{2 f^3} - \frac{f_p^4}{8 f^4} \]

First-order effect removable via L3 phase combination, second order effect remains uncompensated

Plasma frequency:

\[ f_p = \sqrt{\frac{e^2 n_e}{4\pi^2 m_e \varepsilon_0}} \]

Gyro frequency:

\[ f_g = \frac{eB}{2\pi m_e} \]

\( \Theta \): angle between wave direction and B field vector

\( n_e \): electron density

\( m_e \): electron mass

\( B \): magnetic induction

\( \varepsilon_0 \): free space permitivity

\( f \): signal frequency

Second-order error,

\[ d^{(2)} = \frac{K_F}{f^3} \int B \cos \Theta \cdot n_e ds \]
Ionospheric 2\textsuperscript{nd} order errors are usually ignored in the measurement praxis (< 20 cm).

When Galileo becomes operational, these errors have to be routinely mitigated in precise applications.

Anisotropy of the ionosphere due to the geomagnetic field $B$

$\Phi_{Rx}: 51°\ N, \lambda_{Tx}: 10°\ E$

$\Phi_{Rx}: 51°\ N, \lambda_{Rx}: 10°\ E$

$\epsilon: 10°$

$\epsilon: 30°$

$\epsilon: 60°$

$d^{(2)}_I = \frac{K_F}{f^3} \int B \cos \Theta \cdot n_e ds$

Hoque, M.M., N. Jakowski, Mitigation of higher order ionospheric effects on GNSS users in Europe, GPS Solutions, DOI 10.1007/s10291-007-0069-5, 2007

GPS sounding of the Ionosphere onboard a LEO satellite
Auroral particle precipitation - ELDI

Particle precipitation from the magnetosphere causes a locally enhanced ionization in the lower ionosphere.
Alaska Earthquake on November 3, 2002
(M = 7.9; 63.5N / 147.4 W)

GITEWS
Nachweis ionosphärischer Erdbeben / Tsunami - Signaturen in der Ionosphäre (ETSI)

TEC-Messungen (blau) über dem Ort des Epizentrums bis zu 7 Tage vorher im Vergleich zu 27-tägigen Medianwerten (rot).
Wettbewerb der Visionen des DLR

Sumatra earthquake on 26 December 2004
Sampali: 3.62°N; 98.71°E
Filtered TEC from GPS
2.5 - 10.0 min

Ionisationsanomalie
Gradient statistics

- Strong enhancement of gradients on 20 November 2003 observed (up to about 30 mm/km at L1)
- Average values at 1000 km distance:
  - about 1 mm/km (quiet day 0.3 mm/km)
- Maximum level at 1000 km distance: 7 mm/km

Unperturbed day
Europe 10/11/2003

Perturbed day
Europe 20/11/2003
Ionosphärisch bedingte Radioszintillationen

Plasmaturbulenzen
- Hohe Breiten
  • Teilchenpräzipitation
- Niedere Breiten
  • „Bubbles“

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

Superposition von Radiowellen
Starke Feldstärkeshchwankungen
Signalverlust möglich

Radioszintillationen stellen auch für Galileo ein Problem dar.

(Source: ESOC Report CL-COM-RP-1001-TOS)
Satellitennavigation

Die Entfernungsmessung basiert auf der Messung der Signallaufzeit

Operationelle und geplante satellitengestützte Navigationssysteme
- GPS (USA)
- GLONASS (Russland)
- Galileo (Europa)
- Compass (China)

„Anwendungsbeispiel“ für präzise Navigation
An Schulen in Niedersachsen, Hamburg und Mecklenburg-Vorpommern werden kontinuierlich Messungen durchgeführt, archiviert und analysiert.