Summer School Alpbach 2002
Space Weather: Physics, Impacts and Predictions

# GLOTEC

Global real-time TEC map
Satellite Navigation System Reliability Forecast

Cover + 2 + 12 pages = 15 pages

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## Authors – Team 1

**Group 1: Space Weather Prediction Center**
Sergey Apatenkov, Cathrine Fox Maule, Emilia Huttunen, Gero Kleindienst, Stefan Keihas, Benjamin Luethi, Daniel Martini, Noora Partamies, Fabrice Portier-Fozzani, Aveek Sarkar, Carita Siponen

**Group 2: Space Weather Data Center**
Arne Asnes, Marie Backrud, Martin Grill, Stefan Muehlbachler, Pamela Puhl-Quinn, Britt Rosendahl Hansen, Tero Sahla, Sebastian Schaefer

**Group 3: Operative Space Weather Mission**
Adrian Blagau, Lisa Blush, Margit Maberreiter, Steffen Heidicke, Tanguy Thibert, Veerle Sterken, Jochen Zoennchen

## List of participants

## Alpbach 2002
## Team 1

| | Group 1 | Group 2 | Group 3 |
|---|---|---|---|
| Team tutor | Nina von Krusenstierna | | |
| Team leader | Britt Rosendahl Hansen | | |
| Group leader | Cathrine Fox Maule | Pamela Puhl-Quinn | Jochen Zönnchen |
| Presentation | Gero Kleindienst | Martin Grill<br>Arne Asnes | Lisa Blush |
| | Sergey Apatenkov | Marie Backrud | Adrian Blagau |
| | Emilia Huttunen | Stefan Mühlbachler | Margit Haberreiter |
| | Stefan Kiehas | Tero Sahla | Steffen Heidicke |
| | Benjamin Luethi | Sebastian Schäfer | Veerle Sterken |
| | Daniel Martini | | Tanguy Thibert |
| | Noora Partamies | | |
| | Fabrice Portier-Fozzani | | |
| | Aveek Sarkar | | |
| | Carita Siponen | | |
| | | | |
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## 1 Mission Statement

Geomagnetic storms threaten the integrity of satellite navigation (SN) systems. More specifically, the users of single-frequency SN receivers experience loss of accuracy in the calculation of their position. This is due mainly to the existing systems' inability to fully correct for ionospheric delay during severe space weather conditions.

GLOTEC is the solution for these users. Our primary goal is to increase the integrity of satellite navigation systems by

- Providing improved ionospheric delay corrections
- Providing an early warning system based on reliable forecasts of geomagnetic storm activity

## 2 Executive summary

Our team was formed on July 25th 2002 in Alpbach, Austria. We were a diverse crowd of 26 individuals, who were not previously acquainted with each other, but were forced into cooperation. This of course created a state of chaos.

After much confusion a more organized structure was formed, which increased order thereby decreasing the entropy of the system. This structure consisted of a team leader and three groups. The first task of the team was to agree on our project, which in the end became GLOTEC.

After choosing group leaders, who communicated directly with the team leader, order slowly emerged. The team was aware that communication was needed between the three groups and various subgroups were created to work on subjects relevant to more than one group. Several difficult decisions were made along the way and these helped focus each group on our tasks ahead.

Now we present our project and why it is of immense value to you – the present and future users of SN systems.

Satellite Navigation systems use triangulation to calculate the position of a receiver. The integrity and continuity of SN systems is of vital importance to the modern world in which we live. Continuity and integrity is affected when one or more satellites become unavailable or unreliable. There are many reasons why this can happen, but one that can be dealt with is the composition and variation in composition of the ionosphere, which lies between the satellite and the receiver. Depending on what you are using the positioning for, this can have more or less severe consequences.

Who is affected by this? Anyone using a SN solution is potentially affected by the problem of EM signal transmission through the ionosphere. Whether you are laying a road or simply out for a walk in the woods, you might suddenly be without the positioning information on which you are relying.

To this problem, we have developed a solution, which we call GLOTEC.

We propose to do the following: We will deploy a fleet of 19 satellites. One satellite is located at the L1 Lagrange point between the Earth and the Sun and 18 small satellites are located in an Earth orbit. All of these satellites provide data, which our data centre processes and then distributes to the user in need of reliable information.

The system has a projected timeline of 8 or 9 years, but as a continuous service is the intent, a replacement of various technologies will be needed during the project lifetime.

We have deduced a cost estimate, or what some might call a cost guesstimate, for the implementation of GLOTEC. It is our impression that a modest 204 million euros is needed.

Hopefully, we have convinced you of the feasibility of GLOTEC and the need for its implementation.

On behalf of the team, thank you for your attention.

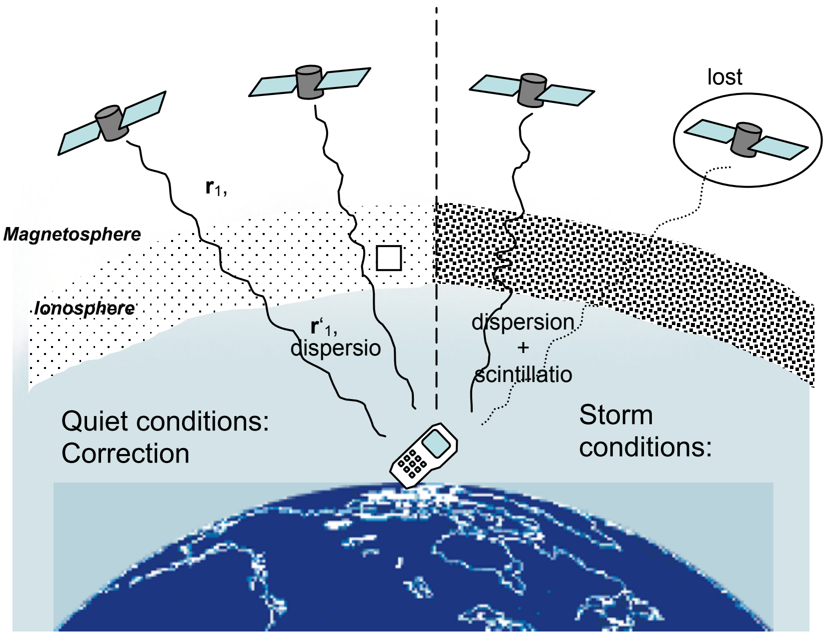
## 3 Background on Existing Satellite Navigation (SN) Systems

The GPS and Galileo systems consist of fleets of positioning satellites (24 for GPS and 27 for Galileo) that communicate to receivers on the ground. They send their position and time information. The similarities and differences between the two systems are summarized in the table below:

| | GPS | GALILEO | GLONASS |
|---|---|---|---|
| Planned # of sat. (currently) | 24+3 spares (29) | 27+3 spares (0) | 24 (9) |
| Orbits | 6 Medium Earth Orbits, 55° inclination, 20´200 km height | 3 MEO (every 120°), 56° inclination, 23´616 km height | 3 MEO, 64.8° inclination, 25´510 km height |
| accuracy (95%) | horizontal: 22 m vertical: 27.7 m | horizontal: 4 m vertical: 7.7 m | ? |
| remarks | 5-8 satellites visible on any spot of the world | very good coverage up to 75° north, interoperable with GPS and GLONASS | |

For users of single-frequency SN receivers, the “Best of All Possible Worlds” situation would be to have contact with at least 3 of these positioning satellites and to receive their information unaltered. In reality, there are obstacles of two forms: Those due to incorrect satellite positioning and poor geometry, and those involving the plasma regions that exist between the satellites and the receivers.

Figure 3




Ionospheric delays (possibly causing errors on the order of 60m) are by far the largest effects that compromise the integrity and continuity of SN systems. The left side of Figure 3 illustrates these effects. They are caused by refraction and dispersion in the atmosphere. To correct for ionospheric delays, a critical parameter, known as total electron content, or TEC, must be broadcasted to single-frequency receivers. There exist many quiet-time models for TEC, such as NeQuick. TEC values can also be directly calculated on an ionospheric grid produced by an ensemble of reference stations (known as SBAS, or, Satellite-Based Augmentation Systems).

Under severe geomagnetic storm conditions, the ionosphere becomes a more dynamic and turbulent environment, as illustrated on the right-hand side of Figure 3. In addition, to dispersion and refraction, a phenomena known as scintillations can severely affect the incoming signal. While TEC variations in the ionosphere affect positioning for single frequency receivers, TEC gradients and irregularities compromise integrity. Scintillations and Faraday rotation in the ionosphere can even interrupt continuity and availability of the SN system. In existing SN systems, nothing is currently done about a warning system for these severe conditions.

## 4 The Challenge: To improve the integrity and continuity of SN systems during geomagnetic storm conditions

GLOTEC is up to this challenge.

Our primary users will be users of single-frequency SN system receivers. Our secondary users will be space weather scientists who will use our data products to study how TEC is affected by geomagnetic storm activity.

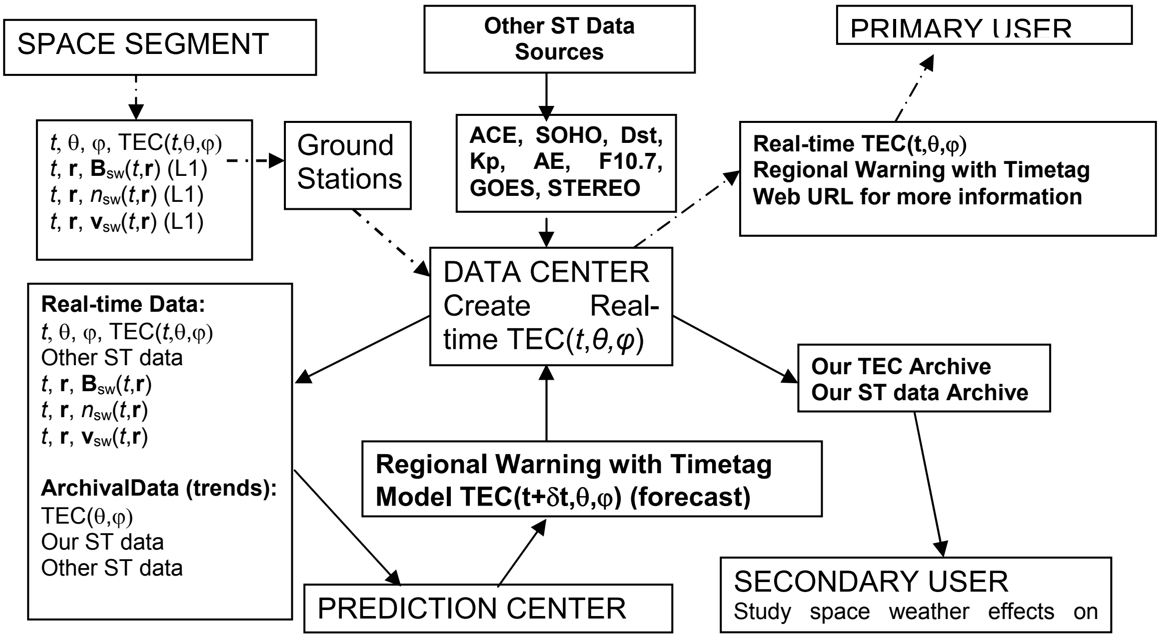
Our primary goal is to provide a warning system which will warn users of potentially compromised position information due to severe space weather. In addition, improved measurement of the critical TEC parameter will be provided to both our primary and secondary users.

To accomplish this, GLOTEC is comprised of three major components: The Data Center, The Prediction Center and the Space Segment.

# 5 The Data Center

## 5.1 Overview of Information Flow

The figure below illustrates the GLOTEC flow of information. The GLOTEC Data Center is responsible for interfaces with the following segments: The Space Segment, the Prediction Center, the various sources of existing Solar-Terrestrial (ST) data, the Primary User, and the Secondary User.




For the Space Segment interface, the data center ultimately receives the raw telemetry data stream from both the L1-situated spacecraft (i.e. $\mathbf{B}_{sw}$, $n_{sw}$, and $\mathbf{v}_{sw}$) and the TEC fleet (i.e. TEC($t$,θ,φ)). These spacecraft, as well as the telemetry scheme are described below in the Space Segment section.

The Data Center transfers data from the Space Segment, as well as other sources of solar-terrestrial (ST) data to the Prediction Center. As indicated in the above diagram, these other sources of ST data are from varied sources and will have a variety of formats. Care is taken to meet the temporal and spatial resolutions required by Prediction Center. The output products of the Prediction Center are then broadcasted to the primary user through the Data Center. This broadcasting procedure is described below.

The GLOTEC Data Center is also responsible for the production of the „real time“ TEC which is ultimately broadcasted to our primary users. This data processing is a rather detailed task and is described in the following section.

The Data Center will also provide GLOTEC archival TEC and ST data to our secondary users, the space weather scientists.

## 5.2 Production of the „real time“ TEC

The procedure for production of near real-time global TEC-maps will consist of a combination of direct measurements and two different TEC models. One model (NeQuick) will provide TEC-values for the quiet time ionosphere, while the second model will provide corrections for the storm time ionosphere. Initially the storm time model (STORM) will be fairly simple, but this is likely to be greatly improved in the future (e.g. from the work of our prediction group). The quiet time ionosphere model will generally have small errors.
The global TEC map will be made from fitting the modelled TEC map to the measured values and such a map will be produced every five minutes to be distributed to the customers. This is reasonable even though 5 minutes is shorter than the time it takes to update the map with global coverage of measurements as there will always be an equal amount of relatively recent TEC measurements.

**Descriptions of the models:**

STORM: An empirical Storm time ionospheric correction model, based on measurements from a long list of ionosonde stations covering latitudes from 83.2 N to 78.8 S. So far this has only been developed for f0F2, but we will assume that a TEC-model (which is proposed) will be available before our mission is operable. The model currently operates in real time, with hourly updates, but once again we assume that this will be improved in the near future (by ourselves if necessary). The error of this model is estimated by comparing the model results with true ionosonde measurements and should be satisfactory for providing error bars for different locations
Input: hourly $a_p$ for the last 30 hours

NeQuick: A quiet time model which improves previous models significantly.
Input: statistical database and sunspot number $R_{12}$ estimated from the 10.7 cm solar radio flux $F_{10.7}$ and current
The model TEC will be a sum of the two models where STORM only contributes during active times. The routine to get a global TEC will be to do a fitting of the model TEC to the true (directly measured) TEC. During quiet times this method will provide high quality TEC values, during storm time the quality of the values will be highly variable. However, as long as we can provide satisfactory error estimates the user will know the error of his position.

**Error estimate:**
The error at a given point will be depending on several factors. For a TEC value at time t0 the error will depend on:

- Density of true measurements in the region
- Time tag of nearby true measurement (large distance in time will increase error)
- The error provided by the models.
- It is also possible to get in estimate of the accuracy of the model TEC by comparing the model with true values where these exist. The adjustment in error should however not be based on agreement in isolated points but rather on agreement over larger regions.

The total error function will have to take all these elements into account to provide the "true" error.

*Note: with TEC we mean the electron number in a vertical column of the specified coordinate.*

## 5.3 Broadcasting the „real-time" TEC and Warning

The TEC data center produces a global real time TEC map and regional storm warning information. These data will be distributed to three user groups, i.e., public internet users, scientific users, and navigation system users.
The internet user will be able to receive the global TEC information and its additional components via web access.
We will provide scientific users with a continuous stream of data relevant for various fields of studies.
Concerning navigation system users one goal is to provide them continuously with real time local TEC information for better calculation of their actual position which they get from a navigation system satellite. Thus, two ways of broadcasting this information will be taken into account. For continental users the required information will be delivered by UMTS and GPRS systems. In regions which are not covered by UMTS we distribute the data via geostationary satellites as a partner of INMARSAT.

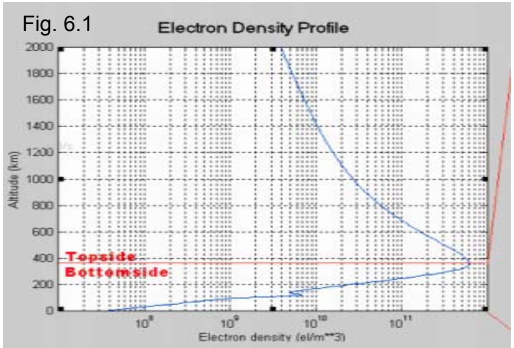
# 6 The Prediction Center: Prediction and warning of compromised position information : ☹, 😐 or ☺

* Positioning Systems are affected by magnetic storms and substorms. To obtain a reliable positioning service, we must globally monitor of the variation of the particle densities in the ionosphere which act as a perturbation term in communications. GLOTEC will provide real time TEC map and eventually scintillation indices.
* Magnetic storms and substorms will be predicted. GLOTEC is going to provide its customers with warnings at 1.5 days and at 1 hour that the position that they will obtain from global positioning system satellites signals (such as GPS or Galileo) might be not accurate. End of alert -service will be also available.

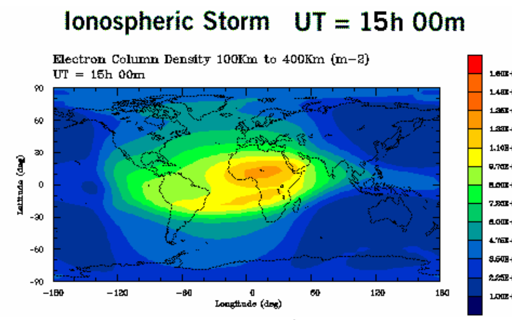
***Responsibilities :***
* Because of the instruments present on the Sun Earth L1 Lagrangian measurement point, warning problem messages are guaranteed 1 hour before.
* When SOHO/EIT and SOHO/LASCO/C2 or STEREO/SECCHI data will be available, we guarantee additional global warning at least 1 day before.

## *Basic Description & functionality*

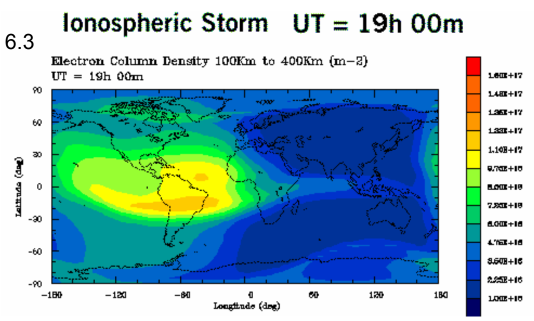
***Description of the TEC (Total Electron Content ) :*** The total electron content (TEC in $10^{16}$ electrons/m$^2$) is the number of electrons in a column of one square meter cross-section along a path from a satellite to a ground receiver through the ionosphere (Figure 6.1).TEC varies by latitude and daytime (Figures 6.2, 6.3). In the daytime, the Sun's ultraviolet radiation usually produces more plasma (and, therefore, TEC) at middle latitudes than in higher latitudes. At night, the auroral ionosphere in high latitudes often has more plasma than the mid-latitude ionosphere. TEC maps are produced in real-time by mapping GPS observables collected from 25 ground stations. In fact, accurate information on TEC is essential for satellite navigation systems. Information on TEC provides a valuable tool for investigating global and regional ionospheric structures. These maps are also used to monitor ionospheric weather, and to nowcast ionospheric storms that often occur responding to activities in solar wind and Earth's magnetosphere as well as thermosphere.




***Description of the scintillation :*** When a signal between satellite and the receiver exhibits temporal fluctuations of intensity and phase because of turbulence and irregularities of electron density it is called scintillation. Phase scintillation induces frequency shift and when this shift exceeds the phase lock loop bandwidth, the signal is lost. Scintillations are strong at high latitudes, weak at middle latitudes and intense in the equatorial region. During solar maximum period, the maximum value is attained at all latitudes when the ionosphere's F region ionization density. The magnitude of scintillations during the solar minimum period is greatly reduced mainly because of decreased background ionization density. At high latitudes, scintillations are found to be associated with large scale plasma structures. Polar scintillation is more conspicuous in winter when solar ionization radiation does not smooth out the irregularities. In the equatorial region, at the time of the sunset, the ionospheric conductivity




Figs. 6.2 and 6.3

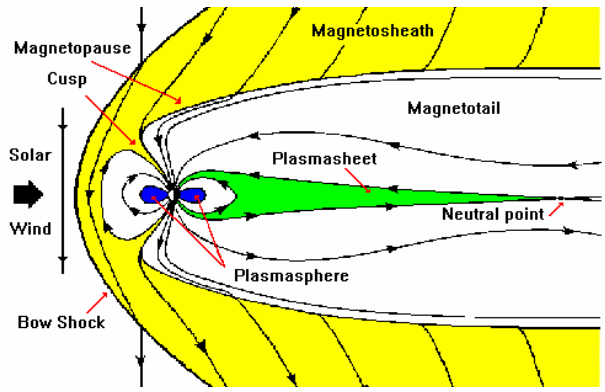



integrated along the magnetic field line changes rather abruptly across the sunset line or the terminator. Large scale plasma bubbles are formed in the bottom side of the ionosphere and rise to great heights. These irregularities cause intense dense L-band (1-20dB) scintillation. It decays shortly after midnight. The trigger mechanisms which make space time variability of scintillation are unresolved (Basu S. & K.H. Groves, 1996, and reference herein). Empirical scintillation model WMBOD is available and could be used to forecast the scintillation.

*Physical Description of the phenomena involved :* Flares are ejecting high energy particles which reach the L1 point about 1 hour later (seen as snow on solar image instruments, CCDs). When concentrating to the effects concerning TEC , the main influence on the Earth is Polar Cap Absorption. Often quasi-simultaneously, CMEs are expanding. If they are oriented toward the Earth, they reach the L1 point. If the z-component of the IMF observed by ACE points southward and reaches a certain value in a given time, together with some evolution of some plasma parameters v, n, Tp, it will create a magnetic storm as it reaches the earth. Classical timescale for a shock to travel from the Sun to the Earth is 80 hrs (from 40 to 120hrs, based on Schwenn et al., 2001).

Baumjohann and Treumann (1997) derived the equations which describe the magnetic ring current, substorms and storms. Particles trapped in the dipole magnetic field are submitted to a drift which creates a ring current.
At certain times more particles than usual are injected from the tail into the ring current, creating additional depression in near equatorial region. When the depression is large, it is called a magnetic storm and had 2 different phases:
1/ For some hours or days, an enhanced electric field injects lots of particles into the inner magnetosphere.
2/ After a day or two, the injection rate goes back to normal and ring current can loose particle by charge exchange and pitch angle scattering.

Another important aspect in Earth Magnetic Disturbances is due to Auroral electrojets, when particles precipitating in the auroral oval are causing significant ionization and increase the conductivity. The Auroral Electrojet index (AE), which is a measure of global auroral electrojet activity, is based on readings of the northward magnetic disturbance from 12 observatories. The amount of dayside magnetic flux merged per unit time depend on the number of southward oriented interplanetary field lines which get into contact with the Earth's magnetopause during a given time interval. According to the actual theory (Chen et al., 2000), the magnetic flux rope of a CME directed toward the Earth might create these disturbances.
A magnetic substorm starts when the dayside merging rate is distinctively enhanced. The flux eroded on the dayside magnetopause is transported into the tail, then after reconnections, the AE index increases. The period of enhanced convection and loading of the tail with magnetic flux corresponds to substorm growth phase. During that period (~ 1 hour), the main effect concerning TEC on the Earth is increasing Auroral ionization. After that, the tail releases the surplus of energy (the substorm onset) and thus starts the expansion phase. For 30-60 min. auroral arc, plasmoid ejections, occurred. After that for about 1 or 2 hours the aurora fade (recovery phase).



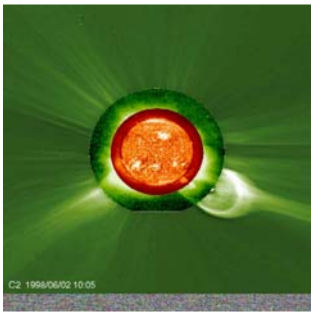
So the main features during storms and substorms which can affect the ionosphere are:

- Auroral precipitations (Joule heating and Currents)
- Potential drop across the polar cap. This leads to plasma drift from aurora regions
- Ring current decay (precipitation in mid latitudes, heating of ionosphere by energetic neutral particles after recharging in the ring current).

Change in the global convection in the ionosphere leads to:

- Change in TEC (Figures 6.2 and 6.3 shows the daily evolution)
- Scintillation.

***<u>Description of the System</u>*** The prediction will be done including two different timescales:
*<u>1/ CME or Flare warning :</u>* To determine the projected speed of a Halo CME we will use a temporal sequence of SOHO/LASCO coronagraph. To know if the observed CME is frontside, we need disk observations. CMEs are often associated with flares and filament disparition brusques. The flare level is determined from GOES with x-ray flux measurements. The SOHO/EIT images provide us the location of the flare (the figure to the left is a composite SOHO/EIT and LASCO image of a CME). Their timing resolution is around 12 minutes, and we estimate that a CME can first be seen on LASCO one hour after the emission (derived from Delaboudiniere et al., 1995, Howard et al., 1995). Synoptic images are taken at least 4 times a day (Moses et al., 1998), so in the worst case the alert of a CME could be given 33 hours before the arrival on Earth. To determine the direction of the expansion and the eventual time impact on the Earth, the solar rotation can be used (assuming the conservation of the main plain direction) with stereoscopic techniques on EUV images together with a time velocity derived from the coronagraphs (Portier-Fozzani et al., 2001). STEREO/SECCHI could be also used in a later phase of the mission for including the 3D aspect of a CME (Inhester et al., 2002).




*<u>2/Storm and substorm alert :</u>* The Earth is divided in three regions: High latitude (HL) regions in northern and southern hemisphere and low latitude (LL) region. Substorm and storm warnings are given to regions most affected by the activity.
<u>SUBSTORMS:</u> Using (IMF) magnetic field and solar wind velocity measurements from ACE and Von Krusenstierna spacecraft at L1 we calculate the epsilon parameter ( $\varepsilon = 10\text{^}7 * V * B\text{^}2\sin\text{^}4(\vartheta/2) * l0\text{^}2$ , where V = solar wind speed, B = magnitude of the solar wind magnetic field, theta = IMF clock angle and l0 = empirical parameter = 7Re ).
When ε > 10^11 W and IMF Bz < 0 for at least 20 minutes the substorm warning (☹) is given to the midnight sector (18:00-02:00 Magnetic Local Time) of the HL region (😐 warning for +/-2h) for the next 2 hours.

<u>STORMS</u>: The Dst value is determined by Burton (1975) is: $dD_{st}/dt = \alpha\varepsilon - \frac{D_{st}}{\tau_R}$ according to the solar wind measurements from the L1 point with $\varepsilon = 10^7 VB^2 \sin^4(\frac{\theta}{2}) l_0^2$
The storm warning level is Dst < - 50 nT and the warning is given separately for the main and recovery phases.

a) During a main phase of the storm we give ☹ warning for 16:00 – 08:00 MLT sector of the HL region (😐 warning for +-2h), and 😐 warning for the LL region for the next 6 hours. If Dst < -100nT, ☹ warning is given everywhere.

b) During a recovery phase, the ☹ warning goes to the midnight sector of the HL region, and 😐 warning to the LL region for the next 3 hours.

- Note that the Auroral Oval location model is based on the auroral AL indexes (and not Kp).

The Future: Improving the modelling of the ionosphere during storm and substorm conditions

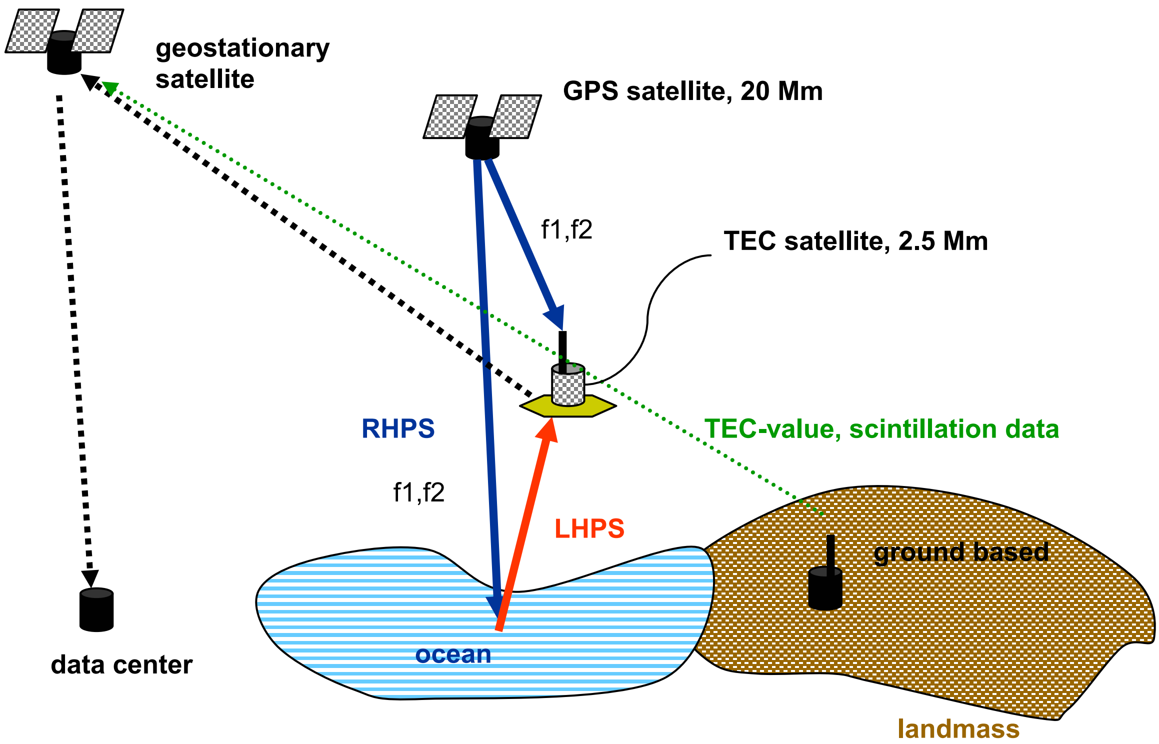
There are no current models that can make any long term prediction of ionospheric disturbances. The only thing which is used currently is models that can predict quiet time future – this is for example NeQuick, of which the only input is f10,7. For storm conditions the only thing that can be done currently is making a warning that something might happen, and this only with a very poor time estimate of when the possible storm will hit Earth. So a general warning can be send out, but unfortunately with very large uncertainty partly because we don't know for sure whether a storm actually will occur, and in the case a storm occurs how it will evolve, how severe it will be and where the effect will be largest. Today it is not until we have measurements at the L1 point that we will be able to give a certain prediction of a storm occurrence, but at that time there will only be about 1 hour until the storm actually hits Earth. One of the aims of future models should be to increase the amount of warning time from one hour, preferably up to three days.

One possible way of improving storm prediction would be to use neural networks. One of the advantages of neural networks is that they do not require a full understanding the physics behind the prediction of the ionospheric behavior, which is indeed very complicated and highly non-linear. The neural network will be trained with old data and the training will continue with the data available from our own satellites as soon as the satellites have started working. The neural network will be trained for the first few months after the system have begun operating, until it can provide a reliable forecast; in this period we will have to rely on the warning system described above only. The input for the neural network will be all the available data from our own satellites and possible ground based stations, this includes the measurements of **B** and proton fluxes at L1, as well as the global TEC maps and S4 measurements provided continuously from the Data Center. Other available data from science satellites can also be used, of special interest will be a measure of the solar activity level. The network will be trained through several storms, the actual broadcasting of predictions to the public will begin when the neural networks prediction are within a tolerable level of uncertainty. The training of the neural networks will be a continuous process, and the networks will be revised on a regular basis by space physics scientists, who are working at GLOTEC headquarters. This is also one of the reasons why it is important to keep an archive on old data as this can be used for the training of new neural networks. The aim of the neural network prediction is to be able to predict the time of arrival, the strength and the (regional) location of ionospheric disturbances from a coming storm that are a threat to the integrity of satellite navigation systems.

# 7 Space Segment Component

## 7.1 TEC Spacecraft Fleet

In order to provide a reliable TEC-Map of the earth our GLOTEC-System consists of 16 Satellites orbiting in 4 different orbits. Each orbit is circular with an altitude of 2.500 km. The satellites are 3 axis-stabilized along the earth-radius-direction. The figure below illustrates the principles of measurements.




### 7.1.1 Principles of Measurements: Over the ocean

Every GPS-Satellite transmits a Right-Hand-Side-Polarized (RHSP) Signal on two frequencies (f1,f2). The GLOTEC-Satellites receive

- the RHSP-Signal coming up directly from the GPS-Satellite **and**
- the reflection of the same signal on the surface of the ocean, which is Left-Hand-Side-Polarized (LHSP)

The TEC-Value and other disturbances in the ionosphere effects the travel time of signals. This value of the effect depends from the frequency. Using 2 frequencies makes it possible to estimate the TEC value.

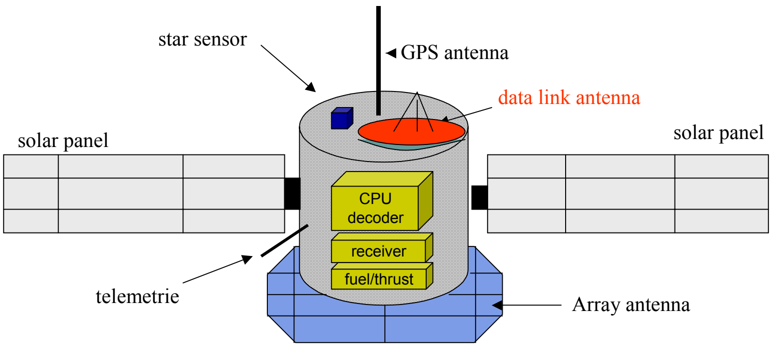
The GLOTEC-System distinguishes the direct Signal from the reflected Signal using polarimeters.

### 7.1.2 Principles of Measurements: Over ground

Over the ground we have extend the existing network of ground-base-stations in three ways:

- the new feature of uplinking the TEC-Value to geostationary-satellites is needed in existing stations without internet-connection
- there are more stations needed around the world in uncovered regions
- in order to estimate ionospheric scintillation-effects we add a special detector to stations on sensible earth-locations

Over ground there is no reflected GPS-Signal available, except from big lakes or other water resources, which can be used by GLOTEC-Sats.

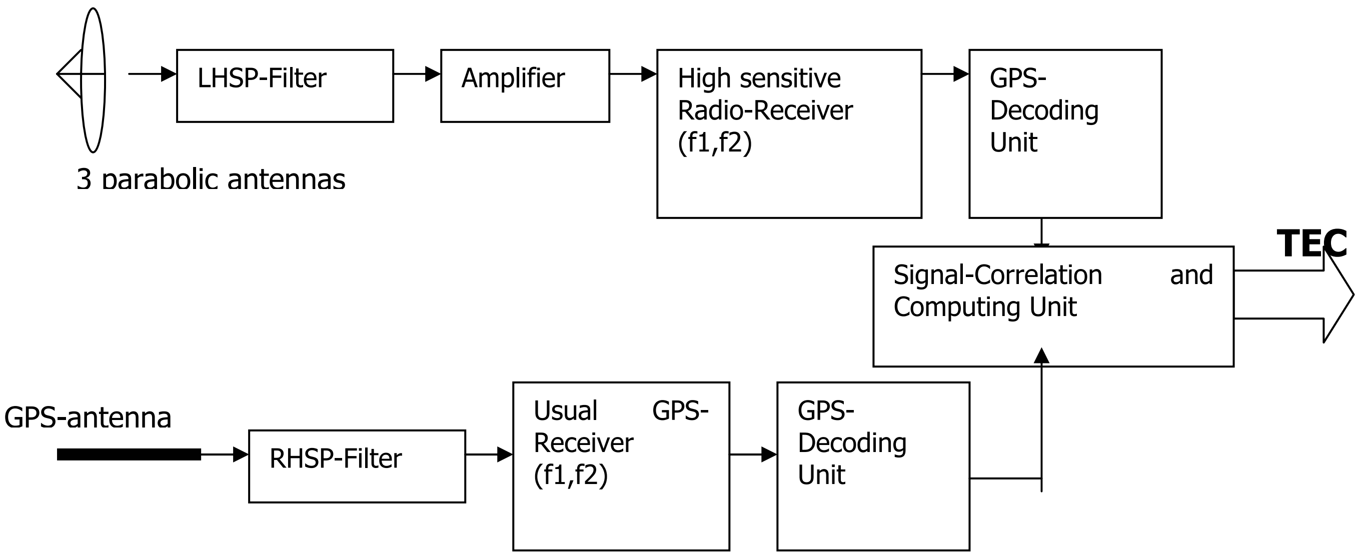



### 7.1.3 Instrumentation: Antennas

- 1 omni directional GPS-Antenna to receive the direct Signals from the GPS-Sats (RHSP)
- 1 Array-Antenna directed always downward to the earth to receive signals reflected by the ocean (LHSP):

How the Array-antenna works: The downward directed antenna consists of patches and changing the phase between these patches will increase the sensibility along the desired direction. This phase-changing can be done according to a program and so we steer the beam to a certain spot of the surface according to the known-position of reflection from the GPS-Satellite. The field-of-view (VOF) of such an antenna is limited to 45° of NADIR for good geometry of the signal path.

- 1 Communication-Link Antenna (40 GHz), using to transmit the TEC-Data to a geostationary Communication-Satellite
- 1 Telemetry-Antenna receiving different operational commands from mission control




### 7.1.4 Instrumentation: Receivers

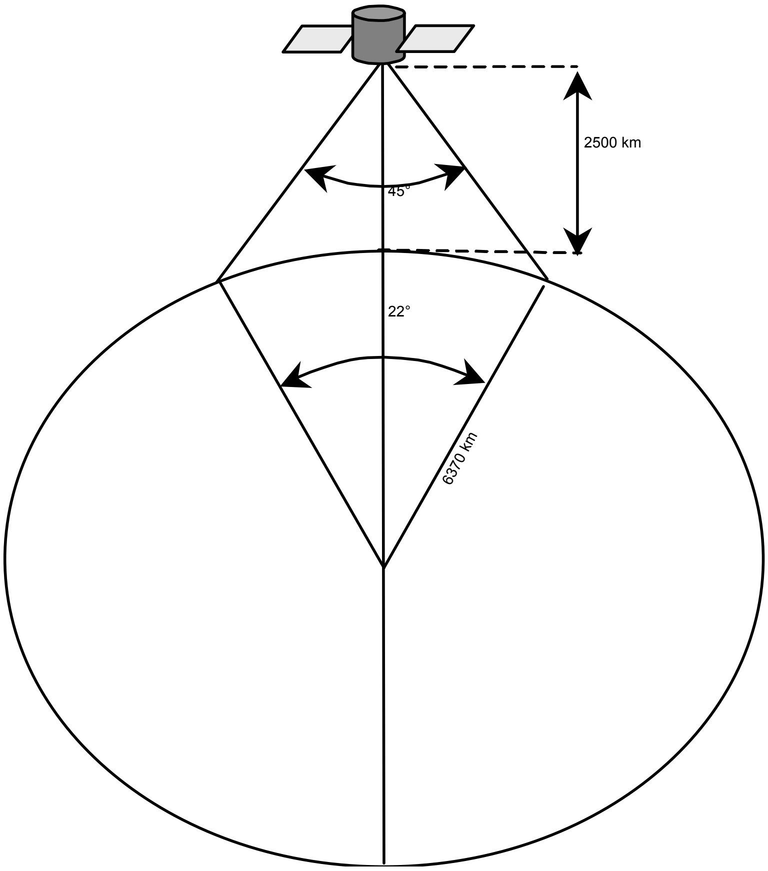
- High-Sensitive 2 Frequency-Radio receiver
- Usual GPS-Receiver (2 Frequencies)

### 7.1.5 Instrumentation: Operational Devices

- Star-Sensor (for attitude-control)
- Gyroscopic sensors with dumpers
- Thrusters for orbit adjustment and initial positioning
- Communication Units for Data-Transfer
- power Subsystem (Solar battery)
- Solar-Array (two 1 sqm deployable Solar-Array with 150 W)
- CPU-Unit
- Fuel for Orbit-Corrections

### 7.1.6 Orbits

Altitude : 2.500 km
Period : about 120 min
Orbit type: circular, polar orbit
Field of View: 23° on earth for each GLOTEC-Sat
Number of Sat's: 4 equally spaced Sat's per Orbit
Number of orbits: 4 orbits uniformly distributed in longitude
Total of Sats: 16 + 2 Spares




## 7.1.7 Estimated Resolutions: Time

The 45°-Field-of-View of the Array-Antenna gives approx. a 23° Band-Coverage on the surface of the earth with an orbit-altitude of 2.500 km. With 4 Satellites per Orbit the time-resolution or our sampling (which means the time interval between the sampling of the same region by two satellites) is approx. 25 min.

## 7.1.8 Estimated Resolutions: Space

The space-resolution over the ocean depends on the location. Assuming we see 6 GPS-Satellite-Links at each time the space resolution in the FOV of the antenna is about 3°.
The space resolution over ground should be a least 5°.
The Gap-Coverage due to chosen orbit produces sometimes at worst a resolution of 20°. In over-sampled Areas we get a much better space- and time resolution.

## 7.1.9 Power

| | | |
|---|---|---|
| Array-Antenna-Receiver: | | 20 W |
| GPS-Receiver: | 5 W | |
| Telemetry-Data-Receiver: | | 5 W |
| CPU: | | 25 W |
| Thermal Control | 25 W | |
| Data-Transmitter: | | 25 W |
| Star-Sensor: | | 5 W |
| Gyroskopic Sensor: | | 5 W |
| Other devices: | 5 W | |
| Total: | | 120 W |

The power requirements will be satisfied by a 2 sqm Solar-array.

## 7.1.10 Launch

We plan to launch 4 ( or 5) satellites with one Rocket at the same time, resulting in 4 launches. As a launching-astem a reconverted russian Missile-Rocket or PEGASUS (USA) will be used.

## 7.2 L1sat

In order to predict the space weather at least one hour on beforehand, a single satellite is being placed at the L1 Lagrange point of the Sun-Earth system. The satellite will provide the prediction group with the proper information on space weather storms reaching the Earth environment. The satellites payload consists of a magnetometer and a solar wind monitor. The magnetometer monitors the magnetic field vector **B**(t), and it is placed on a 1,5 meter deployable boom on the spacecraft to prevent interfering with the spacecrafts own magnetic field. The solar wind monitor provides information like the solar wind ion density $n_{SW}(t)$ in a velocity range of 300 to 700 km/s. Furthermore it measures the velocity vector of the solar wind $\mathbf{v}_{SW}(t)$.

The satellite will be placed in a halo orbit around the L1 point, 1,5 million kilometers away from the Earth. Its amplitude is 400 000 km in the x direction and 150 000 km in the y-direction. The satellite will be launched by the Soyuz-Fregat launcher which is not only well-known for its cheap launches but also for its capabilities (1600 kg into a Lagrange orbit) and reliability (100%).

The satellite will be tracked from the Earth continuously from three groundstations spread over the globe namely in Perth (Australia), Villafranca (Spain) and Kiruna (Sweden). These ground stations need a 15 meter dish antenna. The data downlink requirement is 240 bits/sec (including 3 instruments, instrument housekeeping and spacecraft housekeeping). The spacecrafts antenna is always pointed to Earth during the Halo orbit.

The spacecraft is spin stabilized and provided with a sun sensor, star tracker, thrusters, a passive nutation damper, and backup units of the sun sensor and star tracker. The craft will rotate with a rotation rate of 5 rpm. The AOCS system will provide orbit corrections which are necessary due to the unstable character of the L1 point. Also spinning axis errors are corrected and a slow rotation rate around the spacecrafts z-axis will be provided for keeping the solar cells facing the sun (360° a year). As there is no sun observing instrument aboard, the pointing error may be up to 1°.

The satellite is placed at L1, so in a rather stable thermal environment which differs only slightly from the thermal environment at Earth ($F_{L1}$=1.418 erg/cm$^2$s).
The hazards to be encountered are solar proton events for which a 5 krad dose may be expected for a 4 mm Al shielded component. Also cosmic rays are a second hazard. A rough estimation of the mass of the satellite is 115 kg.

In the design of the spacecraft also cost has seriously been taken into account. The satellite is a simple and low-mass spacecraft. Due to the off-the-shelf technology the reliability is increased and the costs are reduced. Furthermore the spacecraft reaches the L1 point with the aid of the Fregat. Therefore it does not need an independent propulsion system (apart from the AOCS thrusters).

# 8 Cost Estimate

| | |
|---|---|
| **L1 spacecraft:** | |
| Spacecraft | 40 M€ |
| Spacecraft launch (using Russian Soyuz-Fregat launcher) | 37 M€ |
| subtotal | 77 M€ |
| | |
| **TEC measurement satellites:** | |
| Construction of 18 Satellites, ( 750 k€ each) | 14 M€ |
| Launch-Costs (10.000 $/kg) incl. 2 Spares | 10 M€ |
| Building the ground-base-network | |
| Build new stations | 30 M€ |
| Update existing stations | 5 M€ |
| subtotal | 59 M€ |
| | |
| **Data/Prediction Centre and HQ:** | |
| Three ground stations | 6 M€ |
| Data processing centre | 2 M€ |
| Ground station operating costs (4M€ per annum, 10 yrs) | 40 M€ |
| Other maintenance costs (2 M€ per annum, 10 yrs) | 20 M€ |

| | | |
|---|---|---|
| subtotal | | 68 M€ |
| Year 2003 | 150 M€ | |
| Years 2004-2012 | 6 M€ p.a. | |
| Total | | 204 M€ |

## 9 Summary

In this study we have presented some innovative achievements. Our service offers a reliable and continuous global coverage of the Total Electron Content. This enables us to provide the highest possible position accuracy for single frequency satellite navigation receivers. We also offer continuously self-refining "Quality of Service" predictions of high quality, even under severe Space weather conditions.

Work done around GLOTEC will help develop more advanced models for space weather prediction in the future. Also some of the upcoming experiments are going to provide new sources of data which can be integrated into our system. GLOTEC will also help the satellite navigating community to migrate from GPS to GALILEO as seamlessly as possible.

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Useful Web sites :
SOHO http://sohowww.nascom.nasa.gov
STEREO SECCHI http://projects.nrl.navy.mil/secchi/index.html
TEC http://www.windows.ucar.edu/cgi-bin/realtime/spaceweather/ionosphere_movie.html