Space weather and impact on GNSS

Presentation to ESESA workshop.

2 – 3 March 2011. Somerset-west.

Dr Ben Opperman. Hermanus Magnetic Observatory

Ben.Opperman@hmo.ac.za

www.spaceweather.co.za
www.hmo.ac.za

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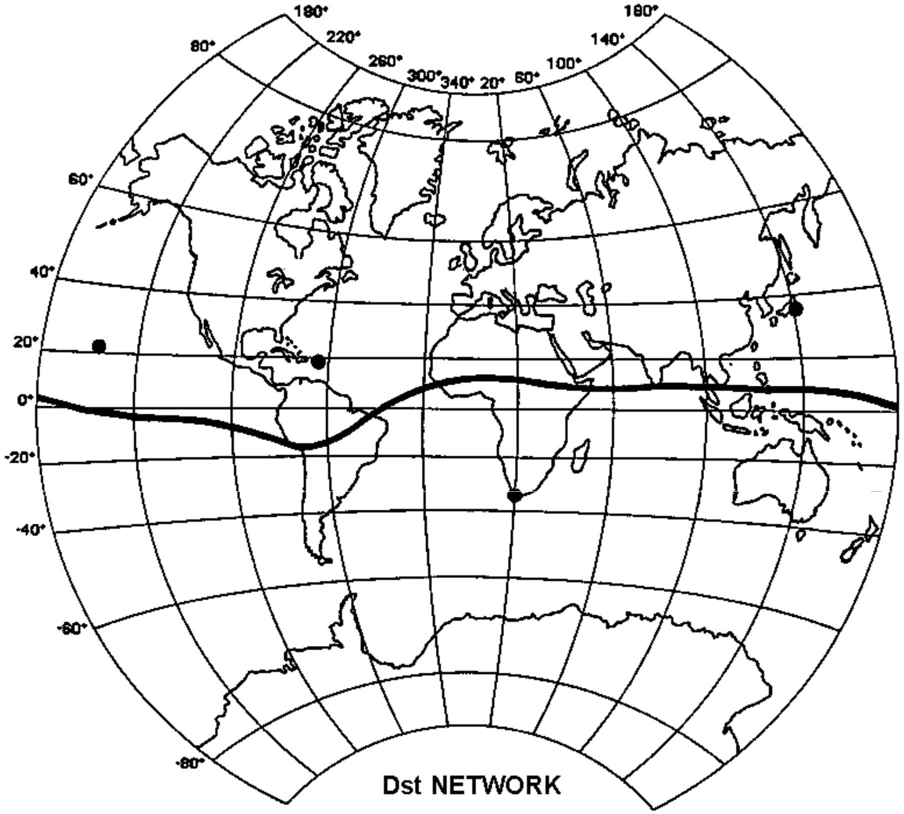
Hermanus Magnetic Observatory (Est. 1932)

Buildings on UCT campus which housed the fist magnetic observatory instruments.

The HMO's first buildings on the outskirts of Hermanus in 1941

First permanent magnetic observatory in South Africa established on UCT campus – moved to Hermanus in 1941.

Hermanus Magnetic Observatory



The **Hermanus Magnetic Observatory (HMO)** is a research facility of the National Research Foundation of South Africa and is situated in the Western Cape. It forms part of the worldwide network of magnetic observatories, which monitor and model variations of the Earth's magnetic field. The HMO's primary research focus is Space Physics and is to be incorporated in the South African National Space Agency

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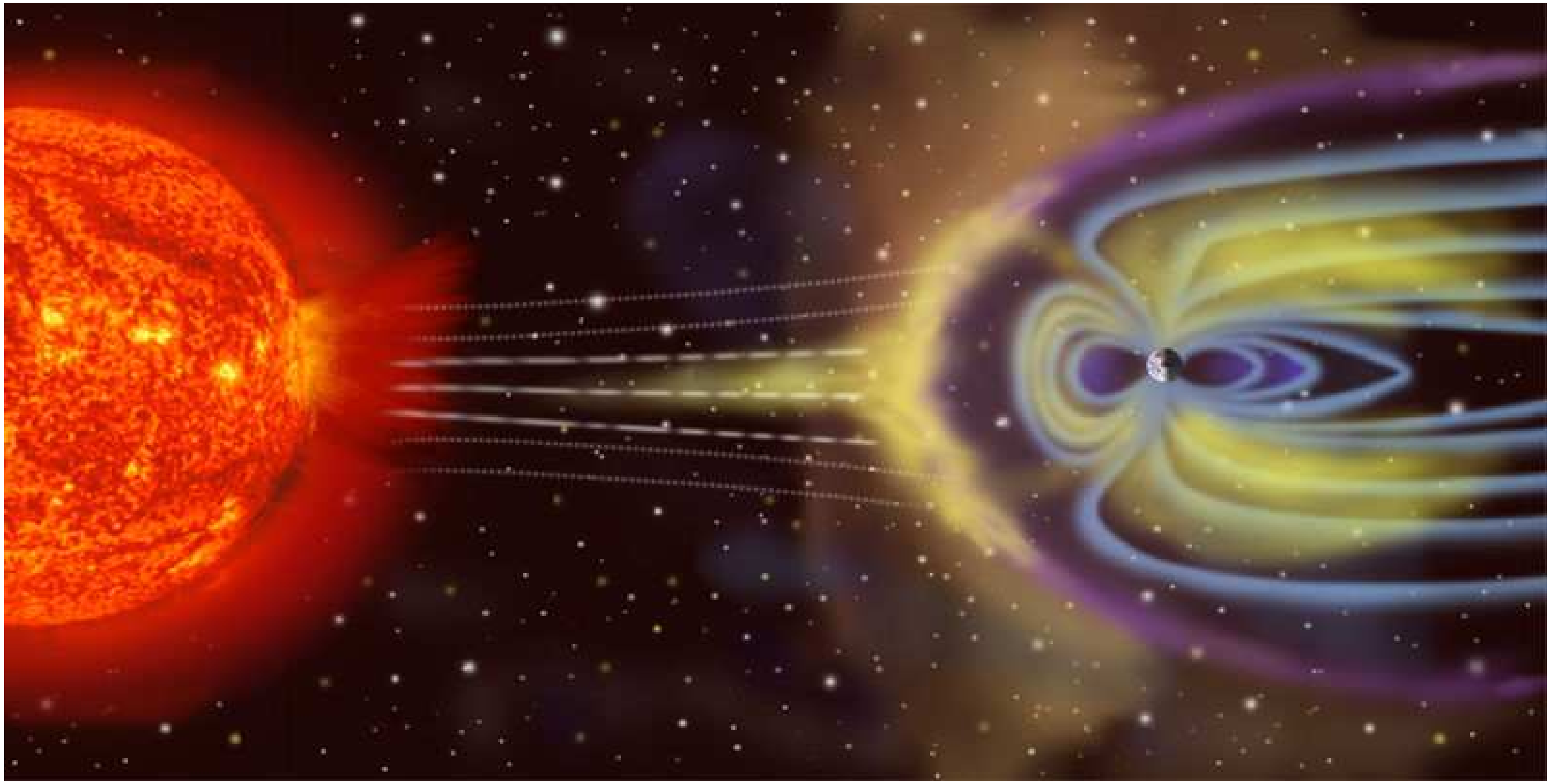
International Space Environment Service

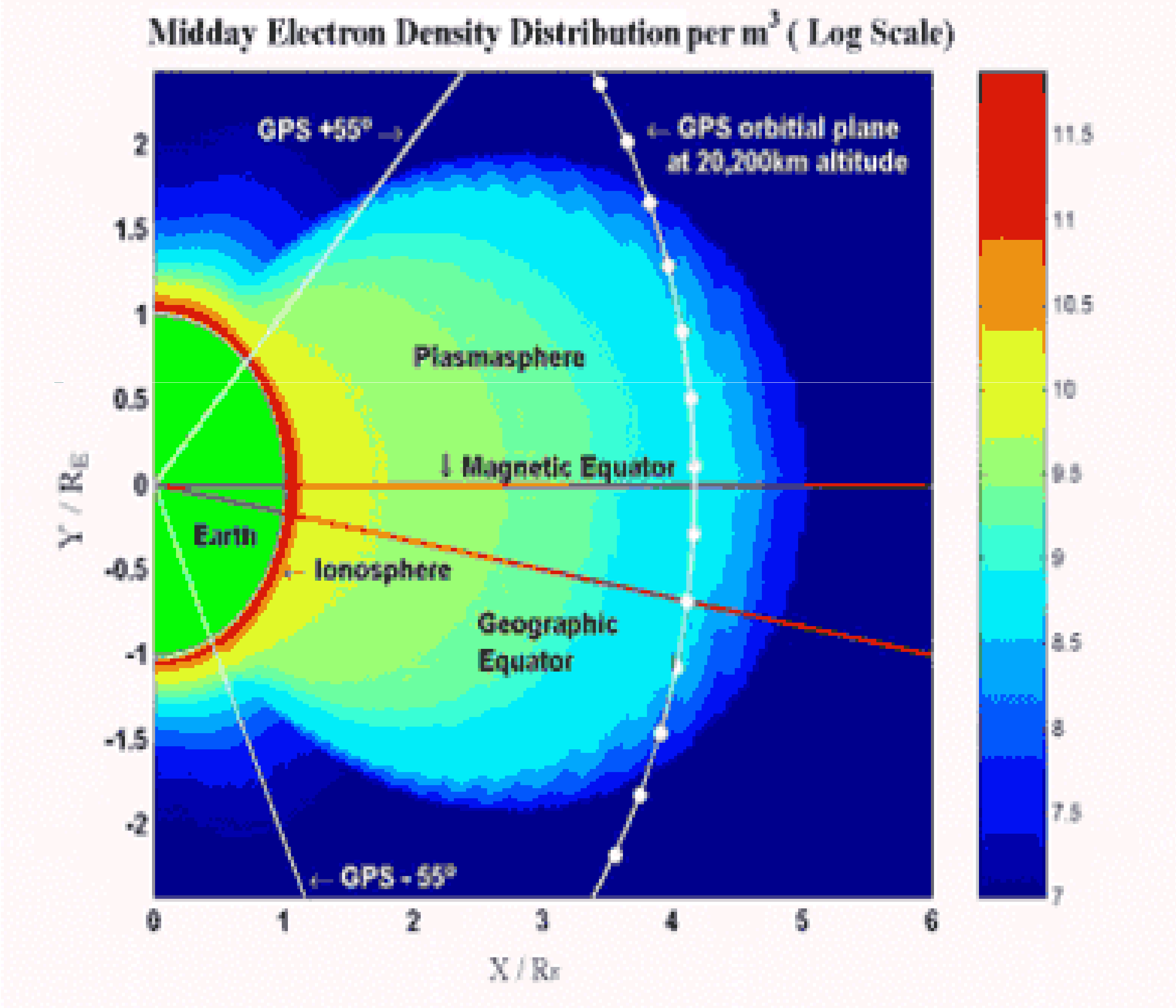
The mission of the ISES is to encourage and facilitate near-real-time international monitoring and prediction of the space environment by the rapid exchange of space environment information to assist users to reduce the impact of space weather on activities of human interest.

http://spaceweather.hmo.ac.za

Solar-terrestrial environment



Near –Earth space environment



Ionosphere:

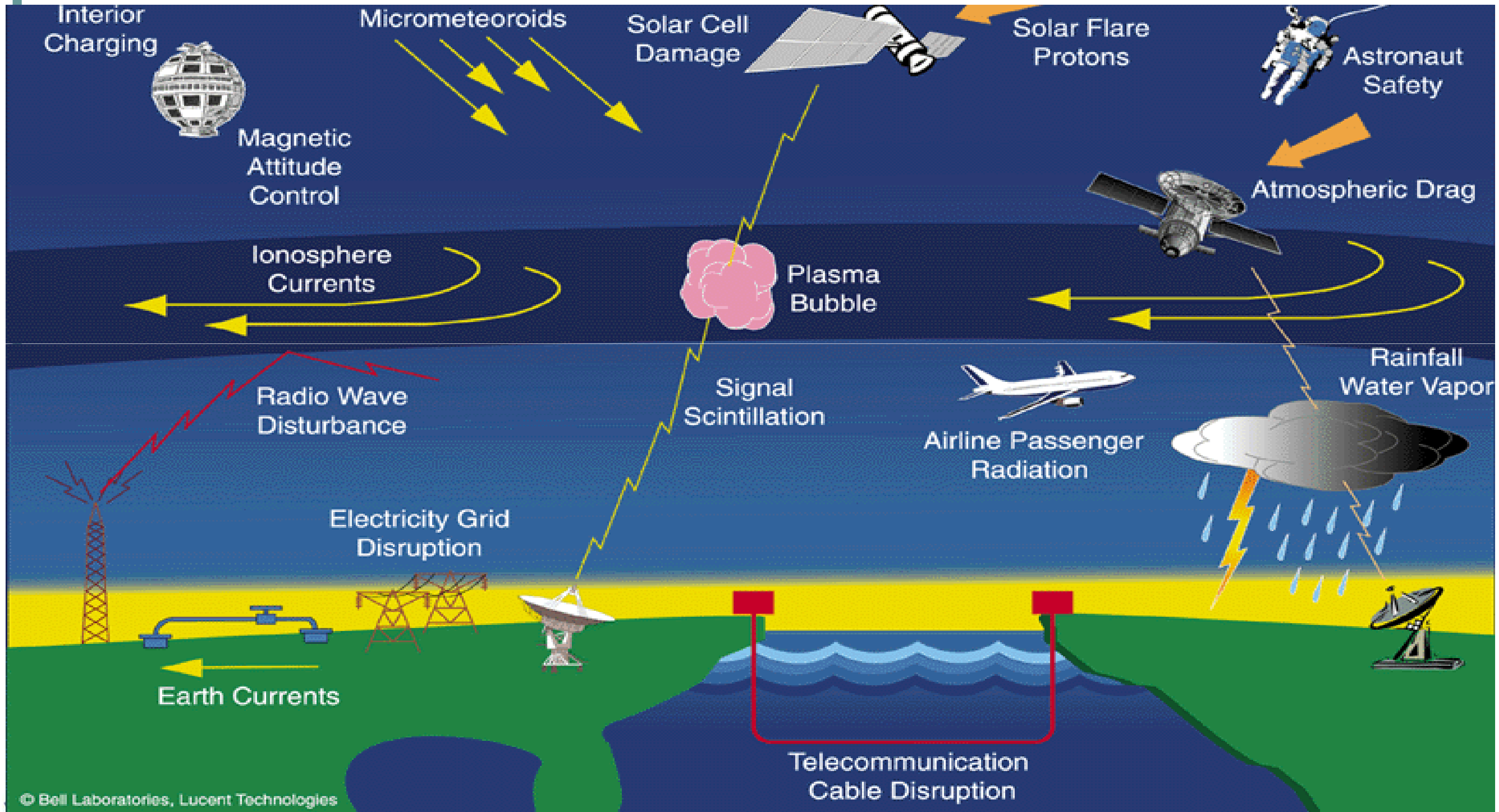
100 - 2000km

Plasmasphere:

2 000 - 35 000 km

Plasma causes group delay, phase advance

Space weather hazards



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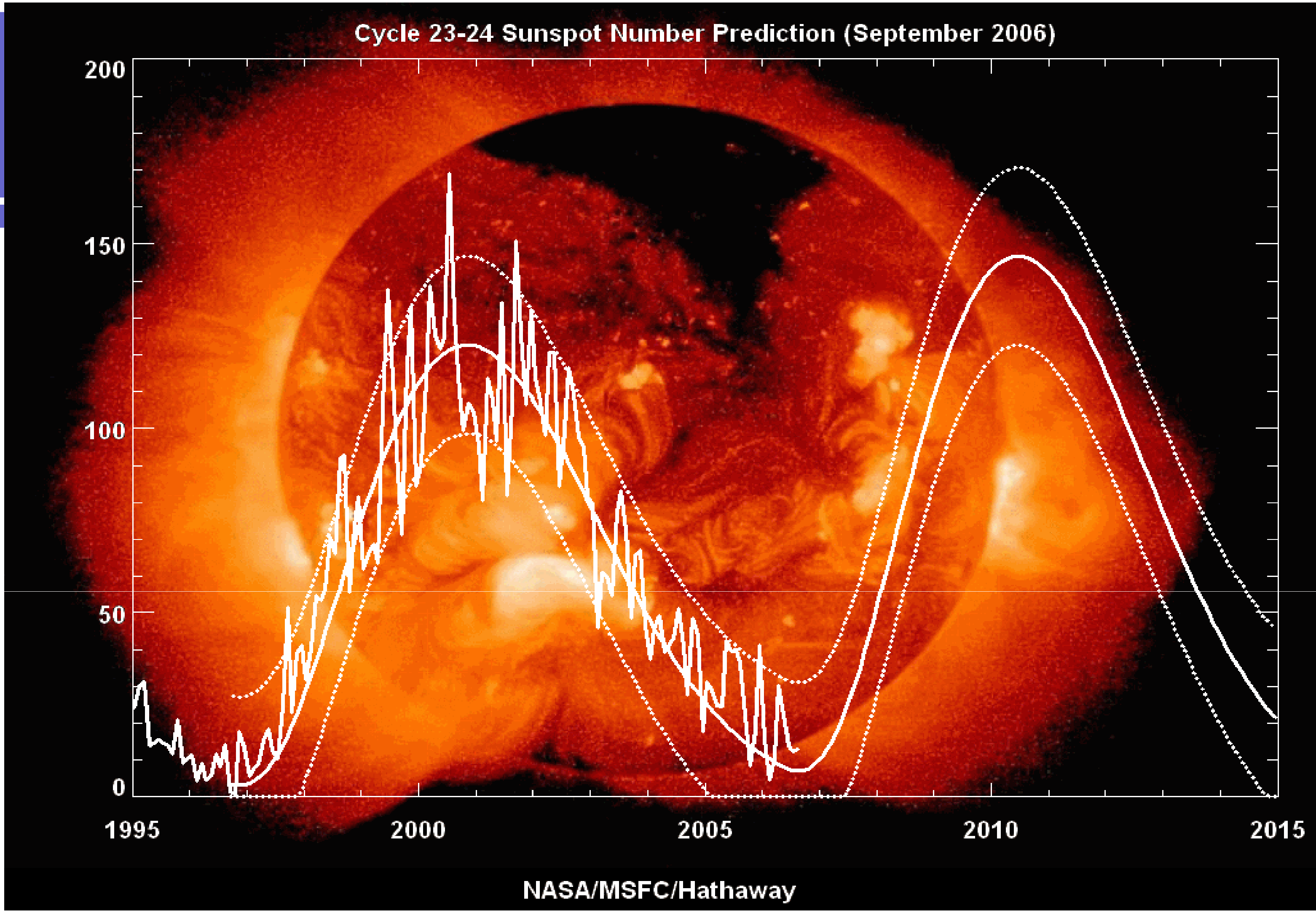
ESKOM Transformer damage

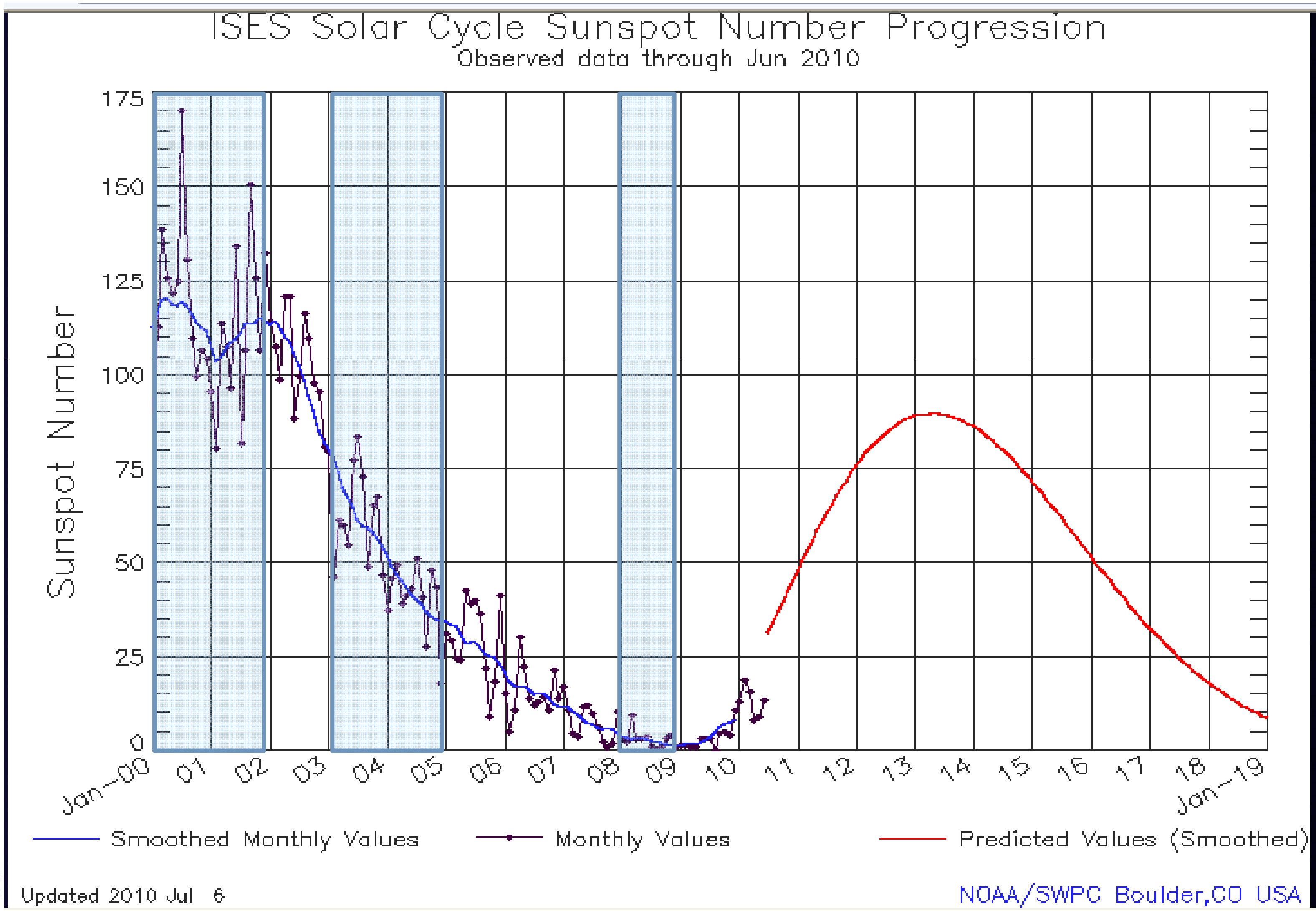
Photos: CT Gaunt



Solar cycle based on number of sunspots

Sunspots are concentrations of magnetic flux associated with flares on the sun. They appear dark because they are cooler than the surrounding. The number of sunspots increase and decrease over an 11 year cycle. The peak of the next solar cycle, cycle 24, is currently predicted to be at about 2013.

Solar Cycle & selected data periods



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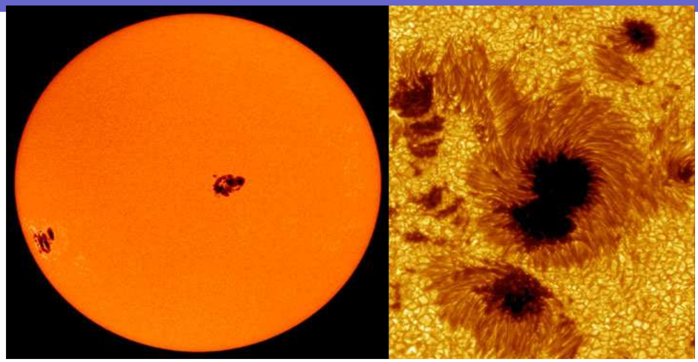
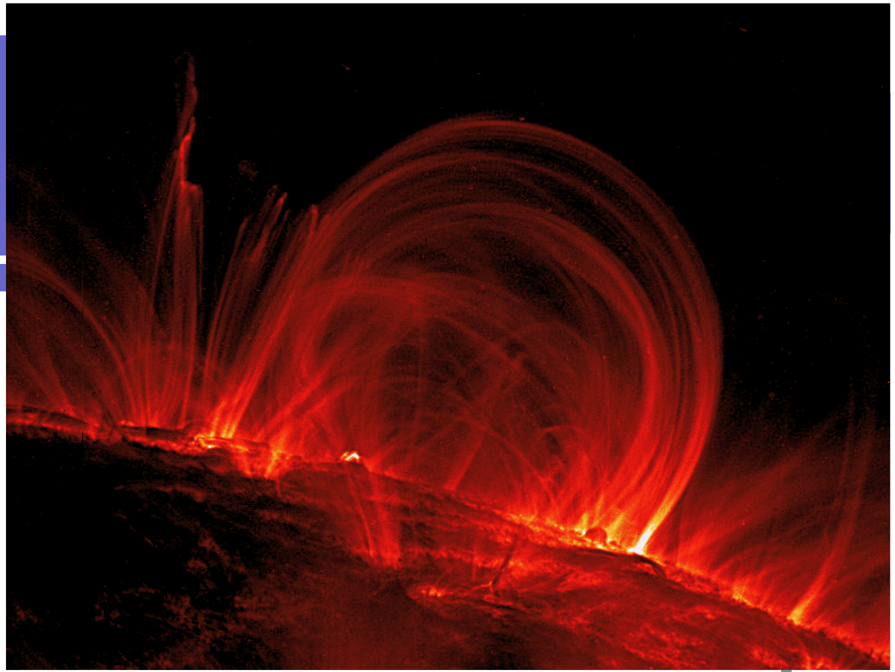
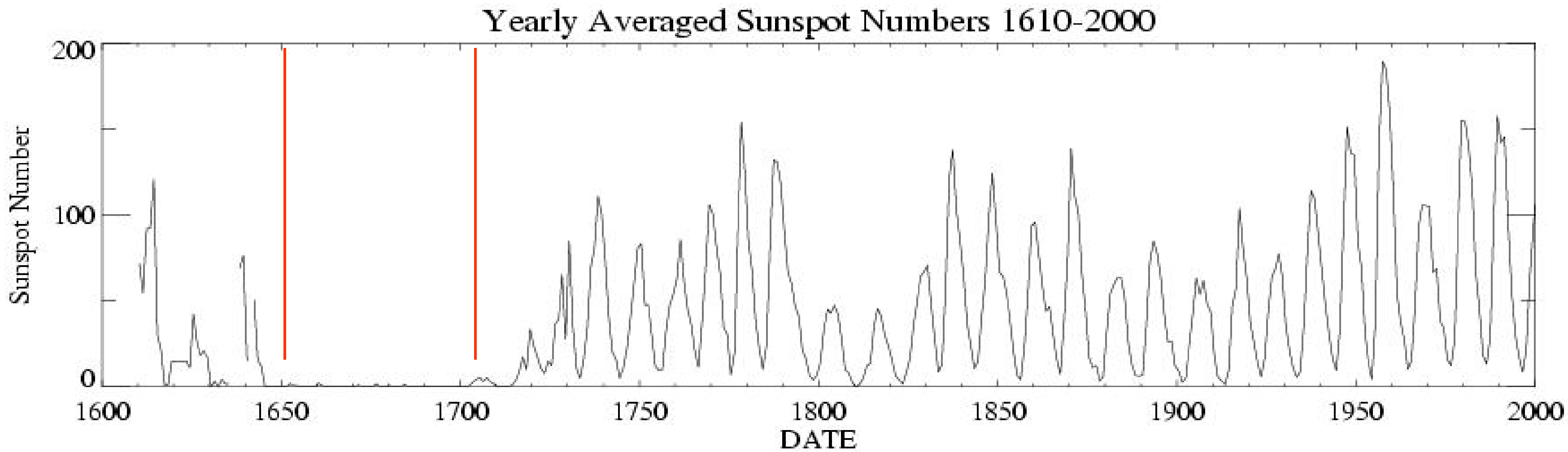
11-year sun spot cycle



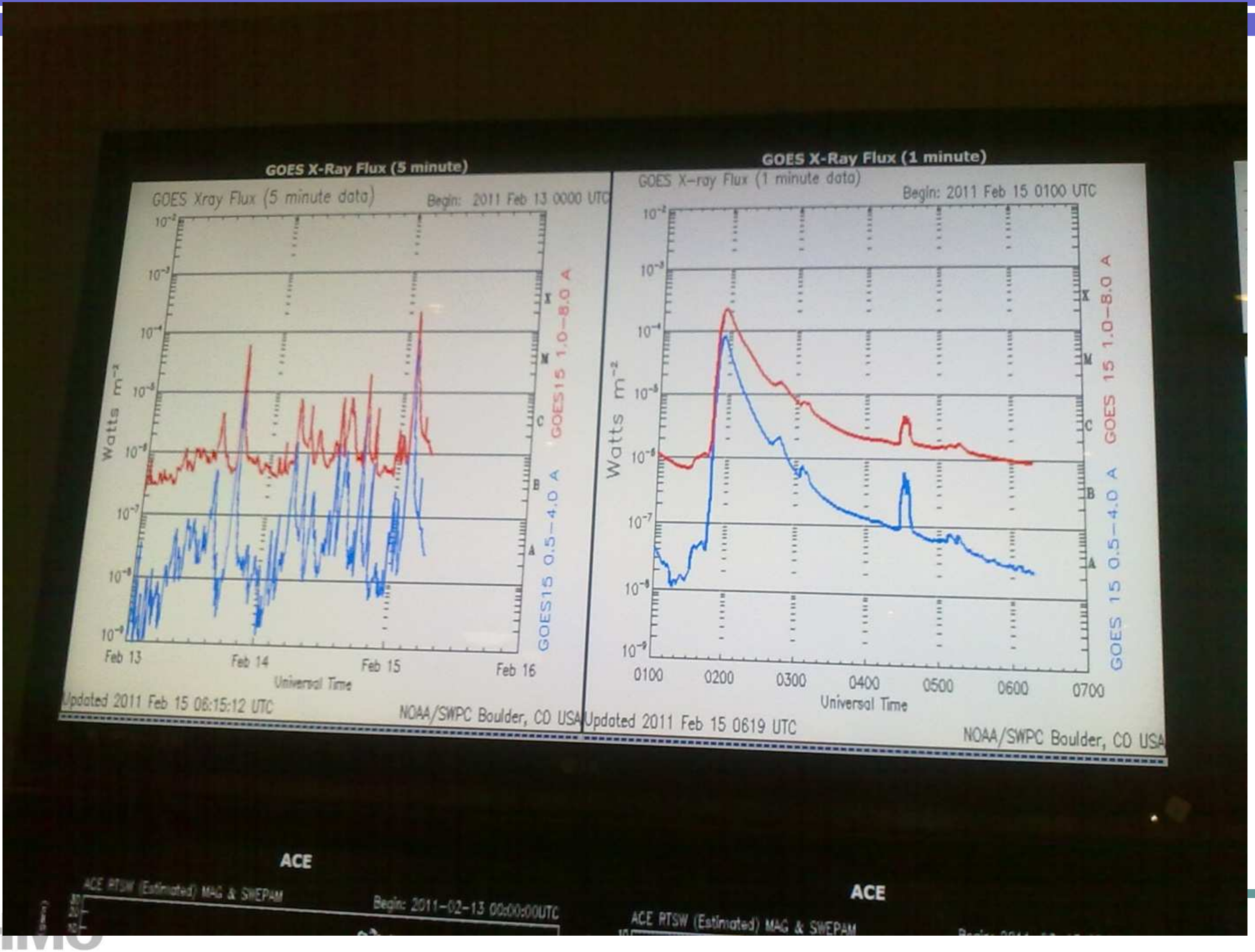




Maunder Minimum 1645-1715

14-15 Feb 2011 geomagnetic storm

GOES observing EM shock from solar X-ray flare



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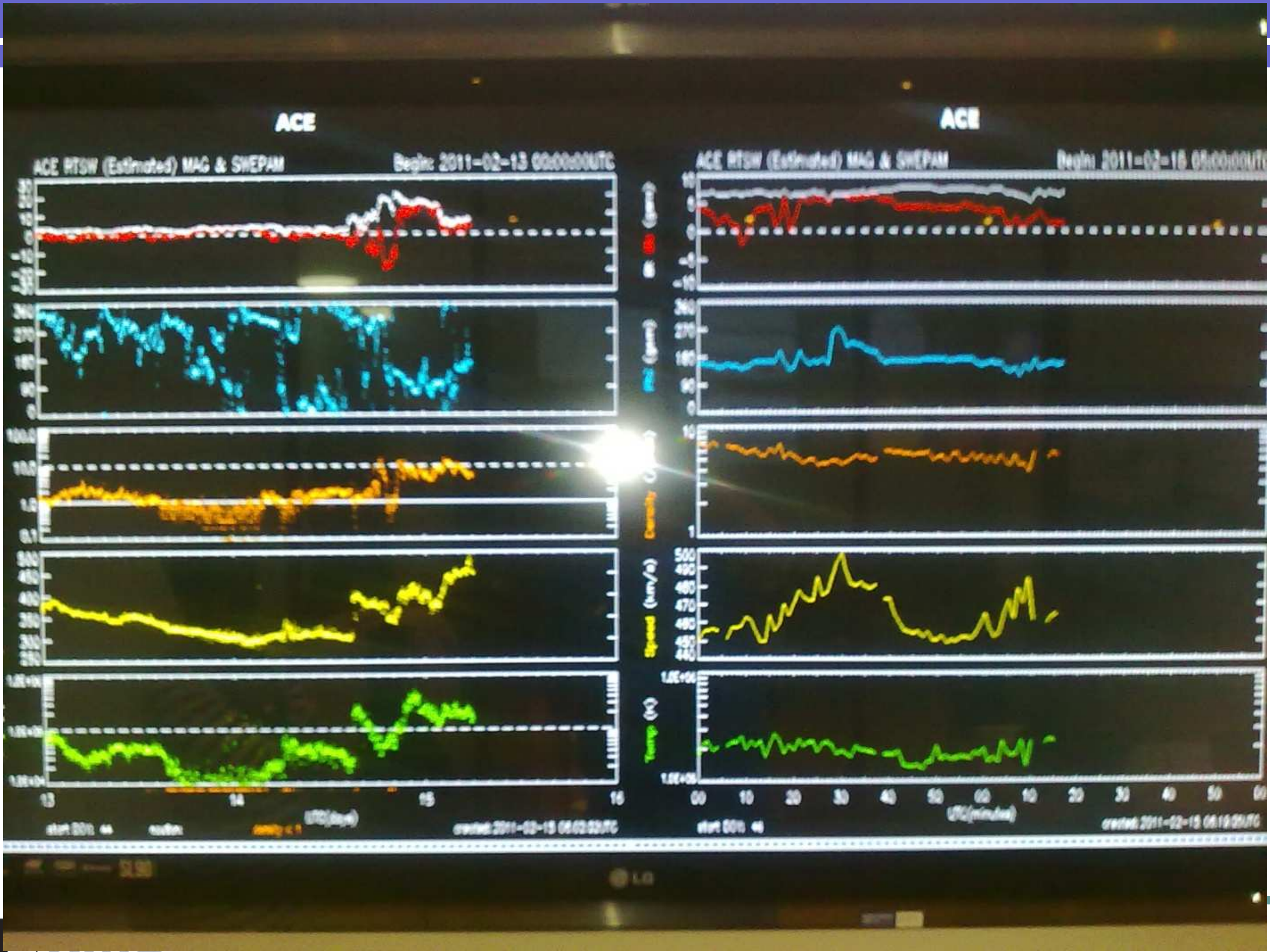
ACE Solar wind measurements



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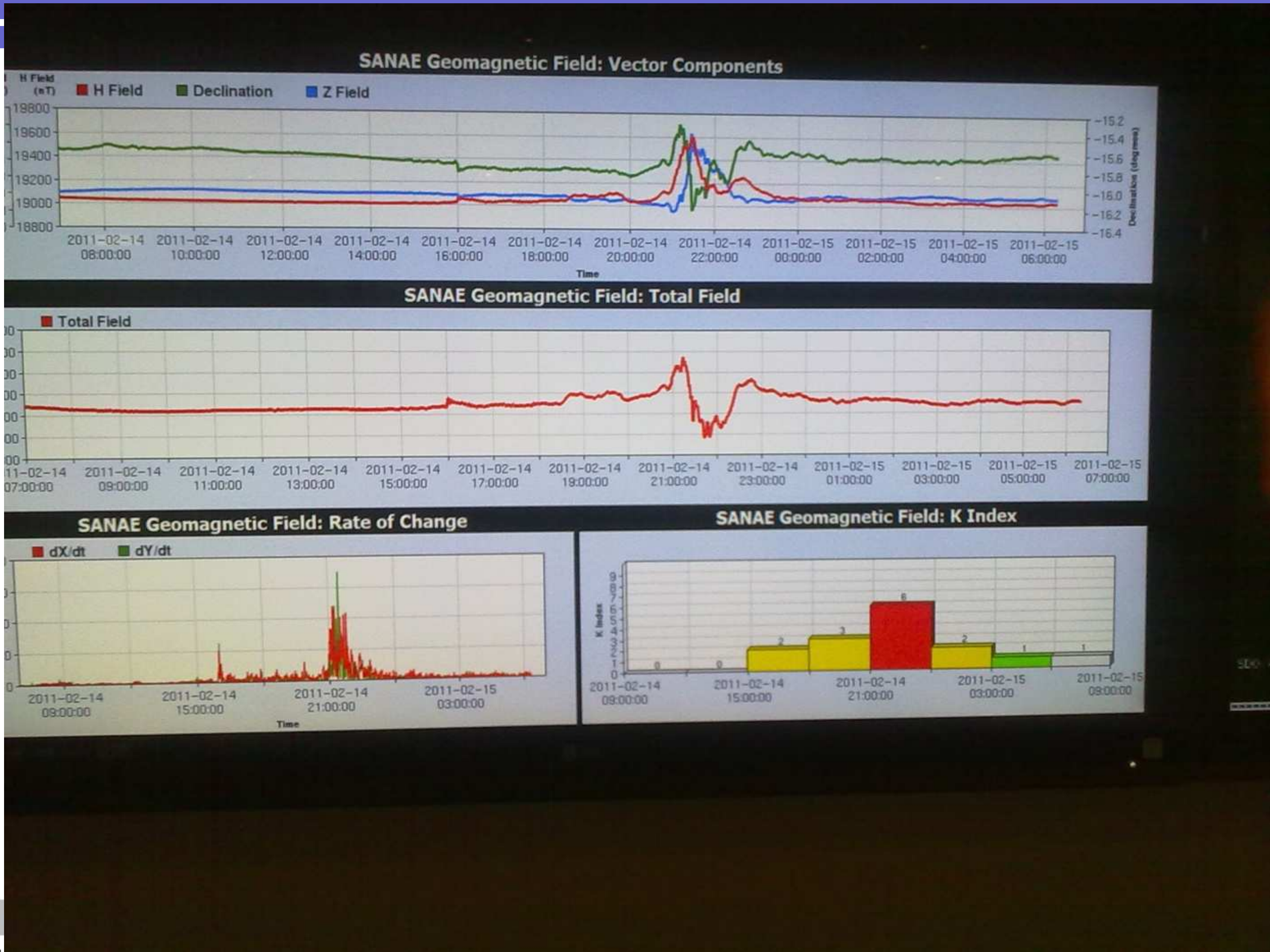
RWC

Magnetograms illustrating disturbed magnetosphere



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Complex sunspot activity

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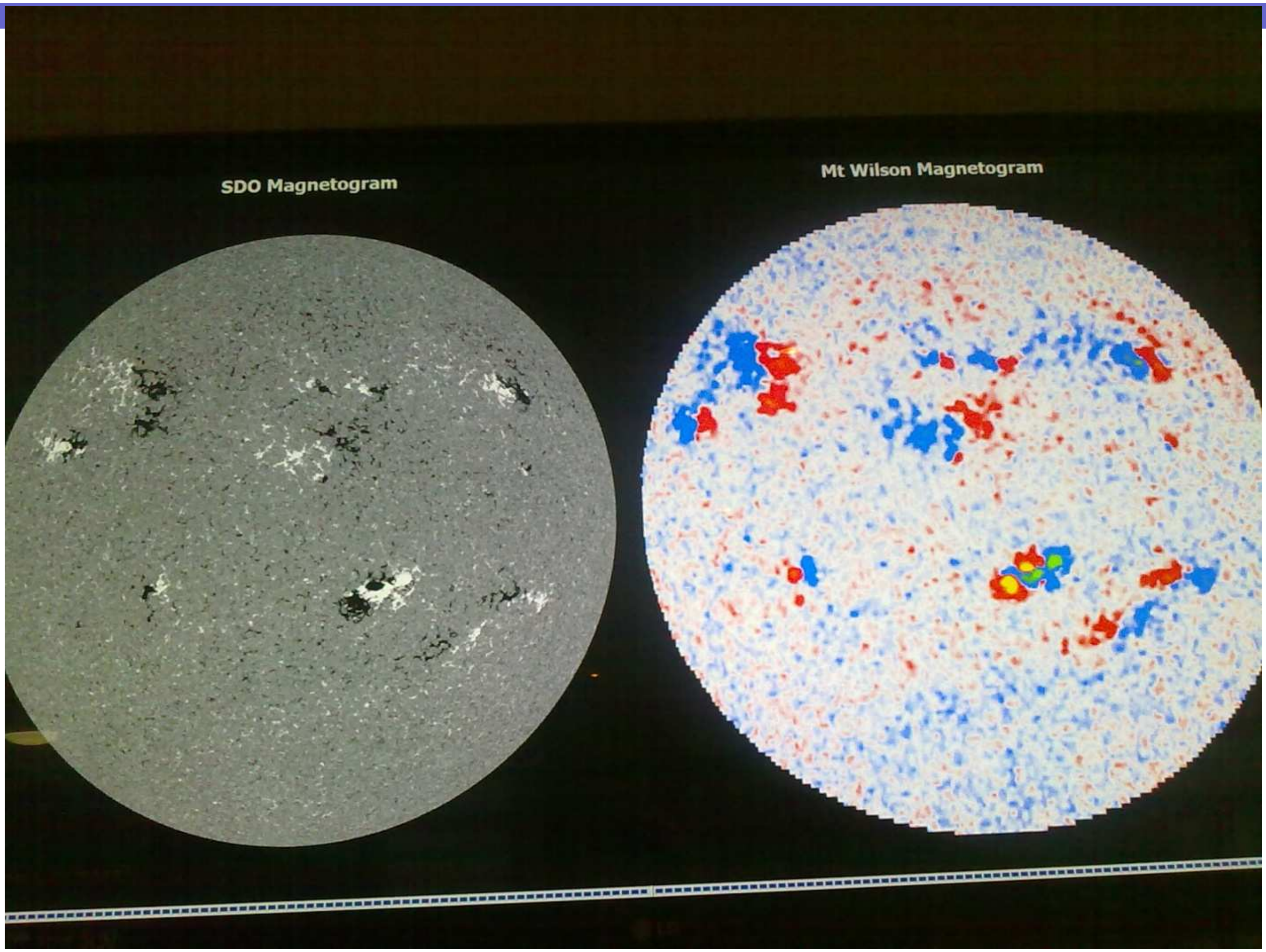
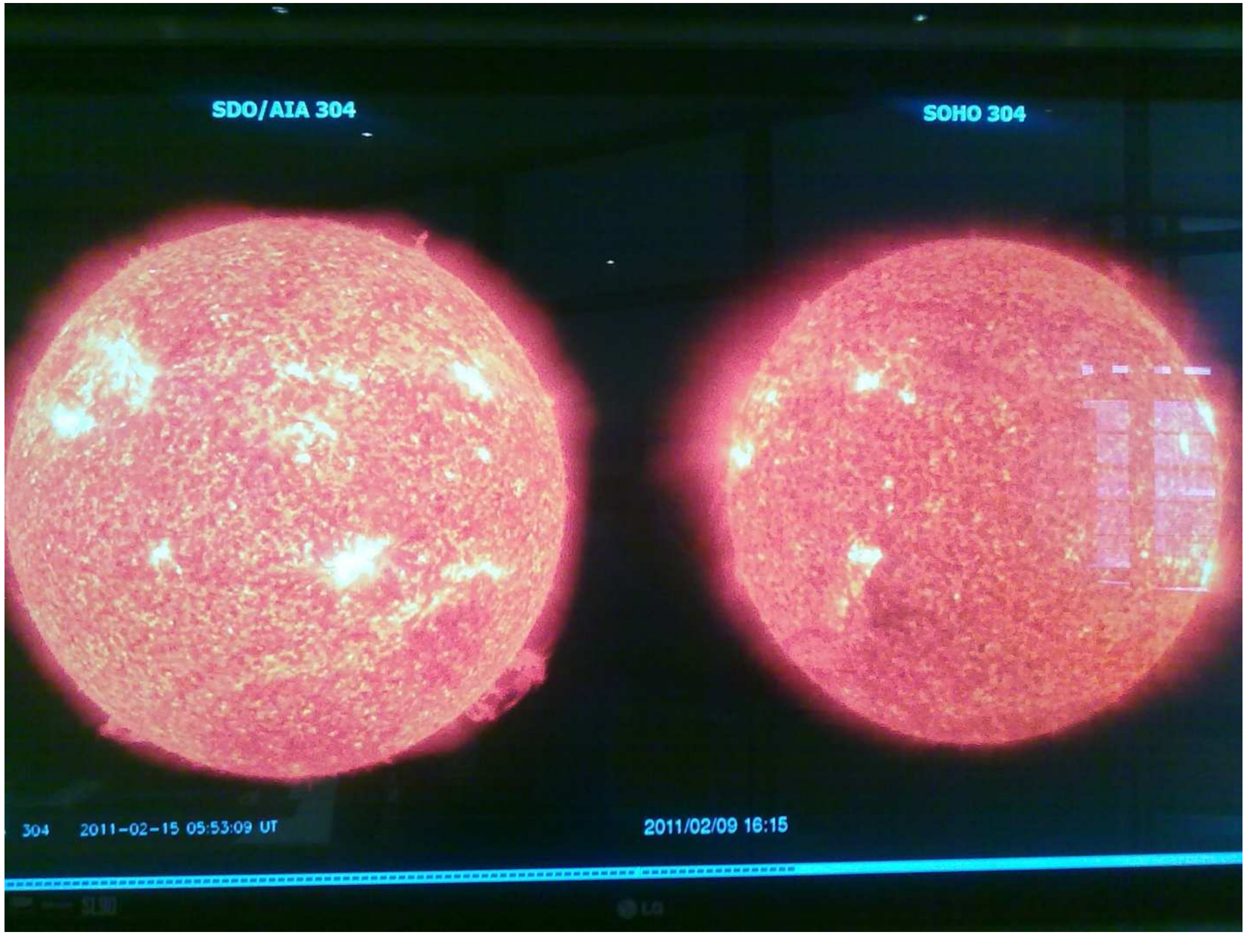
Solar magnetograms



SDO HD solar images



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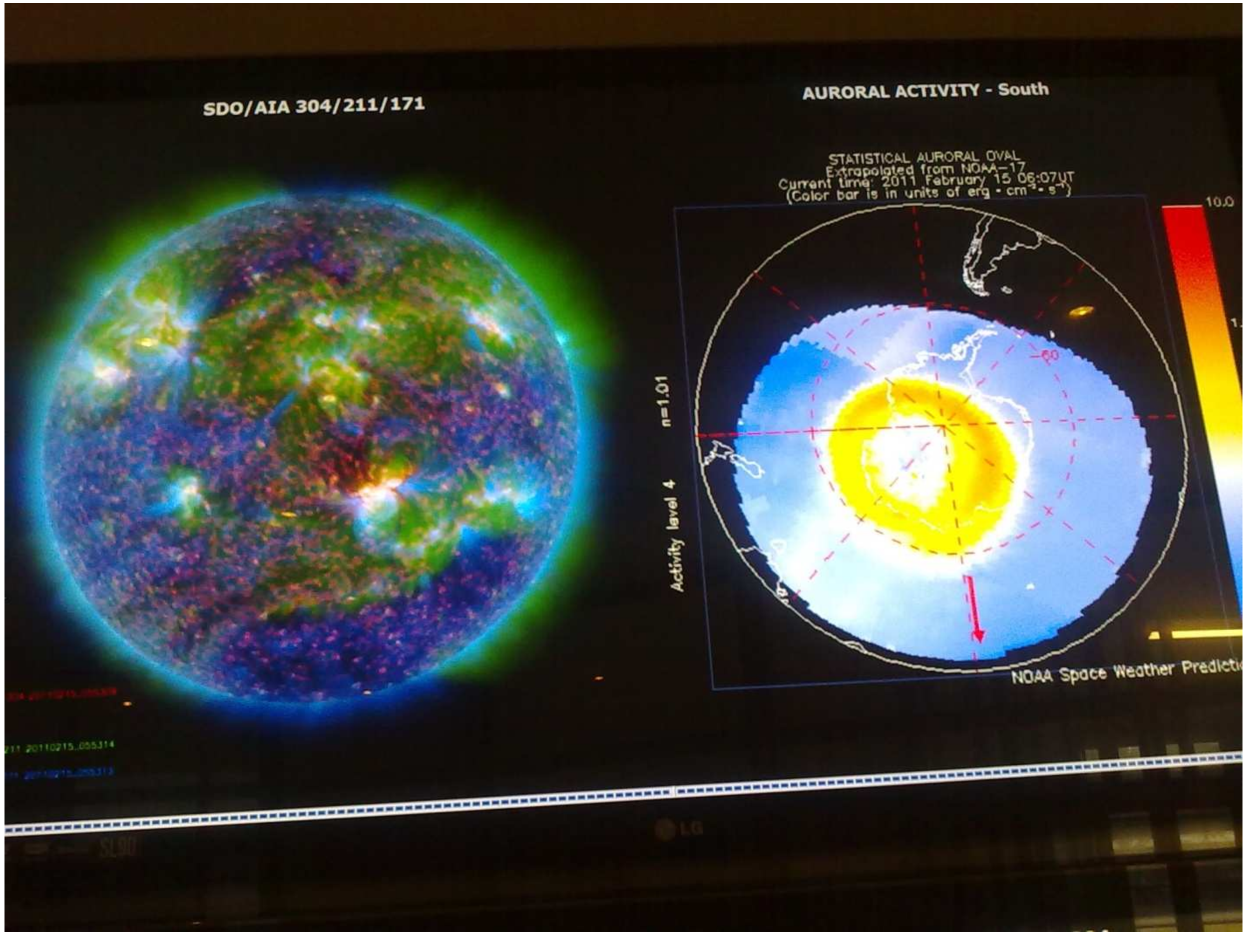
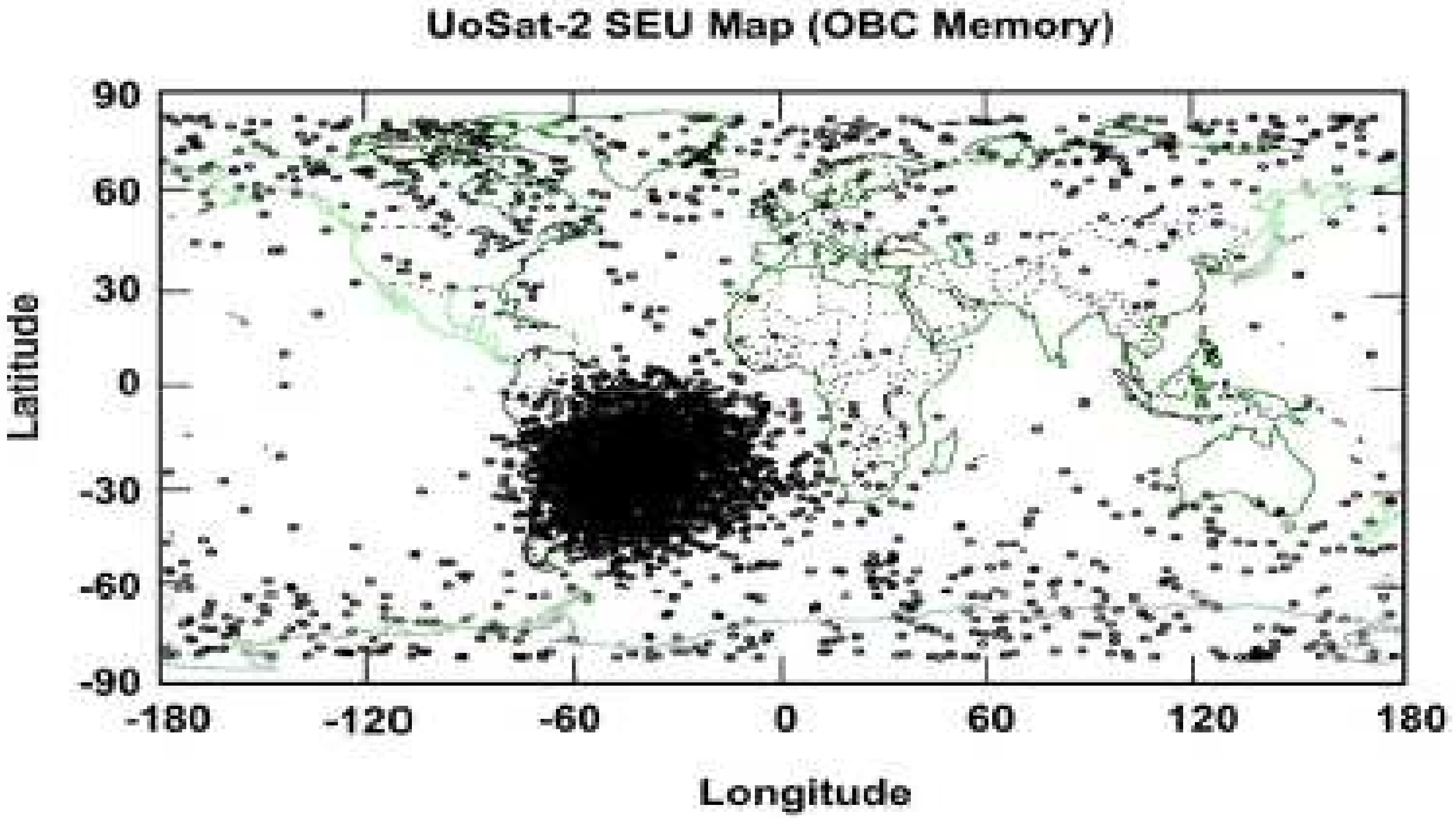
SDO X-ray images



Aurora: Earliest awareness of space weather

Satellite computer memory upset over SAMA



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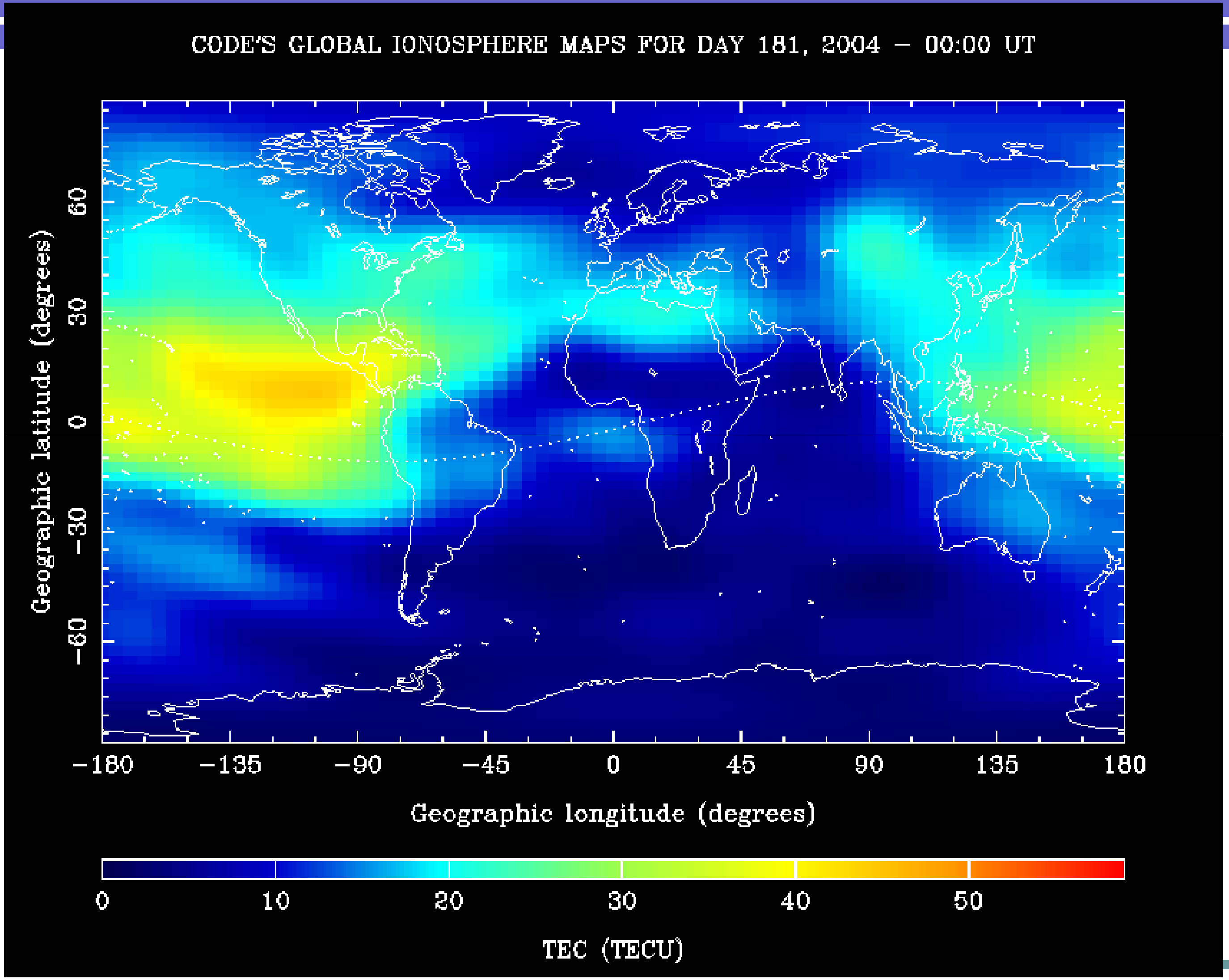
Space science using GNSS

Global TEC variation (IGS)



Global Ionosphere Map (GIM)

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GPS relevance to Space Physics: Ionospheric structure & dynamics

RWC

Ionospheric imaging using GPS data provides the means to create large-scale, time-varying *two-dimensional* maps of electron concentration in the ionosphere with a time resolution of *seconds*. This permits studies of:

- Temporal and spatial distribution of ionization in the ionosphere
- Effects of geomagnetic storms on ionosphere-plasmasphere plasma exchange dynamics
- Mechanisms causing ionospheric scintillation

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Relevance of local GPS derived TEC mapping

- Applications:

  - Space Physics Research (Ionospheric dynamics)
  - Radio Astronomy (SKA, KAT)
  - Precision GPS applications (Surveying, SBAS, GIS (DGPS))

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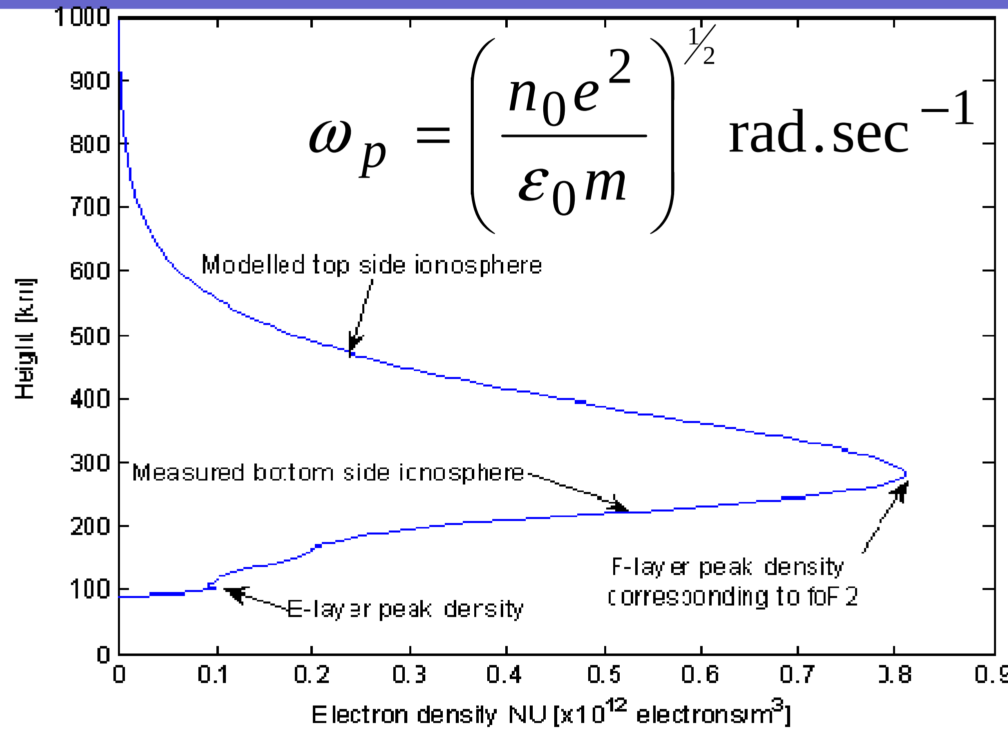
Conventional Ionospheric Measurements

Ionosonde

Ionosonde measurements



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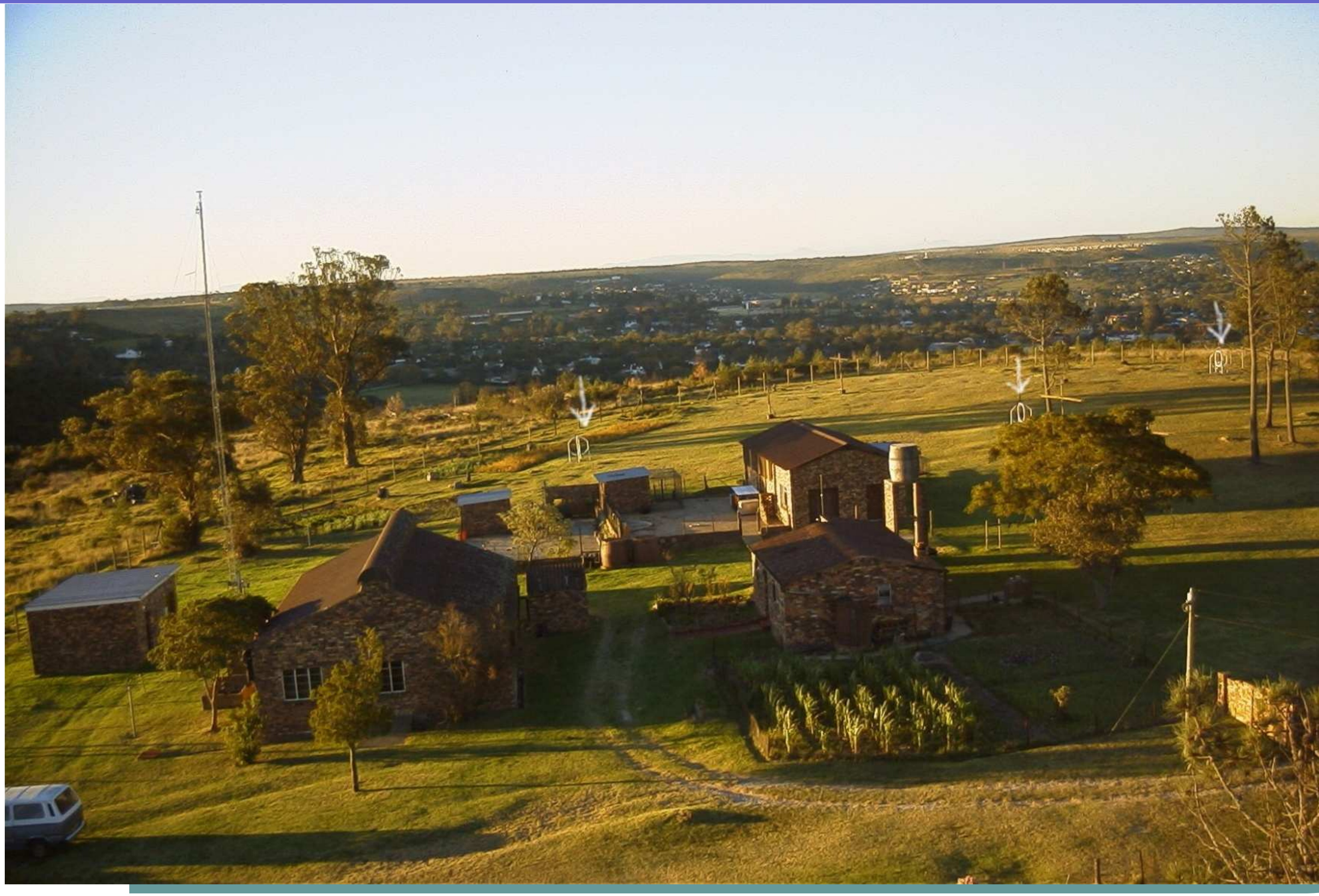
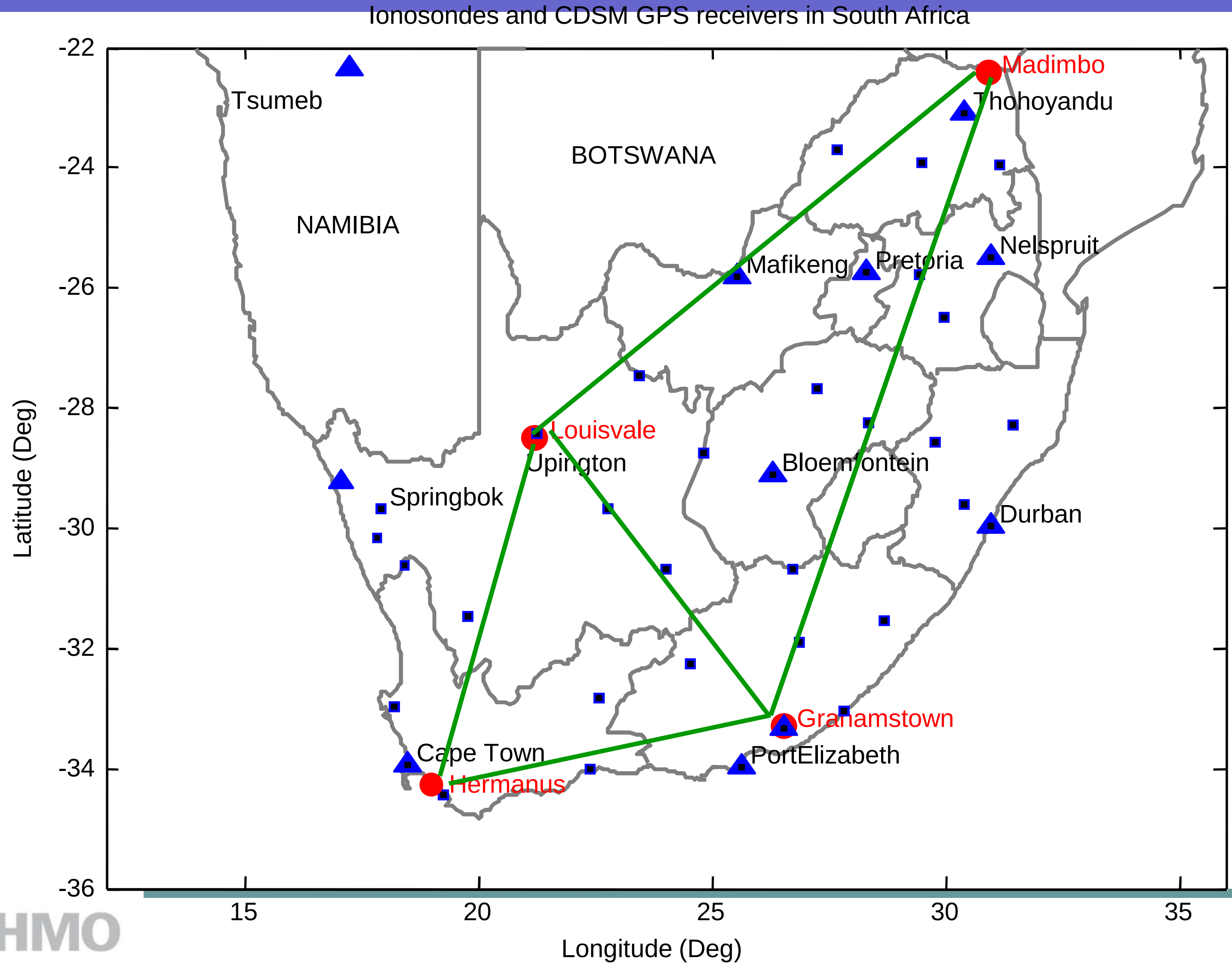
Grahamstown ionosonde



GPS and Ionosonde Network



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Ionosonde limitations

- Cost: R2.3 m per station + running cost
- Spacing: 1000 km between stations
- None elsewhere in Southern Africa
- Data frequently not available or delayed
- Only measures bottom-side ionosphere

New Approach: GNSS (GPS)

Global Positioning System (GPS)

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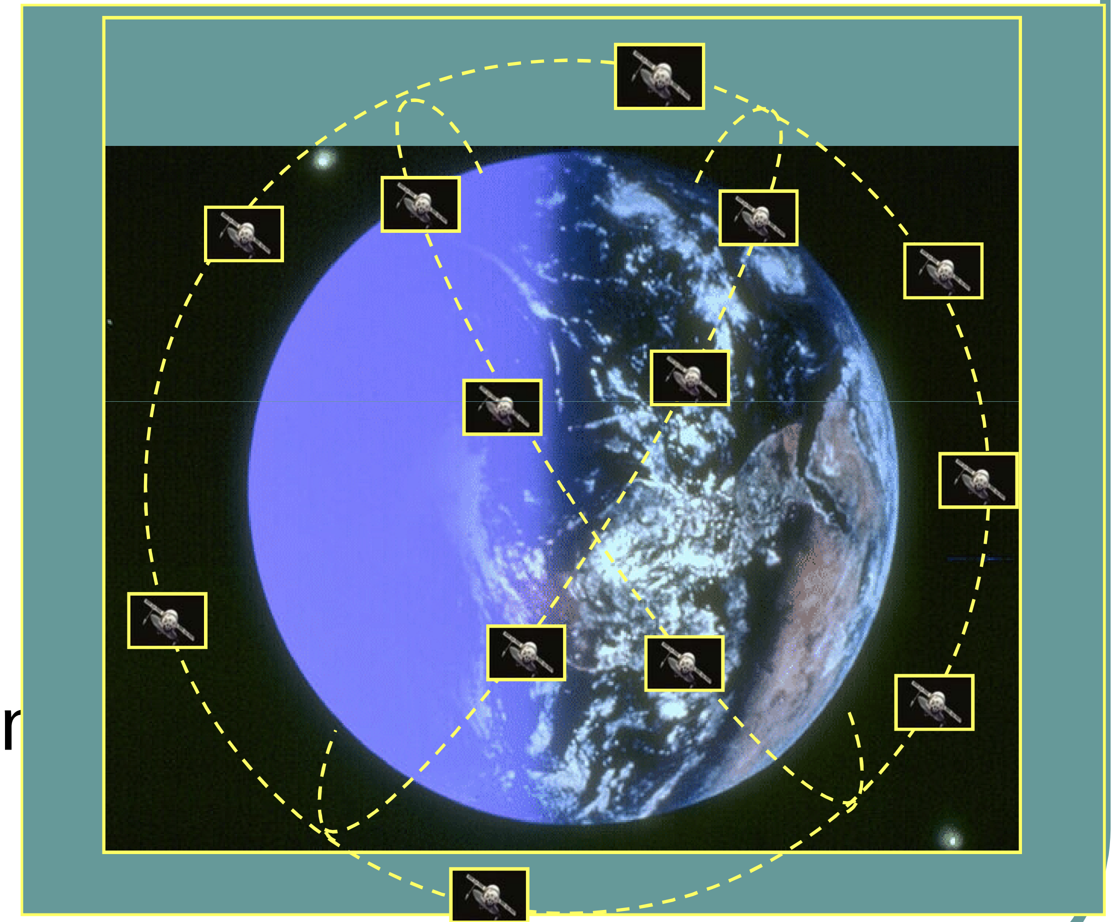
GPS satellite constellation

- 24 satellites
- Six orbital planes
- Four satellites per orbital plane
- Orbital period 12h
- Circular orbit height 20185 km
- Orbit plane inclination 55º inclination



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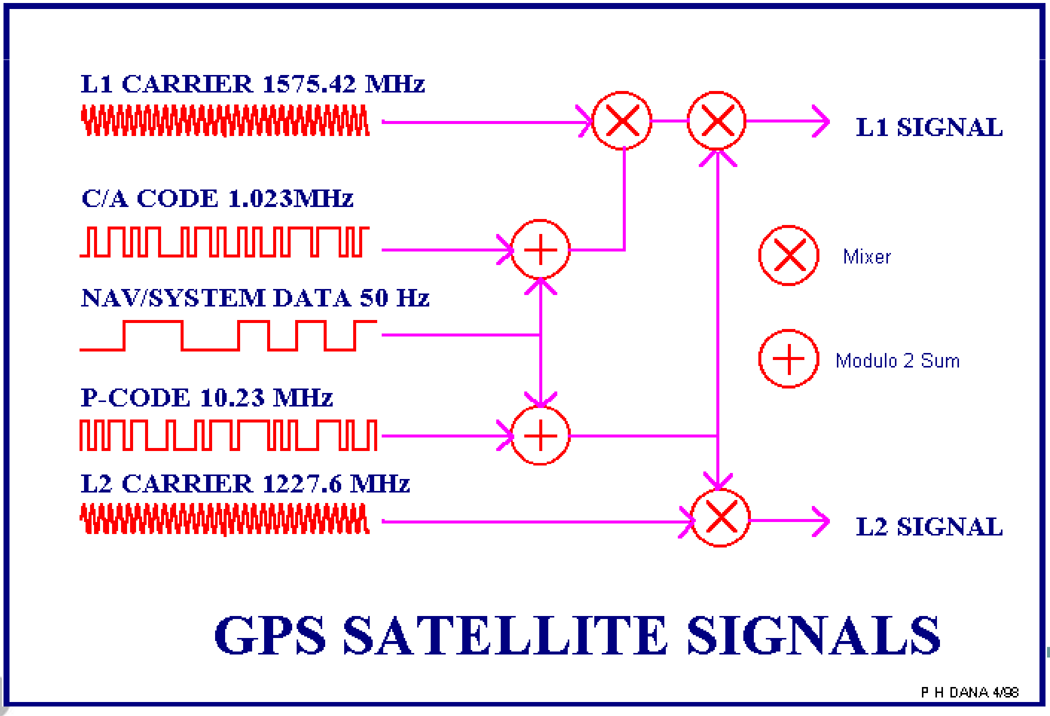
GPS satellite signals

Two carrier frequencies

L1 = 1.57542 GHz, L2 = 1.2276 GHz



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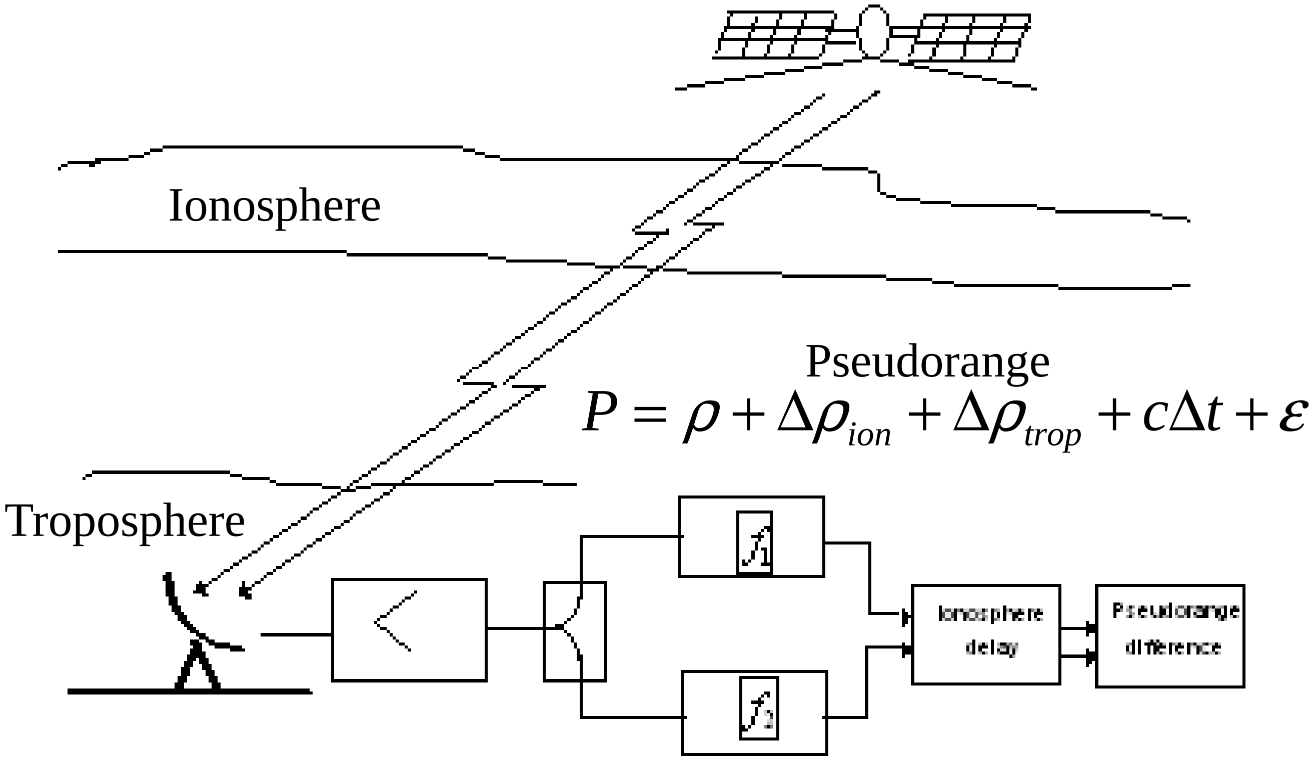
Dual frequency GPS



GPS Ranging Errors

- **Ephemeris data** –(1 m) Errors in the transmitted location of the satellite
- **Satellite clock**—(1 m) Errors in the transmitted clock, including SA
- **Ionosphere**—(20 m) Errors in the corrections of pseudorange caused by ionospheric effects
- **Troposphere**—(1 m) Errors in the corrections of pseudorange caused by tropospheric effects
- **Multipath**—(0.5) Errors caused by reflected signals entering the receiver antenna
- **Receiver**—(1 m) Errors in the receiver's measurement of range caused by thermal noise, software accuracy, and inter-channel biases

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Code-based pseudorange

$$P = c\Delta t = \rho + \Delta\rho_{ion} + \Delta\rho_{trop} + c(\Delta t_c{}^S - \Delta t_c{}^R) + c(b^S + b^R) + \varepsilon$$

$\Delta t =$ measured propagation time using PRN code

$c =$ free - space velocity of light

$\Delta\rho_{ion}, \Delta\rho_{trop} =$ range errors due to ionosphere and troposphere delay

$\Delta t_c{}^S, \Delta t_c{}^R =$ offsets of satellite and receiver clocks

$\varepsilon =$ residual error (multi path interference, random errors etc.)

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Carrier-phase based pseudorange

$$L = N\lambda = \rho - \Delta\rho_{ion} + \Delta\rho_{trop} + c(\Delta t_C{}^R - \Delta t_C{}^S) + \lambda B + \varepsilon$$

$N =$ measured number of cycles since phase lock

$\lambda =$ carrier wavelength ($\lambda_{L1} = 197$ mm, $\lambda_{L2} = 207$ mm)

$\Delta\rho_{ion}, \Delta\rho_{trop} =$ range errors due to ionosphere and troposphere delay

$\Delta t_C{}^S, \Delta t_C{}^R =$ offsets of satellite and receiver clocks

$B =$ initial phase ambiguity (integer number of cycles)

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Total Electron Content (TEC)

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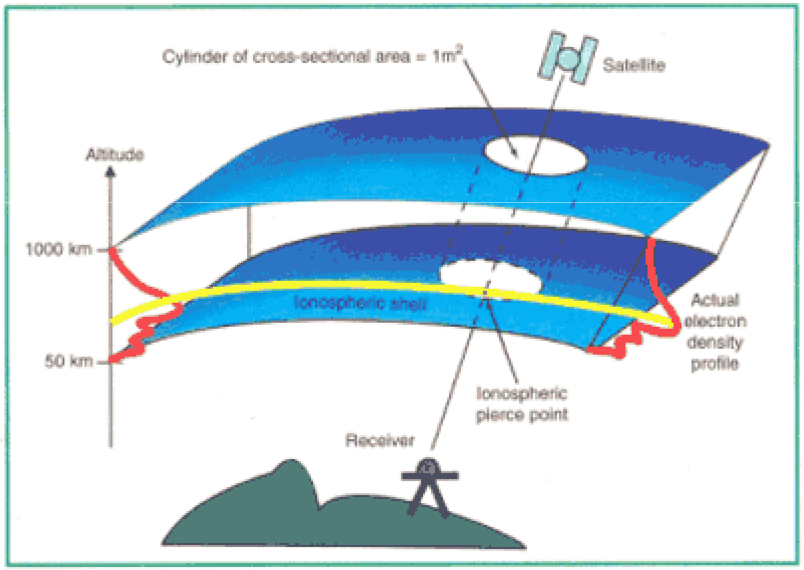
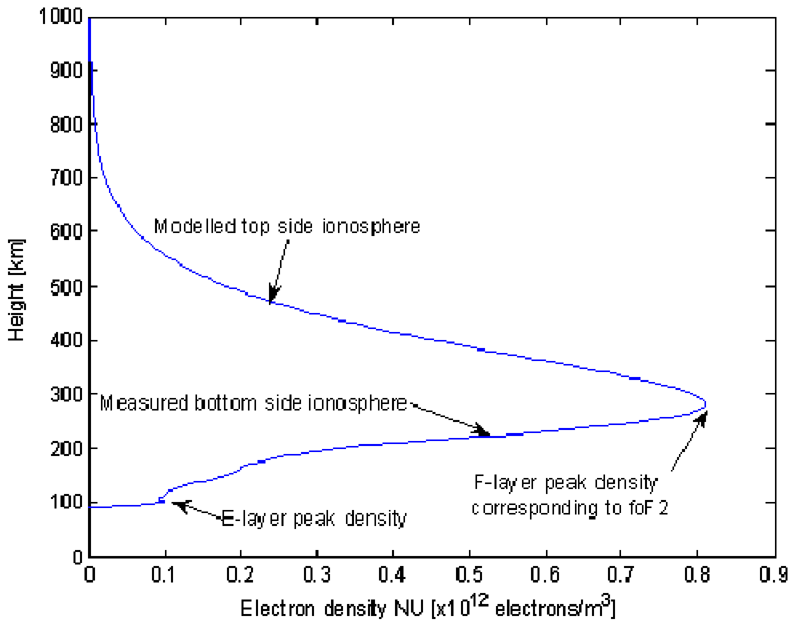
TEC definition





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Total Electron Content (TEC)

Along a given signal path between a Satellite (S) and Receiver (R), the total electron content (TEC) is defined as the line integral of the free electron density:

$$\mathrm{TEC} = \int_{R}^{S} N_e(\lambda, \phi, h, t)\, ds.$$

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TEC delay vs frequency

The Ionosphere is a dispersive medium, i.e. ionospheric refraction (subsequently *delay*) is frequency-dependent, hence different for L1 and L2 frequencies.

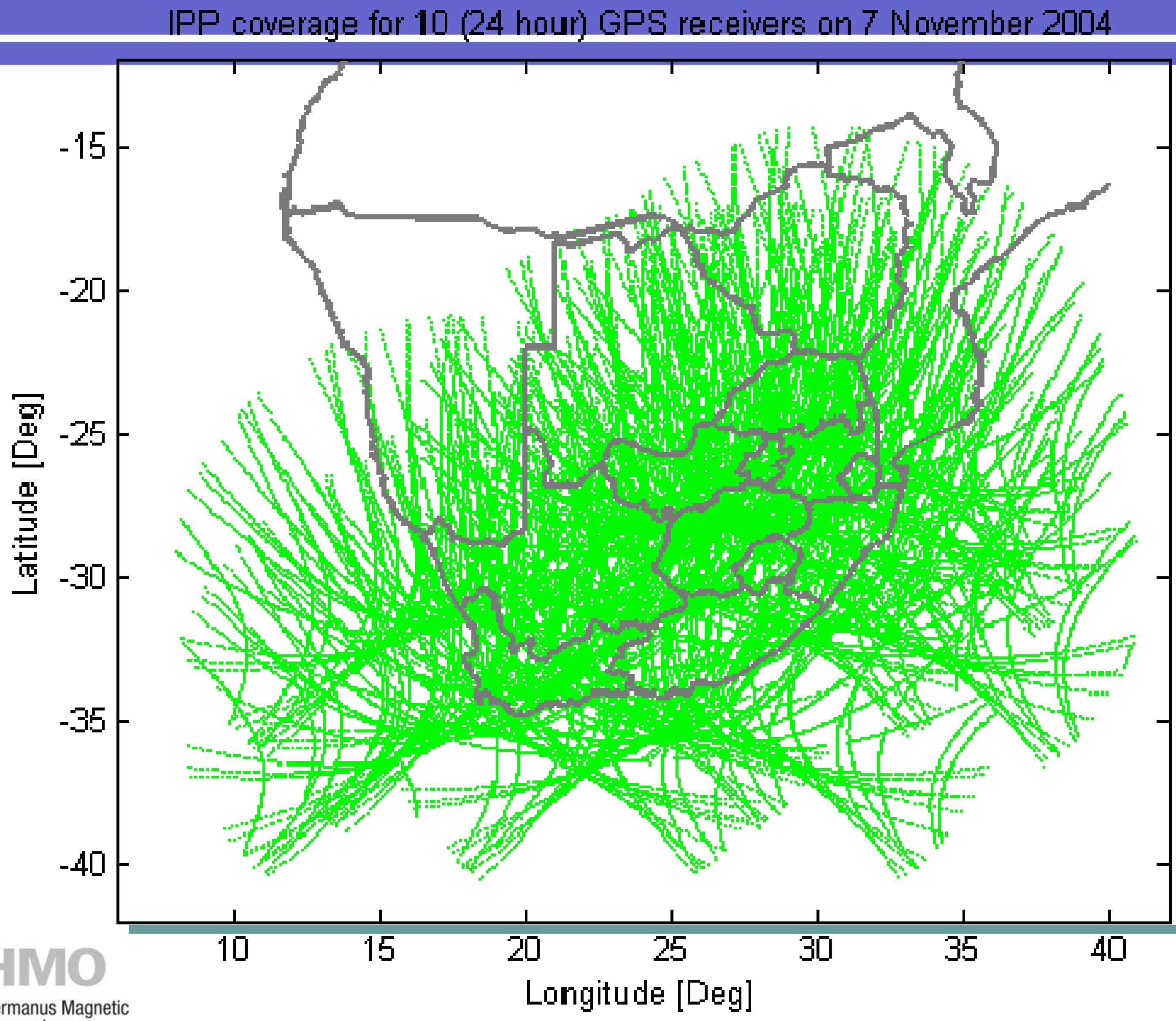
$$\Delta\rho_{ion} = c\Delta t_{ion} = \frac{\alpha \cdot TEC}{f^2}$$

$\Delta\rho_{ion}$ = ionospheric range error [m]

TEC = Total electron content [TECU]

f = carrier frequency [Hz]

IPP Coverage of multiple GPS receivers



HMO Regional TEC Model

- Slant TEC derived from L1, L2 phase observables
- Vertical TEC estimated using SHM (10-18 degree, order)

$$TEC(\lambda,\phi)=\sum_{n=0}^{N}\sum_{m=0}^{n}\overline{P}_{nm}[\sin(\phi)]\{a_{nm}\sin(m\lambda)+b_{nm}\cos(m\lambda)\}$$

$\lambda =$ Sun-fixed longitude

$\phi=$ geographic latitude

$\overline{P}_{nm} =$ Normalized associated Legendre functions

$a_{nm}, b_{nm} =$ desired SHM coefficients

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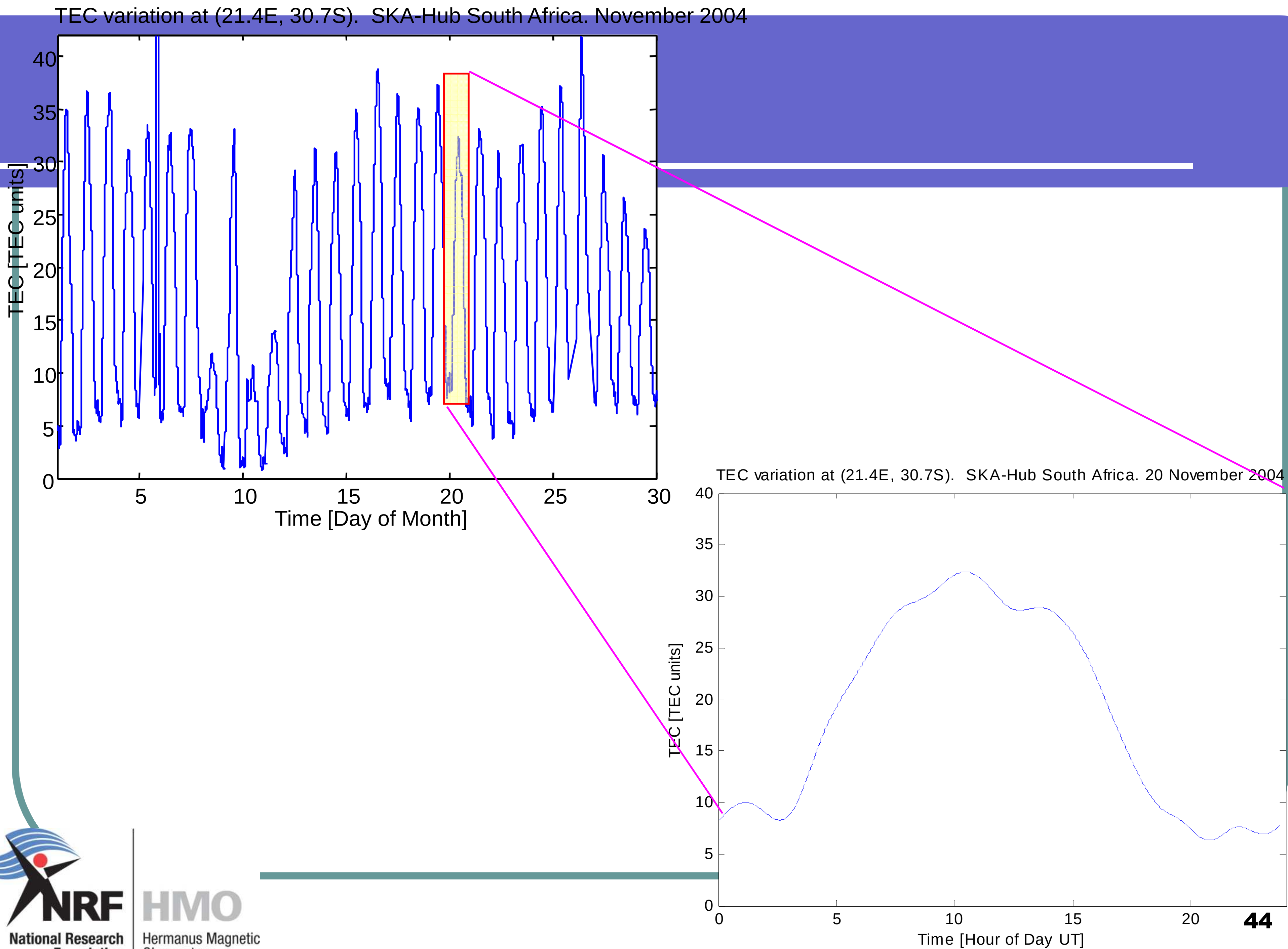

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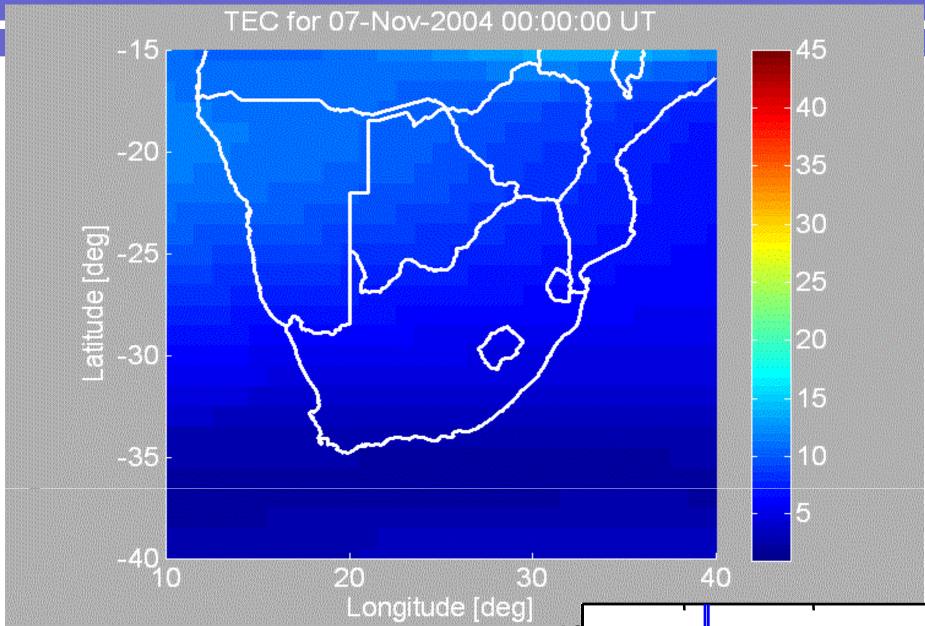
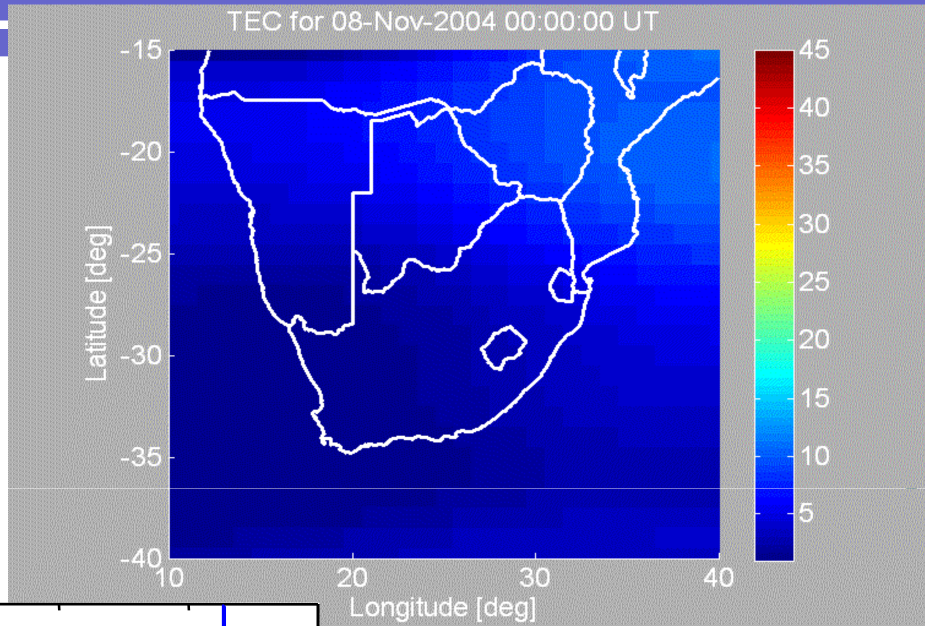
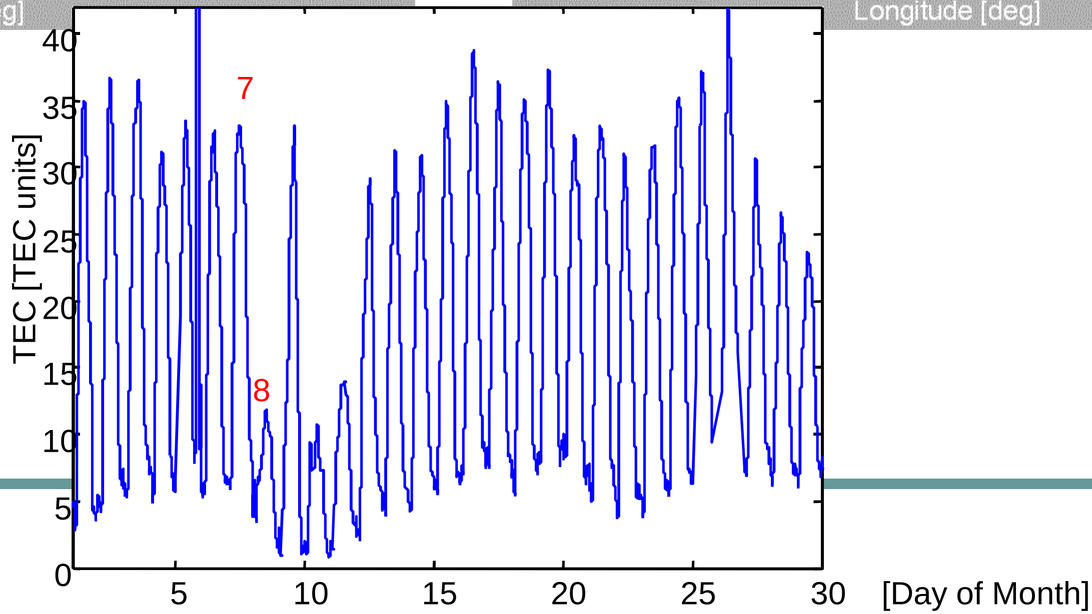
Geomagnetic storm 7-8 Nov 2004







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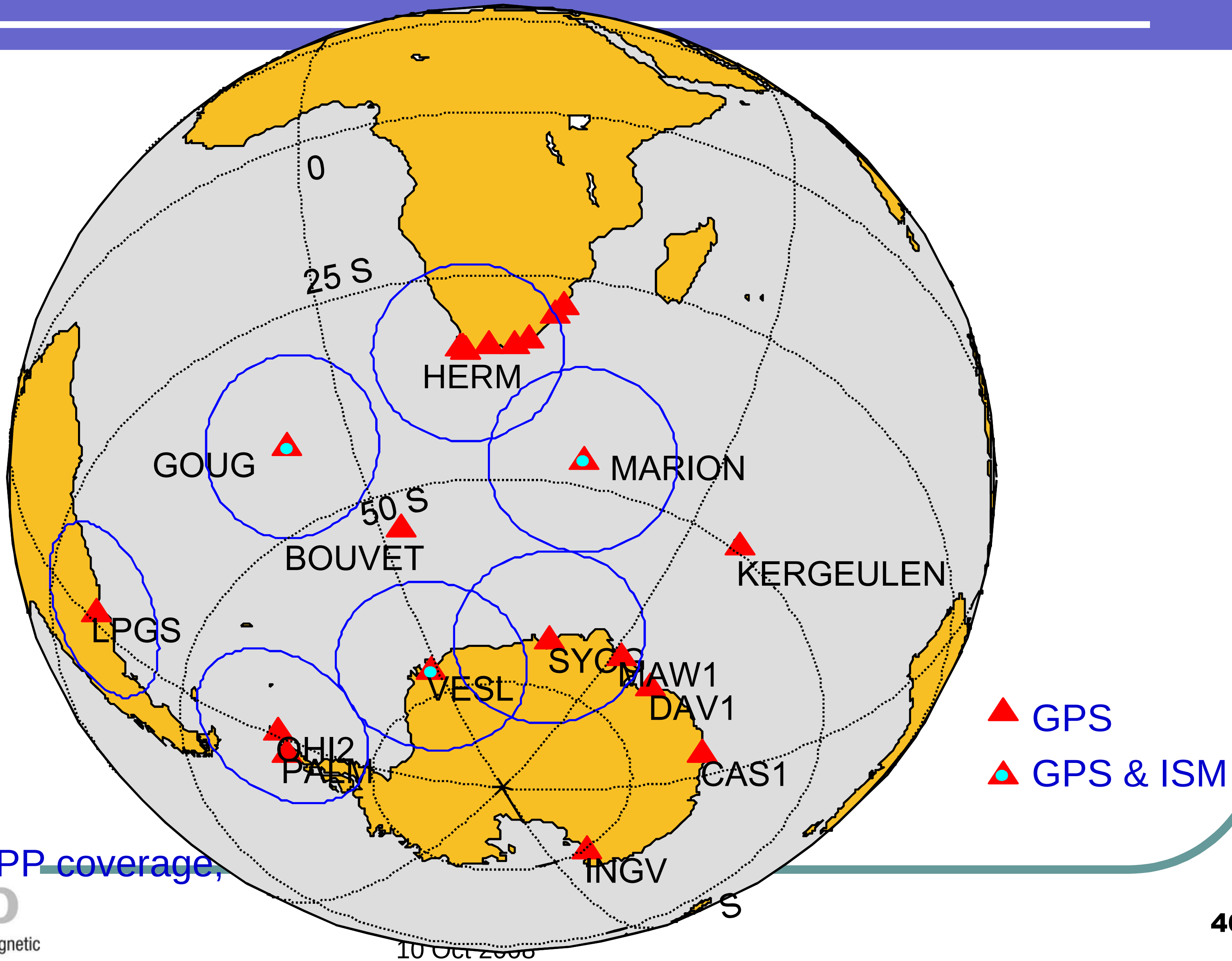
Coverage of Antarctic and South Atlantic Islands GPS and Scintillation Receivers near the South Atlantic Anomaly



10° elevation IPP coverage, hmF2=350 km

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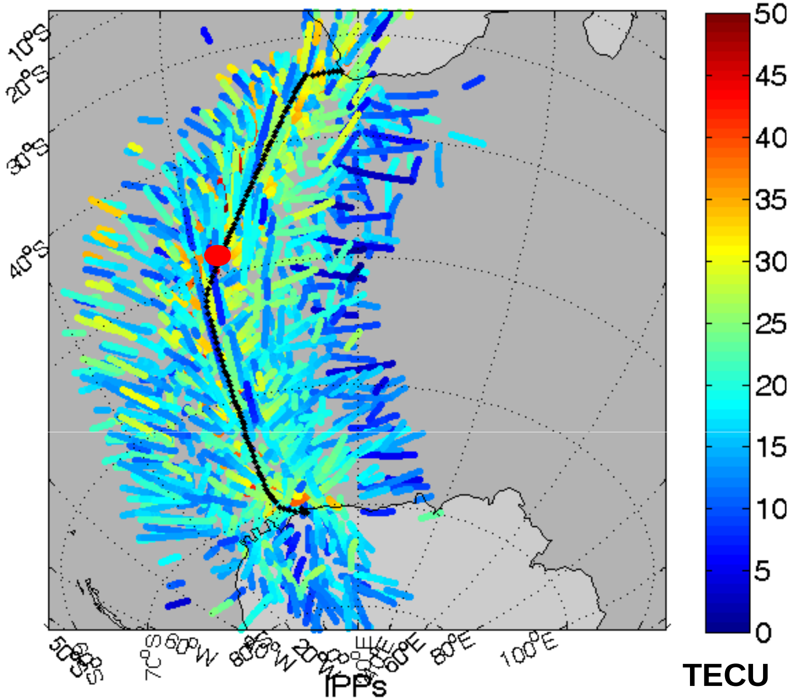
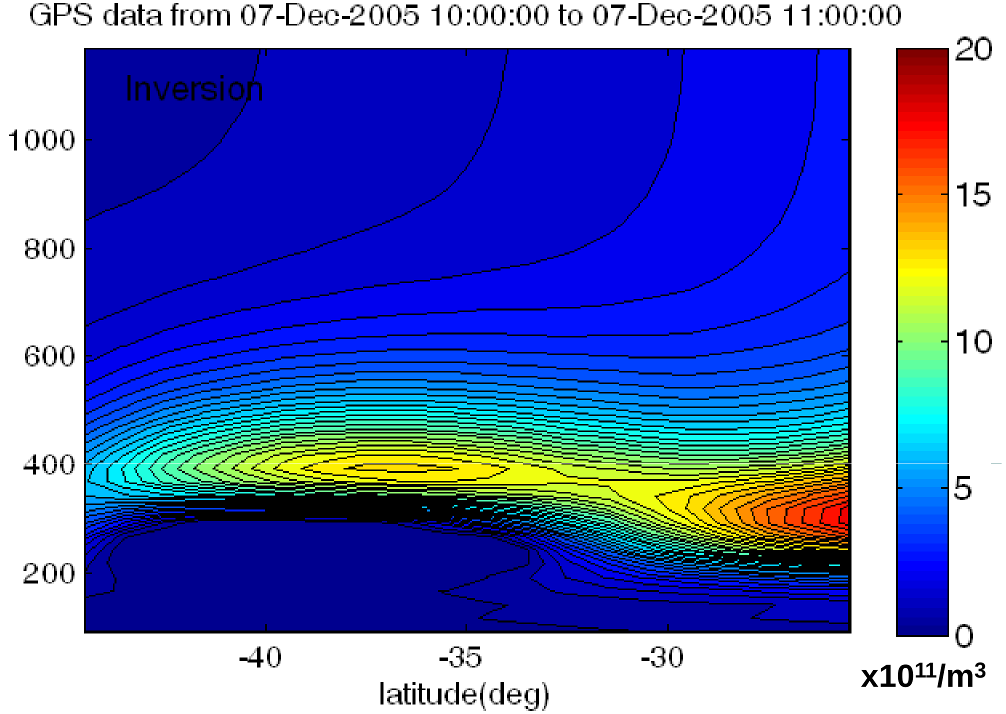
10 Oct 2008


S.A. AGULHAS
IMO 7628136

South Atlantic Ionospheric measurement campaign



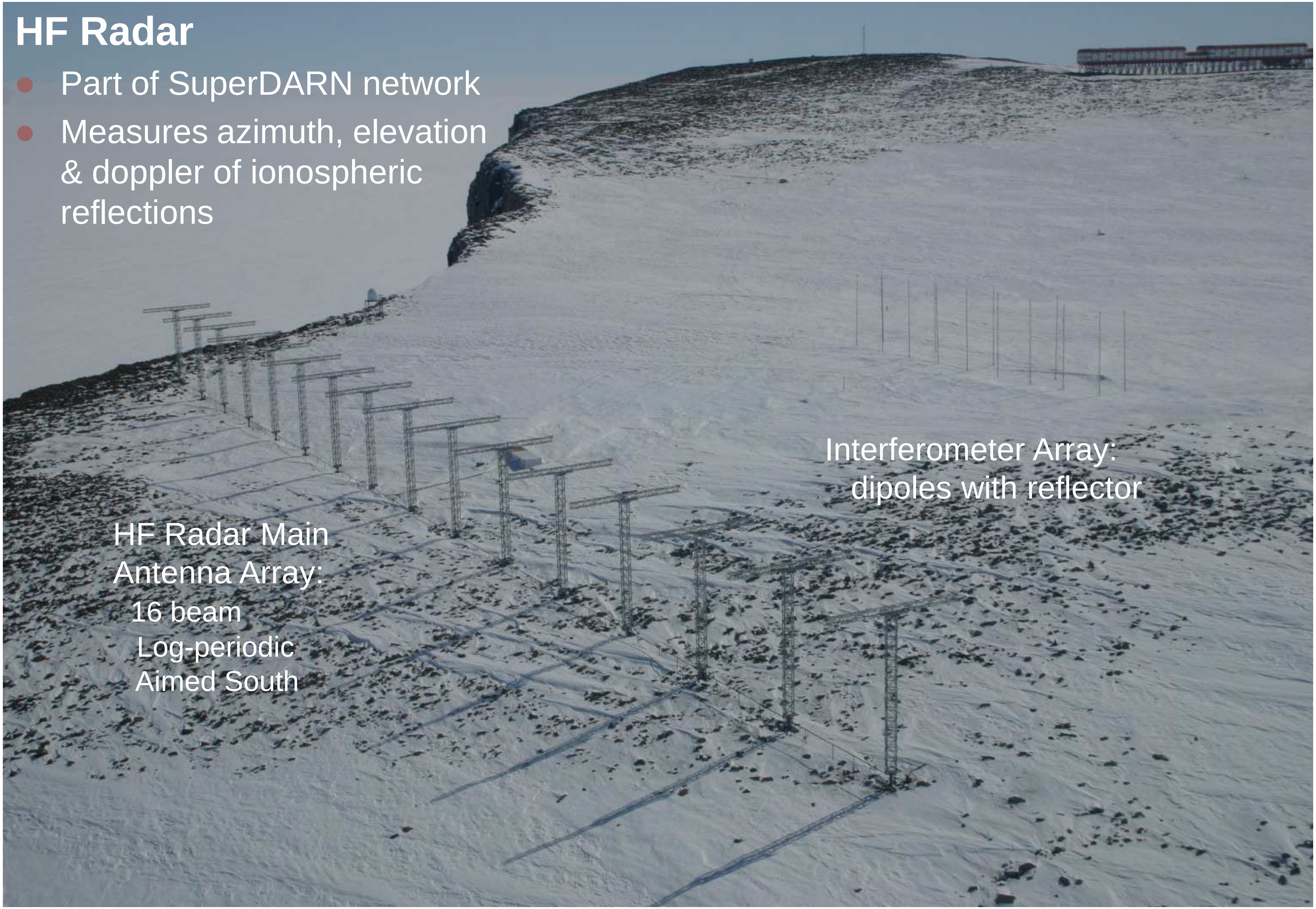


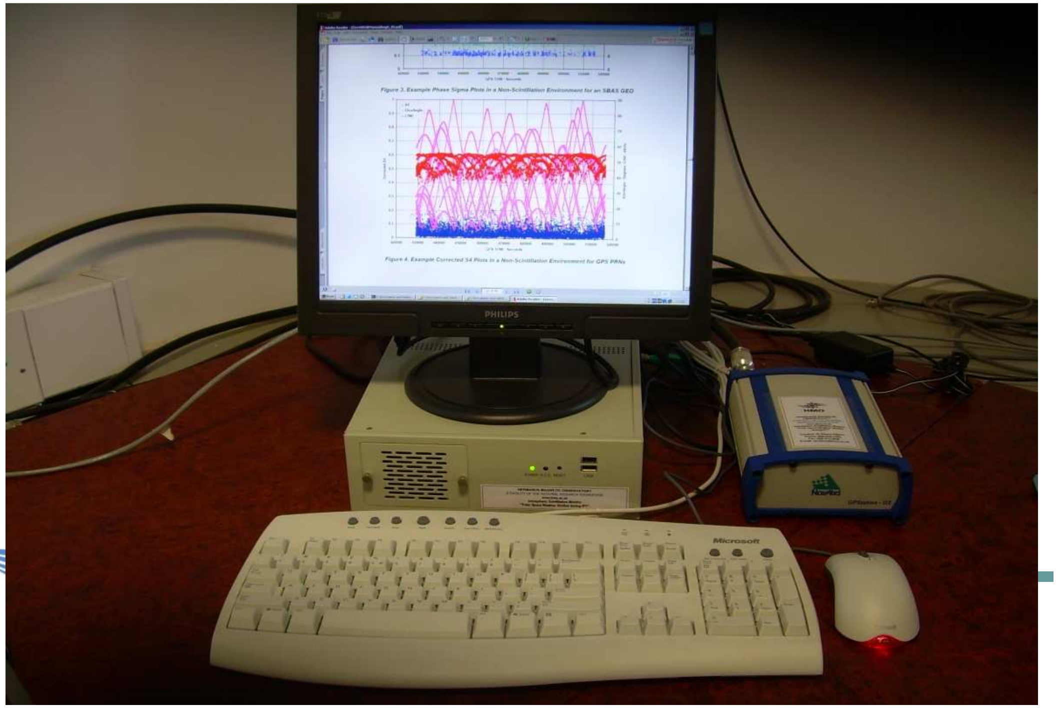
Ionospheric Pierce Points (IPPs) at hourly intervals for all satellite ray paths observed along the route of the SA Agulhas on its first trip to Antarctica during which measurements were made of the ionosphere over the South Atlantic Ocean using a GPS dual frequency receiver. The colours indicate bias-corrected VTEC at the IPPs.

Electron density distribution ($x10^{11}$ $/m^3$) along longitude $=0^o$ at 10:00 UT. Derived by ionospheric tomography using MIDAS from measurements made during the trip of the SA Agulhas to Antarctica on day 7 of the trip. The location of the ship at the time is shown by the red dot on the trajectory. Note the interesting high latitude structure resolved by the inversion.

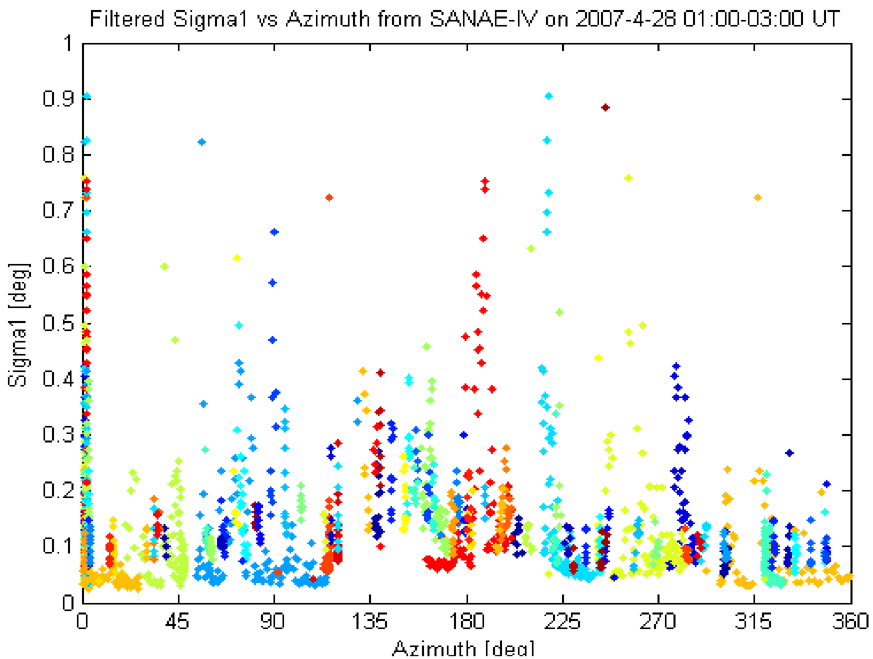
HF Radar

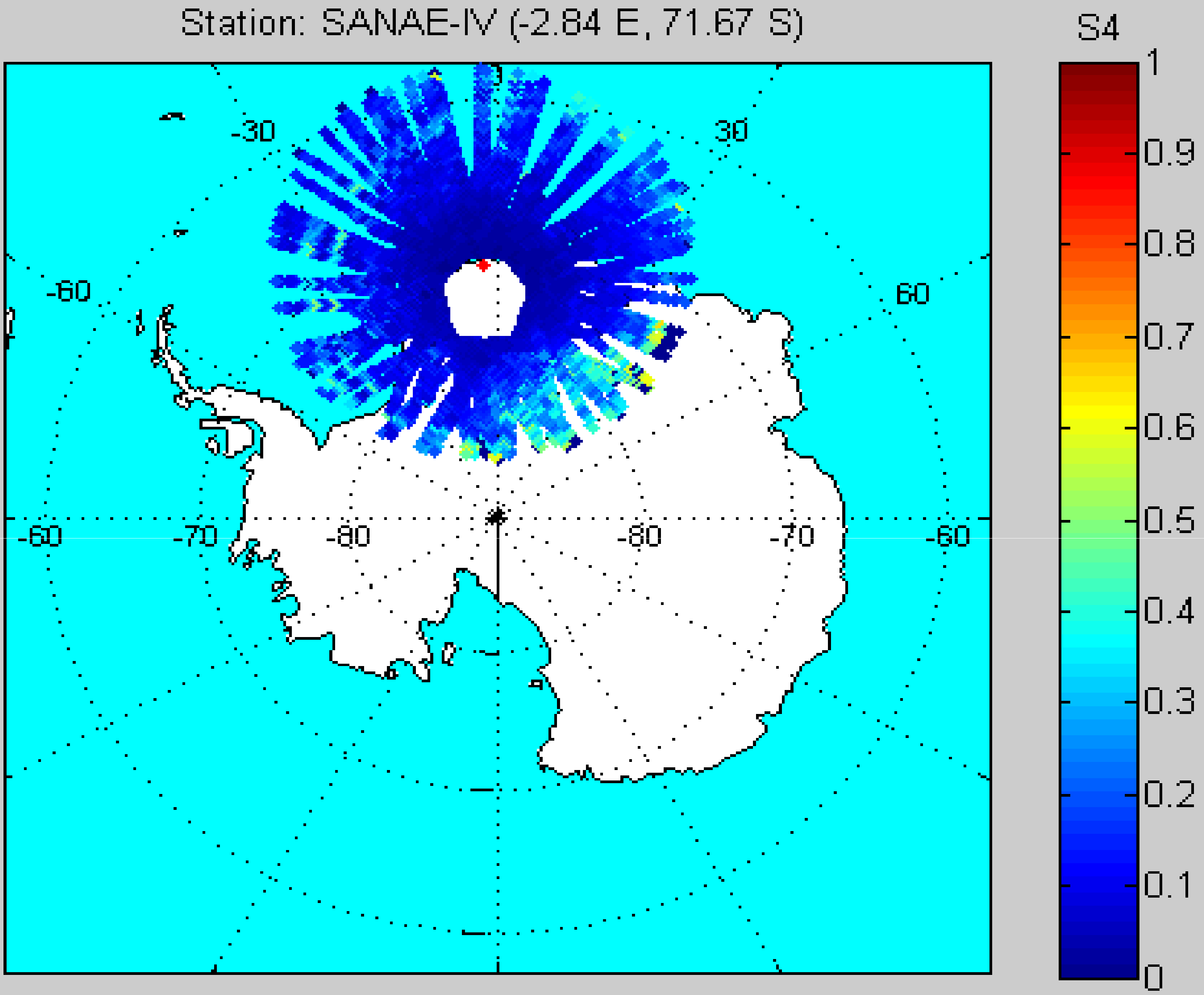
- Part of SuperDARN network
- Measures azimuth, elevation & doppler of ionospheric reflections





- **Ionospheric Scintillation Monitor (ISM)**
- Antenna: Novatel GPS-533 L1/L2 with choke-ring & radome
- Receiver: Novatel GSV4004B
- Owned by HMO
- Logging 1 minute data since 25 Dec 2006
- Data uploaded daily to HMO via ftp
  - 2.5 MB/day





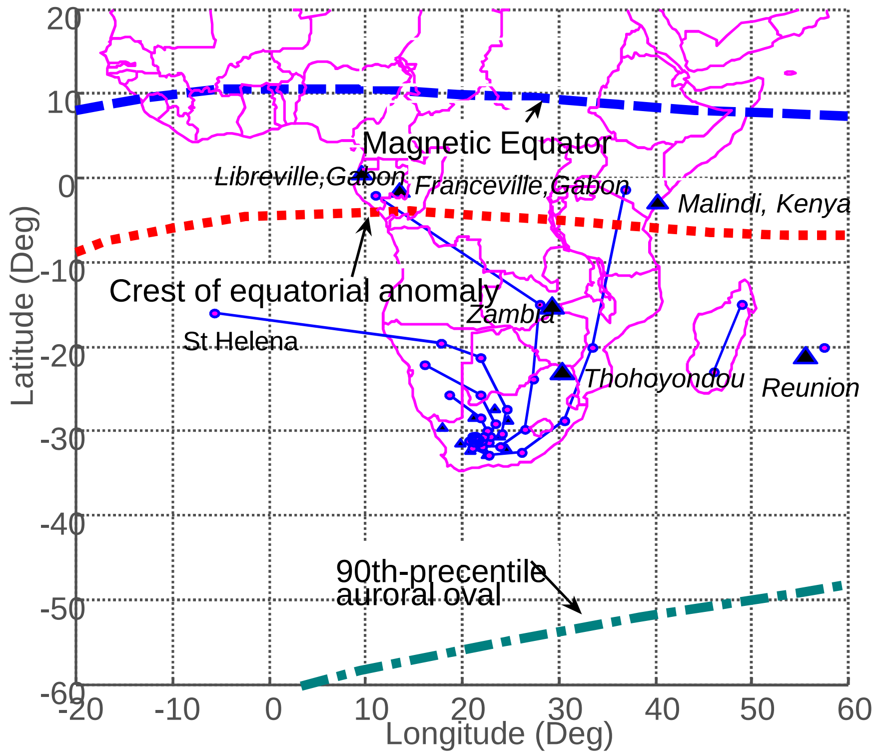
SANAE ISM 15 August 2007 00:00 to 23:59 UT

Application to

SKA SOUTH AFRICA
SQUARE KILOMETRE ARRAY

Study Objectives

- TEC variability
- foF2-TEC correlation
- Spread-F occurence



SKA hub (Northern Cape), Namibia, Botswana, Mozambique, Madagascar, Mauritius, Kenya, Gabon, St Helena

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Faraday rotation

- A plane-polarized wave propagating parallel to a magnetic field in a plasma experiences a circular rotation of its plane polarization

$$\Psi = -\frac{e^3}{2\pi m_e^2 c^2}\frac{1}{\nu^2}\int_0^d n_e B_{\parallel}\, ds$$

Ψ : angle of rotation of Electric vector in radians

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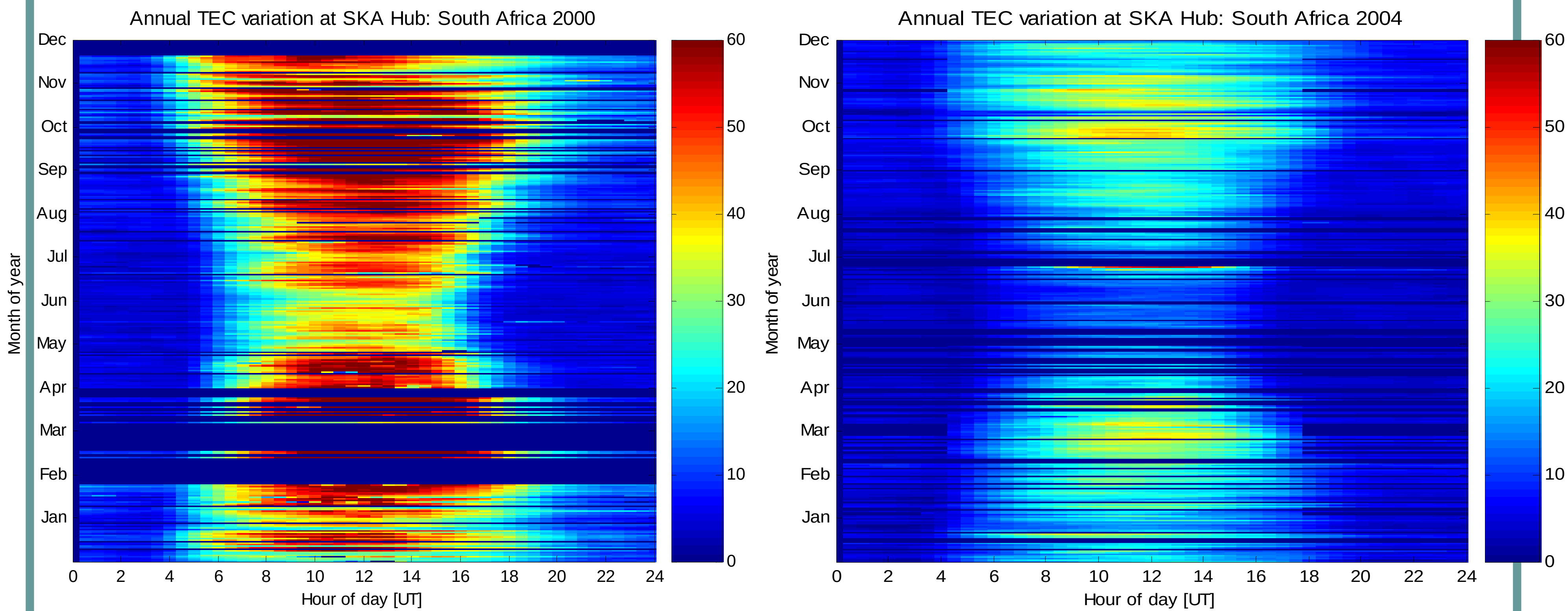
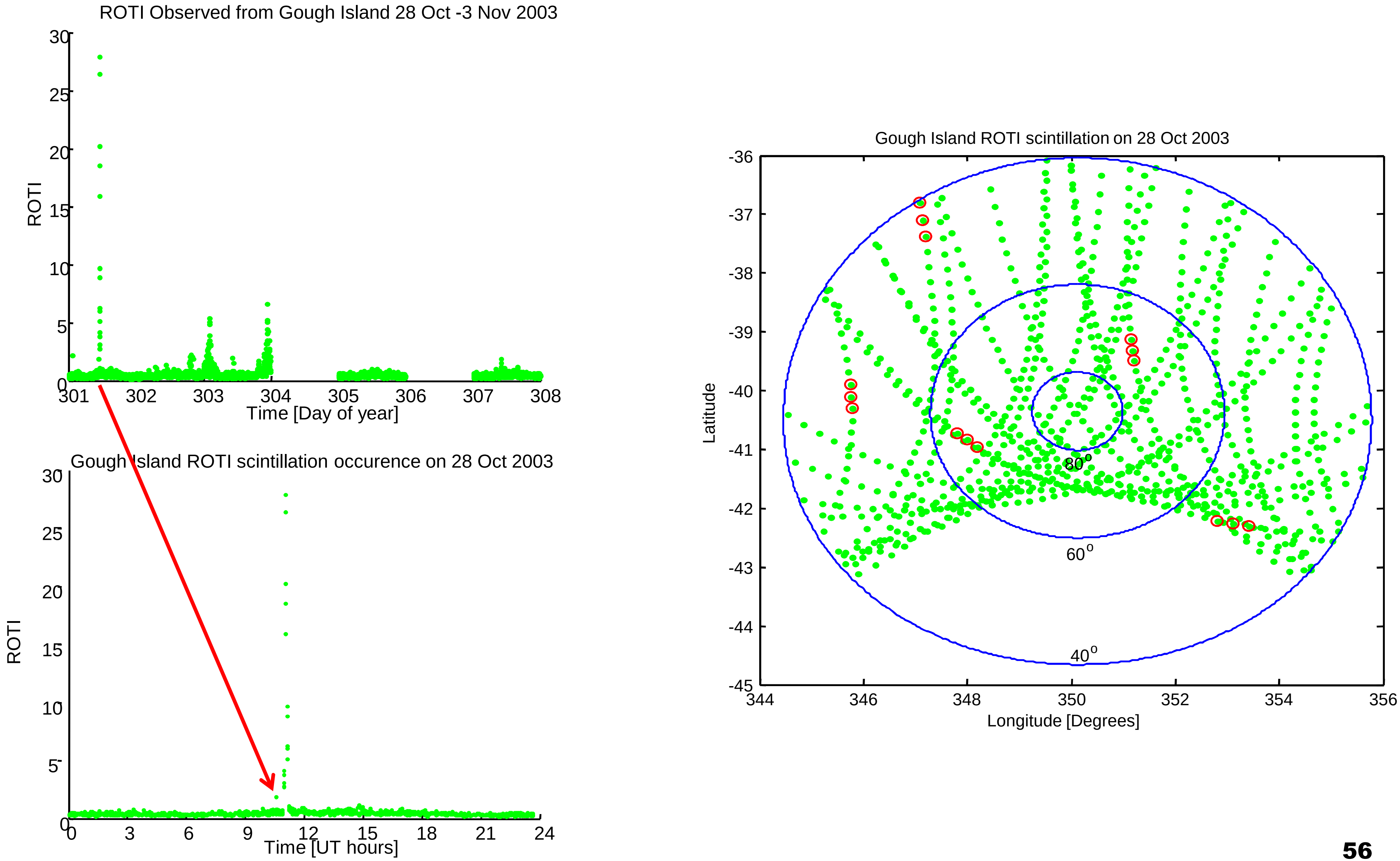
SKA Ionospheric stability study

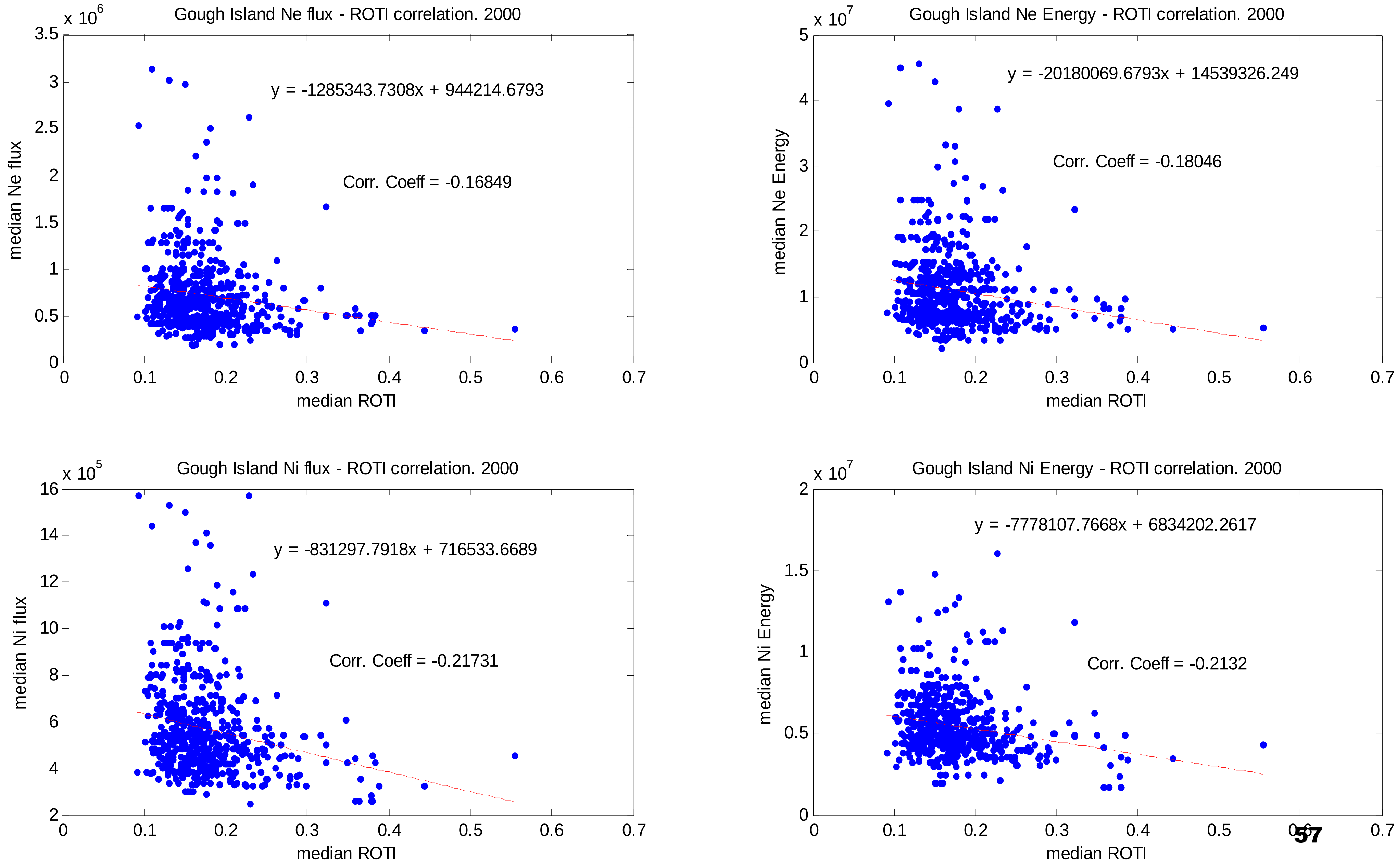


Diurnal, seasonal and solar cycle TEC variation

SKA-Hub (21.4E, 30.7S).

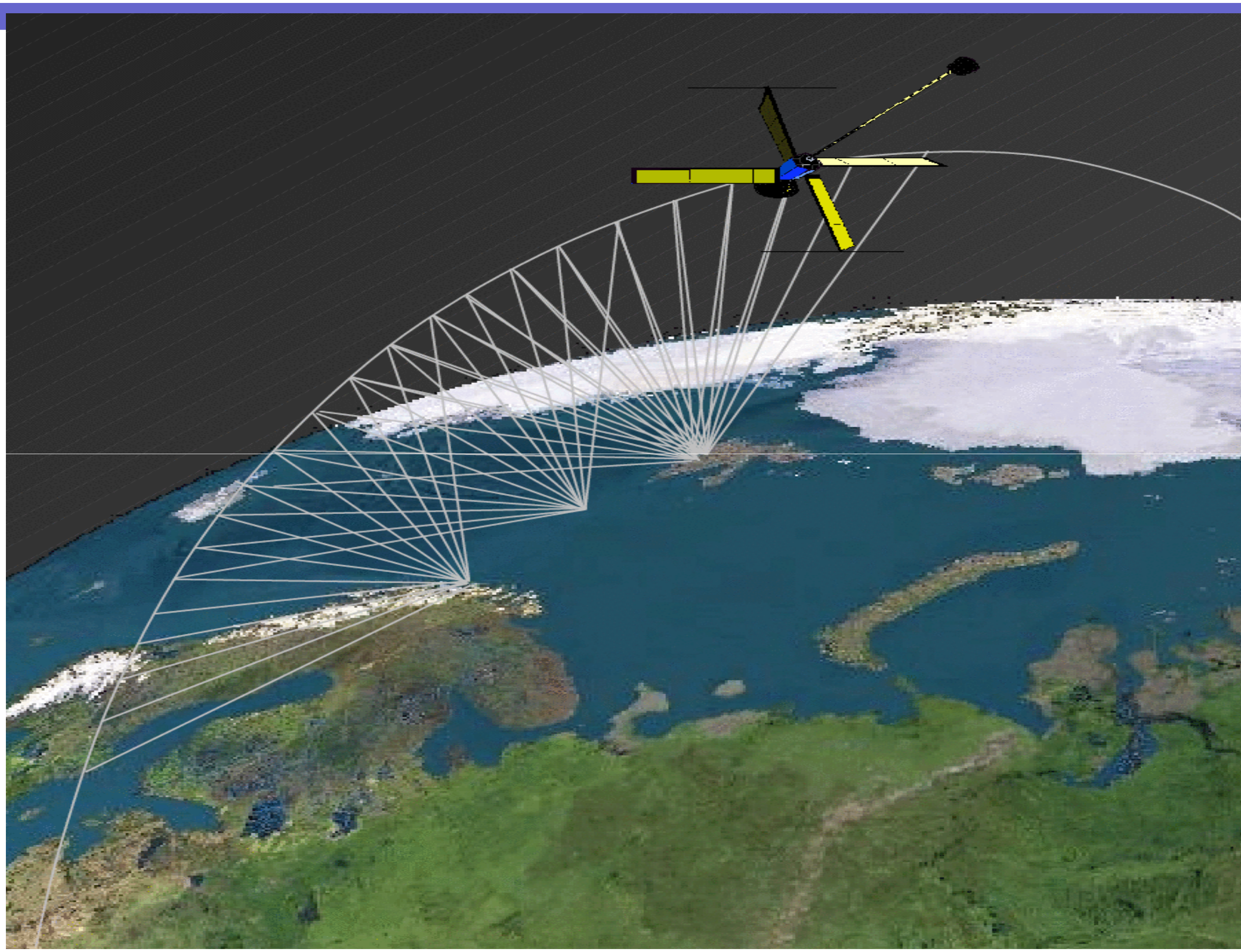


ROTI Observed from Gough Island 28 Oct -3 Nov 2003
ROTI
Time [Day of year]
Gough Island ROTI scintillation occurence on 28 Oct 2003
Time [UT hours]
Gough Island ROTI scintillation on 28 Oct 2003
Latitude
Longitude [Degrees]
80°
60°
40°



Gough Island Ne flux - ROTI correlation. 2000
x 10^6
median Ne flux
median ROTI
y = -1285343.7308x + 944214.6793
Corr. Coeff = -0.16849
Gough Island Ne Energy - ROTI correlation. 2000
x 10^7
median Ne Energy
median ROTI
y = -20180069.6793x + 14539326.249
Corr. Coeff = -0.18046
Gough Island Ni flux - ROTI correlation. 2000
x 10^5
median Ni flux
median ROTI
y = -831297.7918x + 716533.6689
Corr. Coeff = -0.21731
Gough Island Ni Energy - ROTI correlation. 2000
x 10^7
median Ni Energy
median ROTI
y = -7778107.7668x + 6834202.2617
Corr. Coeff = -0.2132

Computerised Ionospheric Tomography (CIT)



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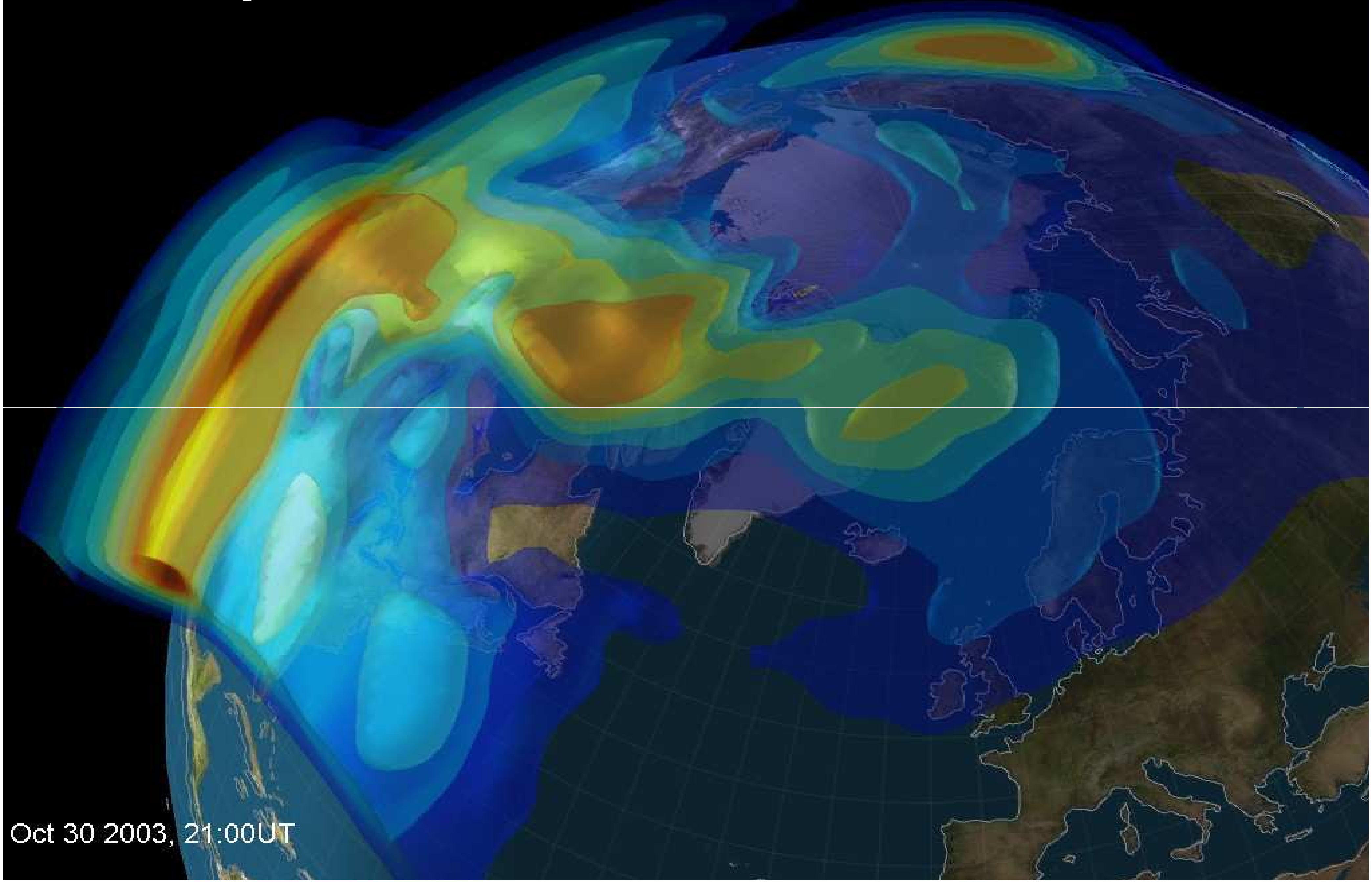
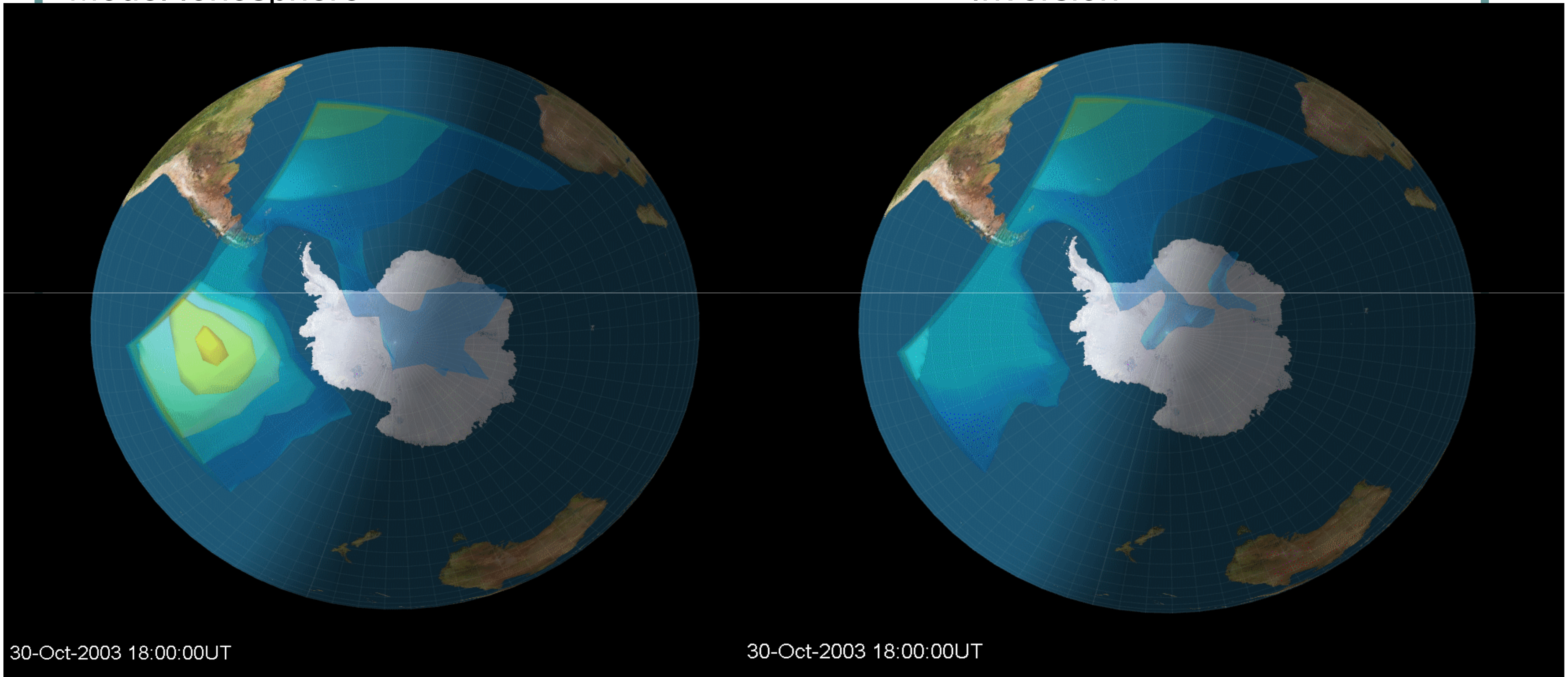
MIDAS – high latitude



Computerised Ionosheric Tomography using signals from extended GPS coverage. Polar space weather studies.

Model Ionosphere Inversion



Images Courtesy of Paul Spencer, Invert, University of Bath

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GPS occultation

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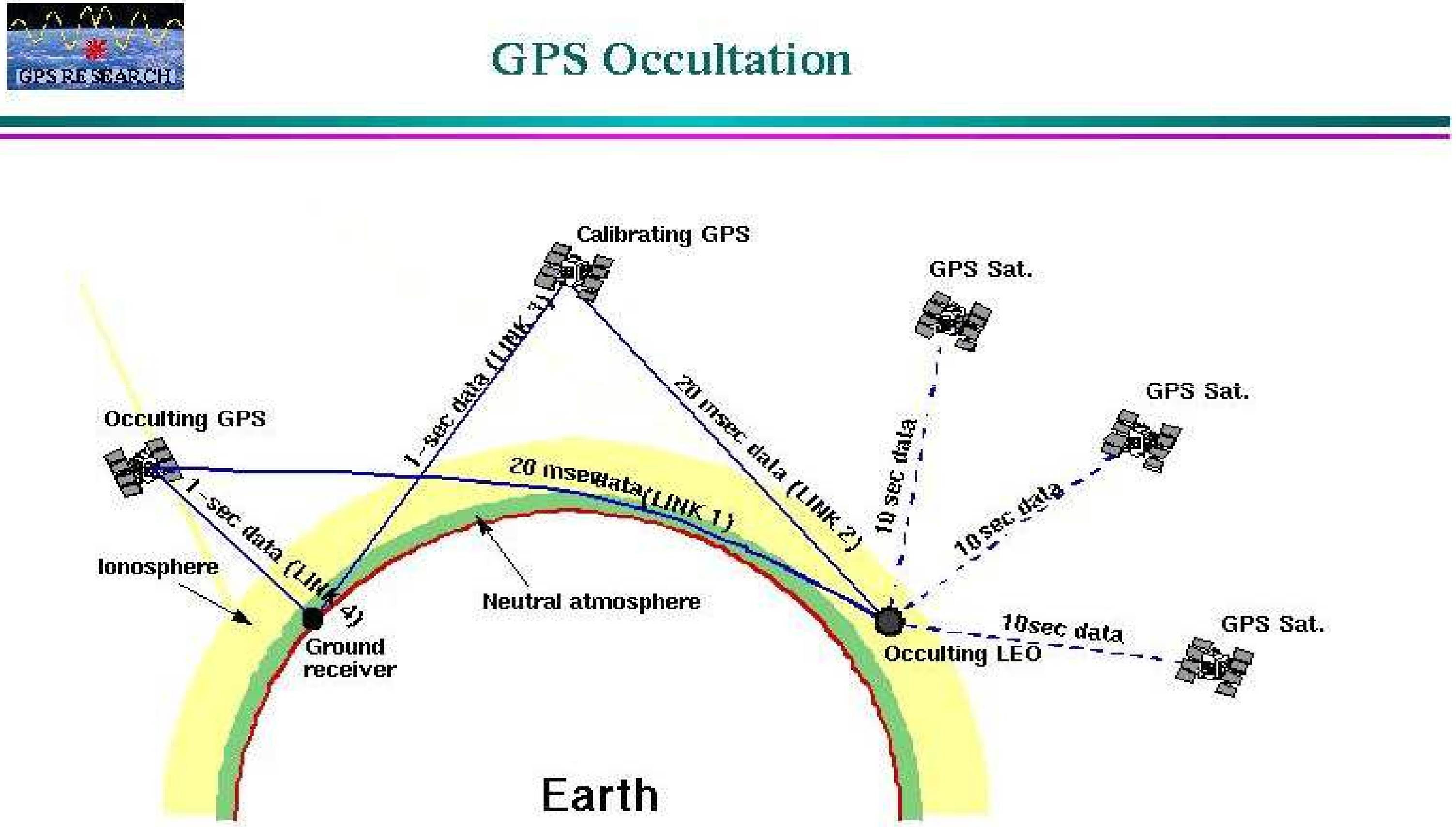
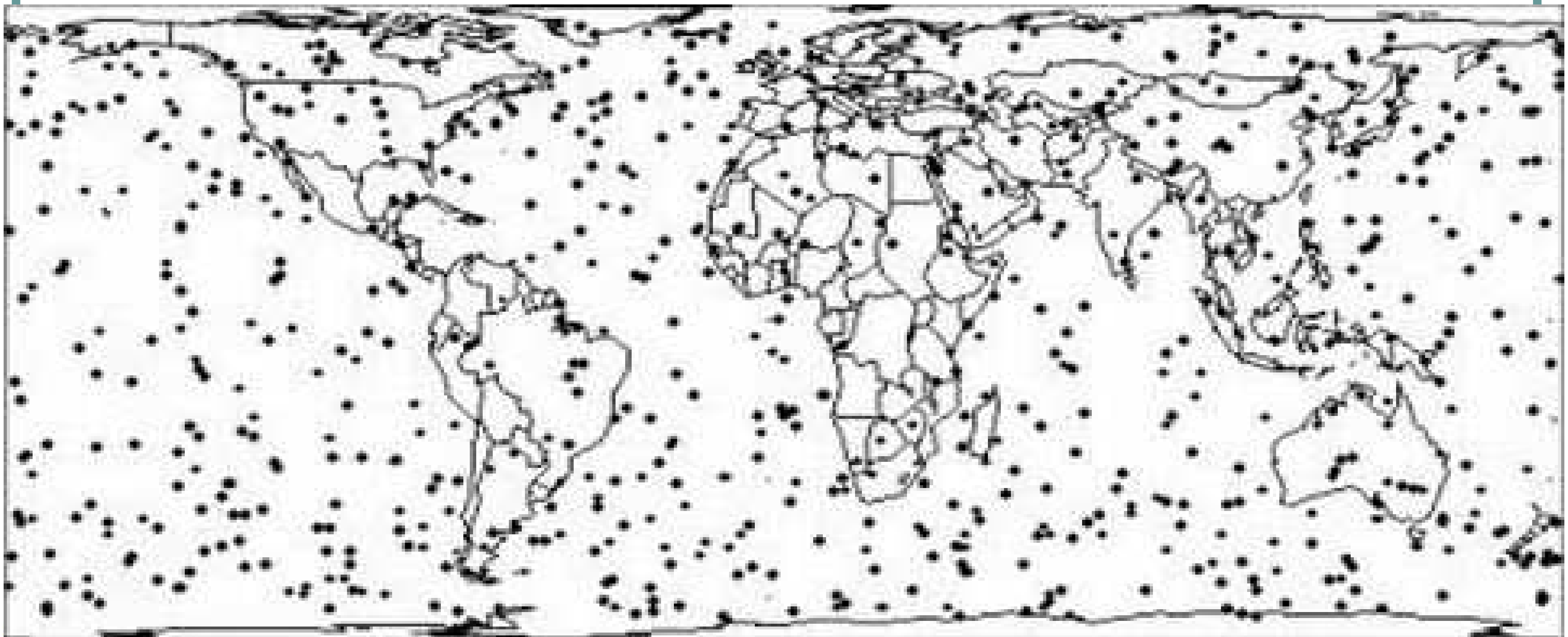
Occultation double differencing



Double differencing techniques are used to reduce clock errors.

Occultation frequency

- Hundreds of occultations observed per day
- Occultation event lasts 1-2 minutes



Number of occultation events occurred during 24h for a LEO satellite with i=98 deg and H=600km (http://geodaf.mt.asi.it/html/GPSAtmo/space.html)

LEO augmentation of numerical weather forecasts, climate systems studies

- Global coverage
- High vertical resolution
- Long-term stability
- All-weather capability

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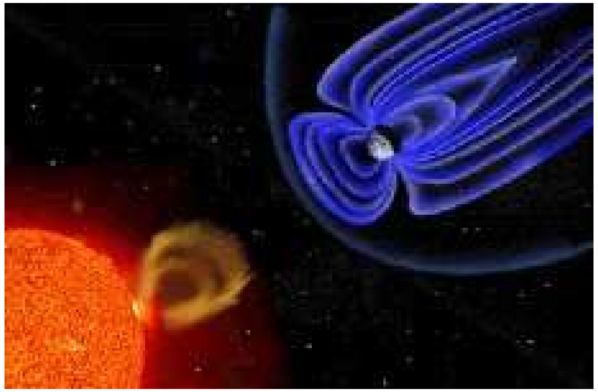
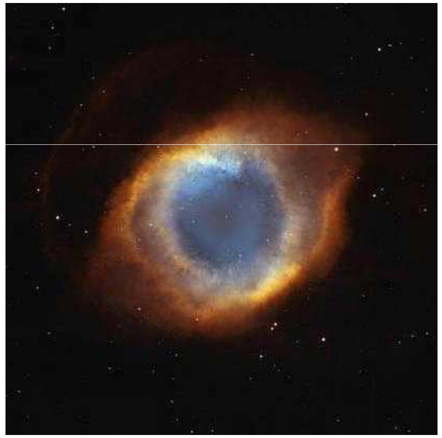
Surveys & Mapping





Thank you

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