HMO Space Weather Infrastructure and Ionospheric Applications of GPS in South Africa

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Hermanus Magnetic Observatory, A Facility of the NRF

Matjiesfontein Space Geodecy Station
Technical Workshop 16-19 March 2009

Overview

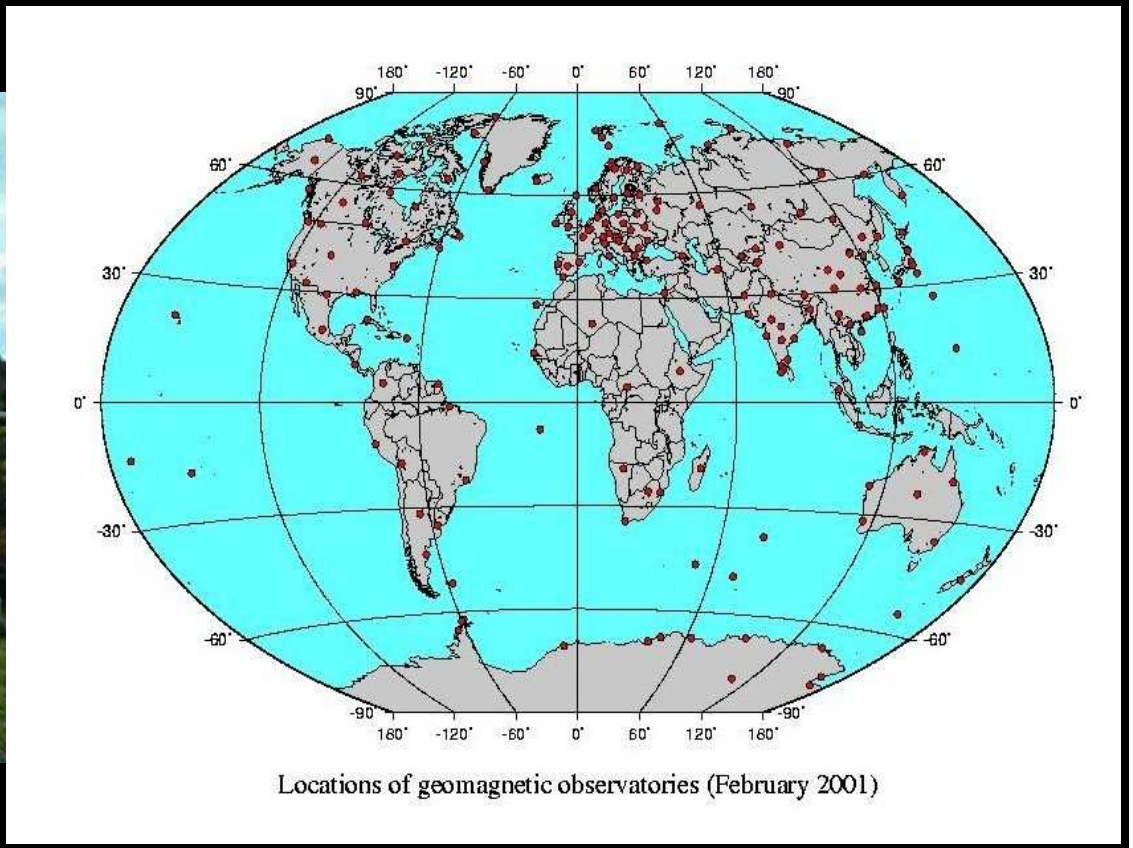
- HMO
- Space Weather
- Our interest in the ionosphere
- Advantages of using GPS for ionospheric observation
- GNSS Coverage from RSA GPS network
- Total electron content mapping over South Africa
- Ionospheric Tomography
- Ionospheric Scintillations
- HMO Space Weather infrastructure in Antarctica, Marion & Gough Islands

2nd International Polar Year (1932-33)

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

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

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



Locations of geomagnetic observatories (February 2001)

The **Hermanus Magnetic Observatory (HMO)** is a research facility of the National Research Foundation 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.

HMO activities directly aligned with the NRF's core missions are:

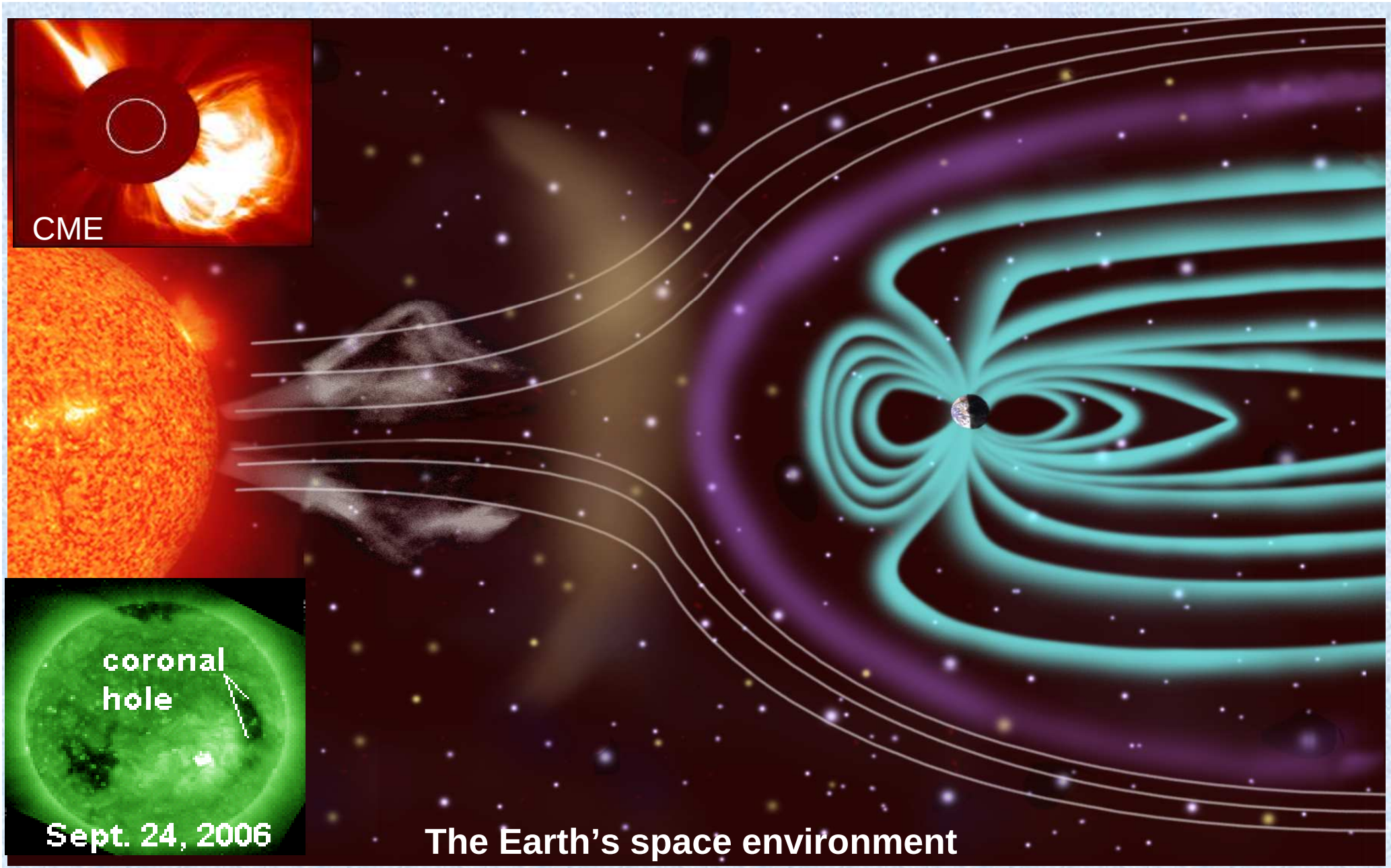
- Postgraduate student training and research capacity building
- Science outreach programmes for school educators and learners

Why study the ionosphere ?

- Scientific Research
  - Structure and dynamics of the ionosphere
  - Total electron content (TEC)
  - Electron density variation with altitude
  - Space weather monitoring, modeling and prediction

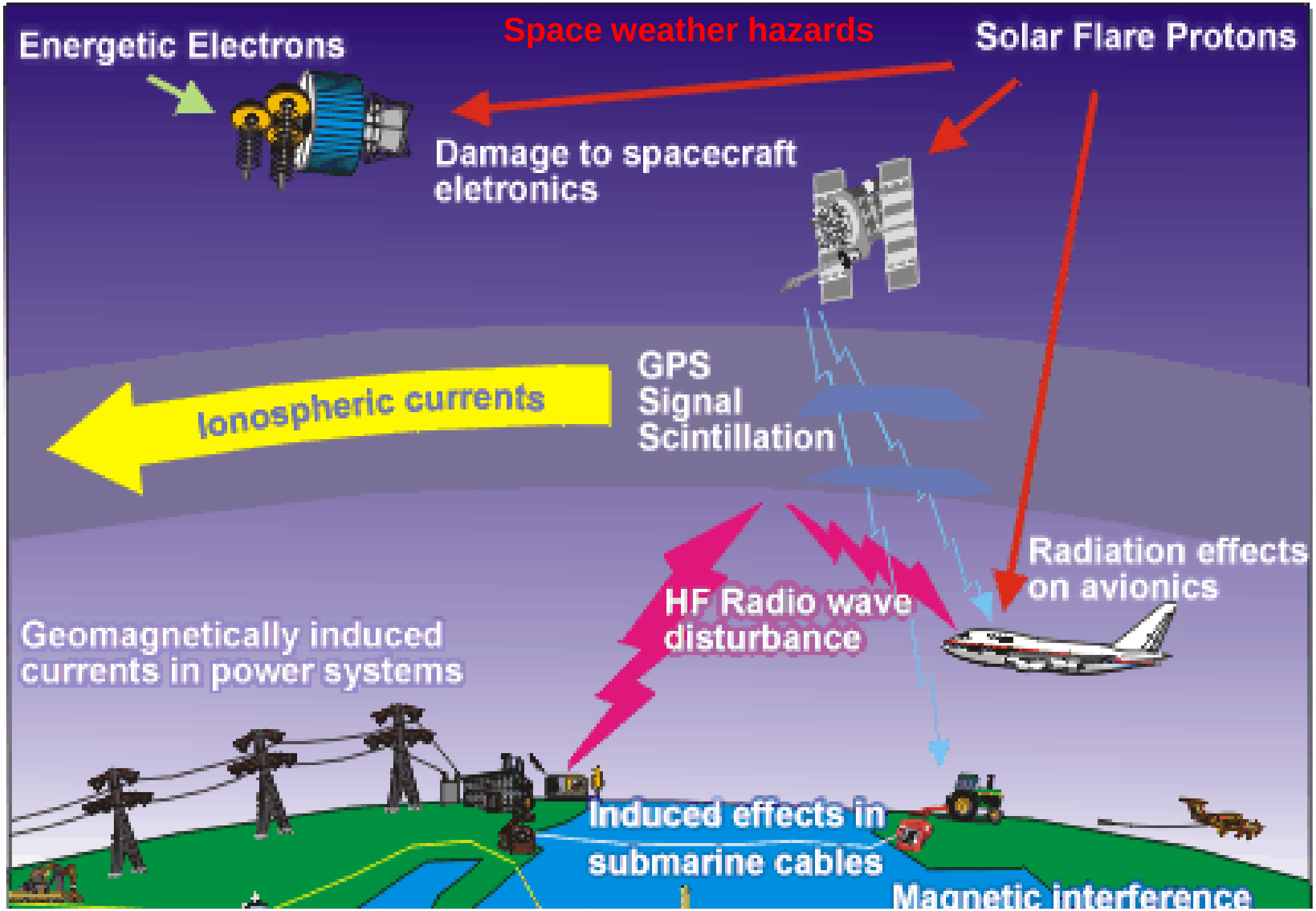
Why study the ionosphere ?

- Practical Applications
  - High Frequency (HF) (3-30 MHz) Radio
  - HF Direction finding using SSL
  - Radio Astronomy (KAT, MeerKAT, SKA)
  - Error correction for GPS positioning applications:
    - Navigation, Surveying, Geodesy, Other
  - Ionospheric Scintillation
  - Error correction for Satellite-borne altimeters
  - Over-the-horizon HF Radar (SuperDARN)



Schematic diagram of the sun, solar wind, and Earth's magnetosphere, the environment in which space weather is generated.

http://www.hmo.ac.za


Space weather hazards
Energetic Electrons
Solar Flare Protons
Damage to spacecraft
eletronics
Ionospheric currents
GPS
Signal
Scintillation
HF Radio wave
disturbance
Radiation effects
on avionics
Geomagnetically induced
currents in power systems
Induced effects in
submarine cables
Magnetic interference

HMO Established as the Regional Warning Centre of the International Space Environment Service

The International Space Environment Service (ISES) is a permanent service of the Federations of Astronomical and Geophysical Data Analysis Services (FAGS) under the auspices of the International Union of Radio Science (URSI) in association with the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG).

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 reduce the impact of space weather on activities of human interest. The HMO became the regional warning centre (RWC) for Africa in 2007.

ISES REGIONAL WARNING CENTRES

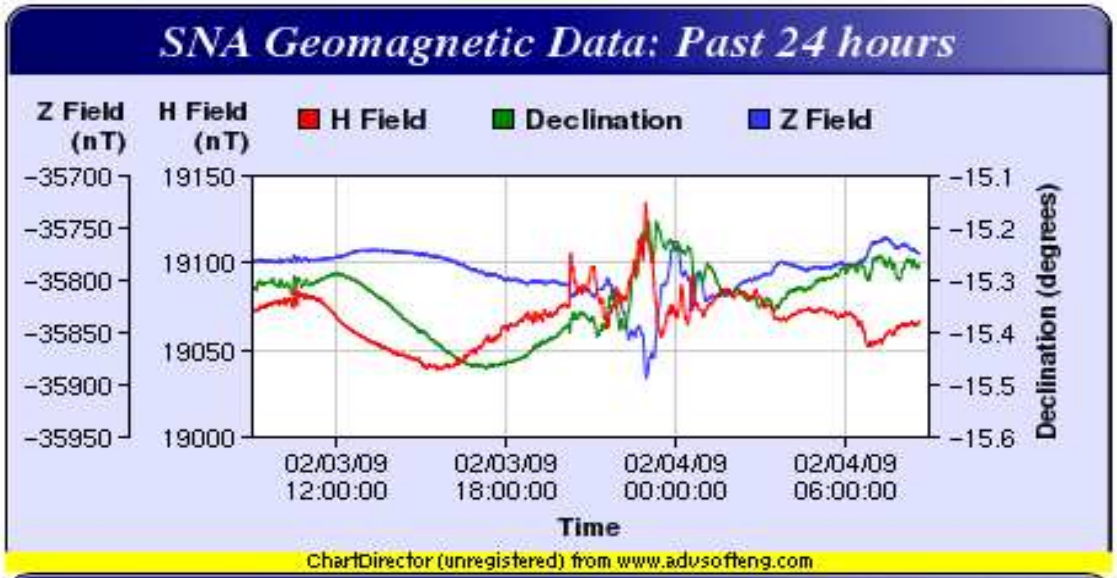
http://spaceweather.hmo.ac.za

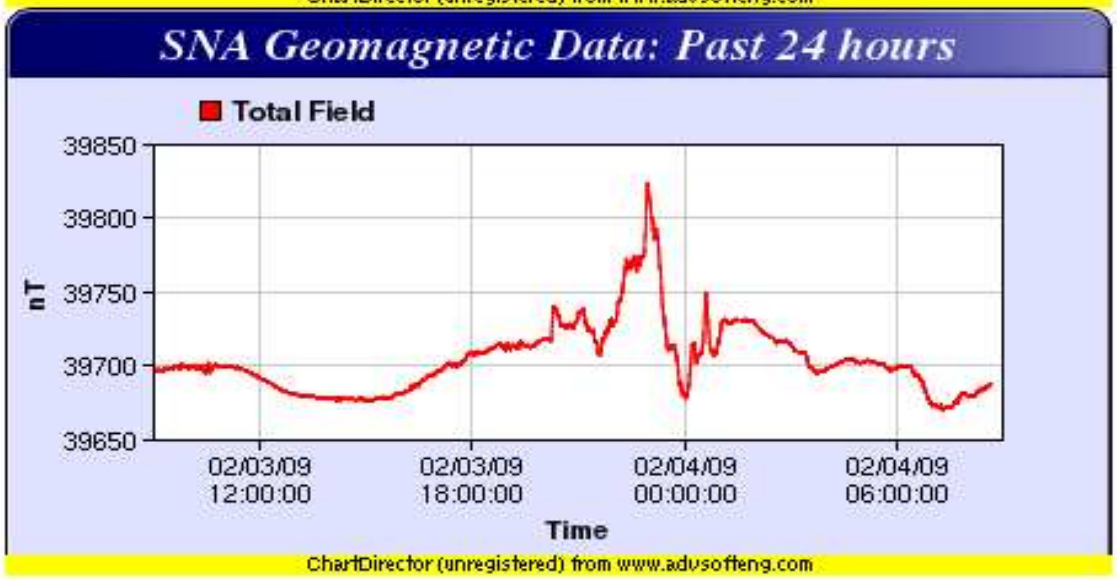
ISES Regional Warning Centre for Africa

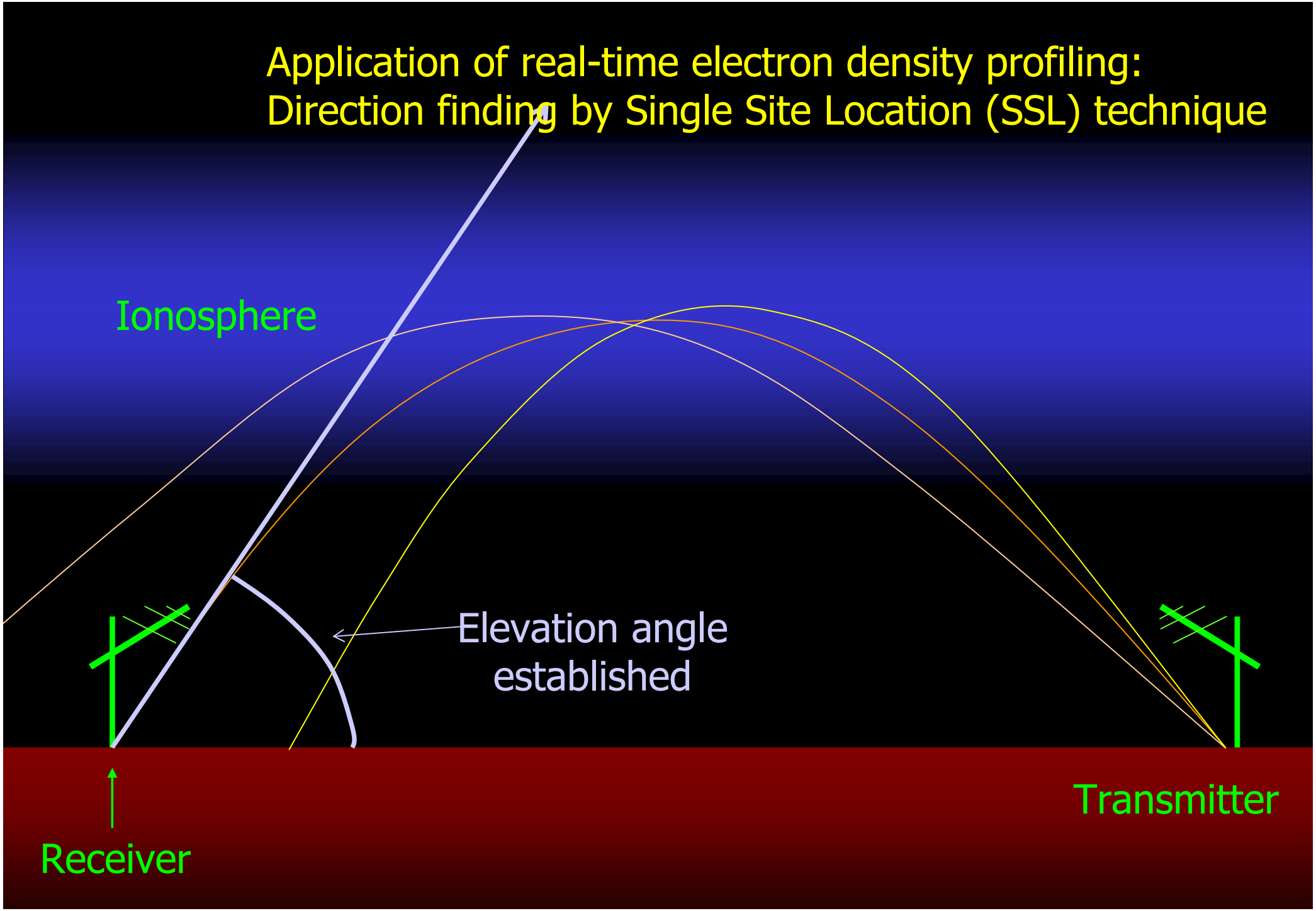
HMO

open all | close all

- Real Time Data
- Geomagnetic Data
  - Hartebeesthoek
  - Hermanus
  - Keetmanshoop
  - SANAE
    - Current
    - Magnetic Field Graphs
    - Magnetic Field Indices
- Ionospheric Data

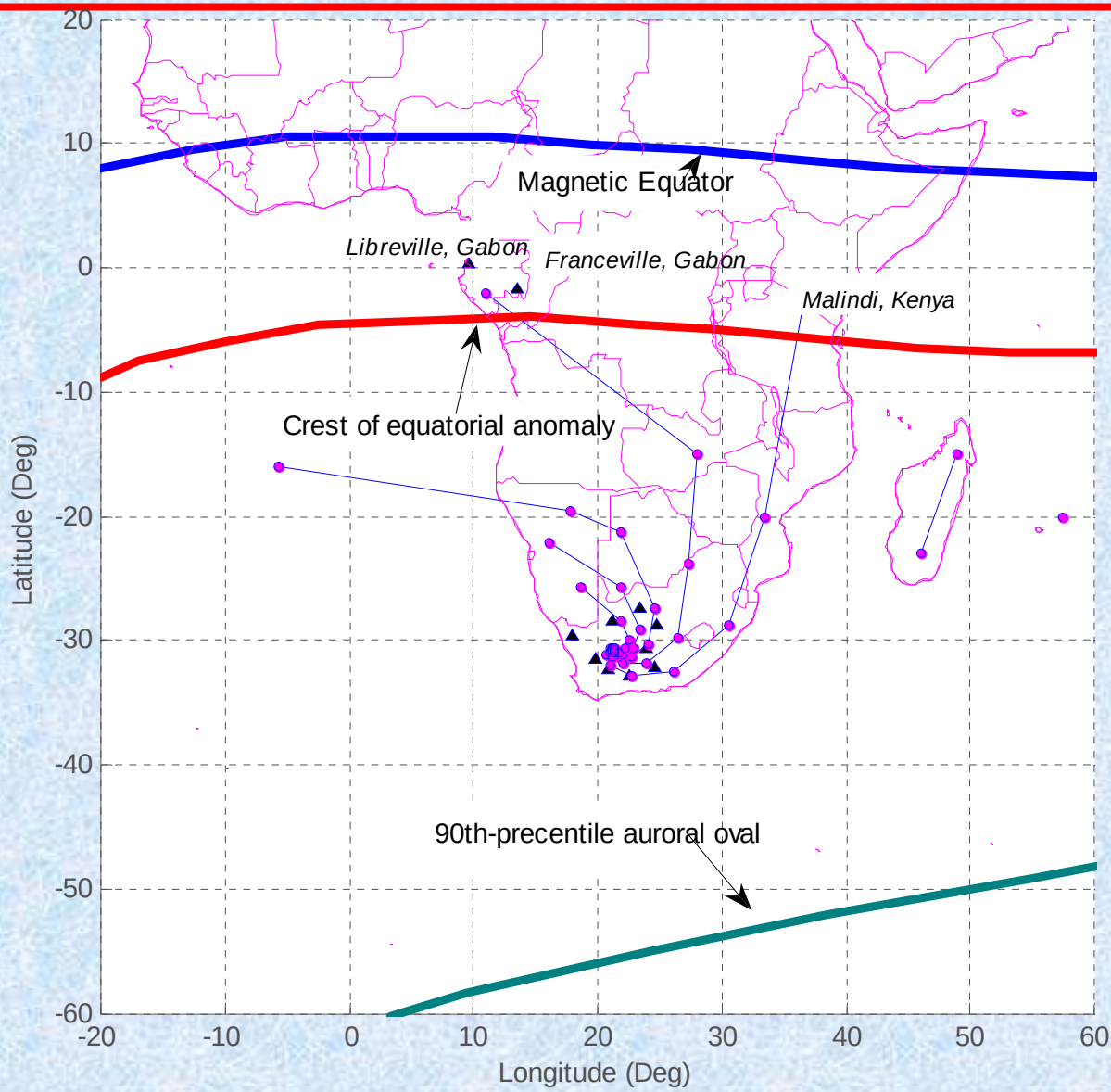





Application of real-time electron density profiling:
Direction finding by Single Site Location (SSL) technique
Ionosphere
Elevation angle
established
Receiver
Transmitter

Radio Astronomy:

Variability of the ionosphere over proposed SKA-hub



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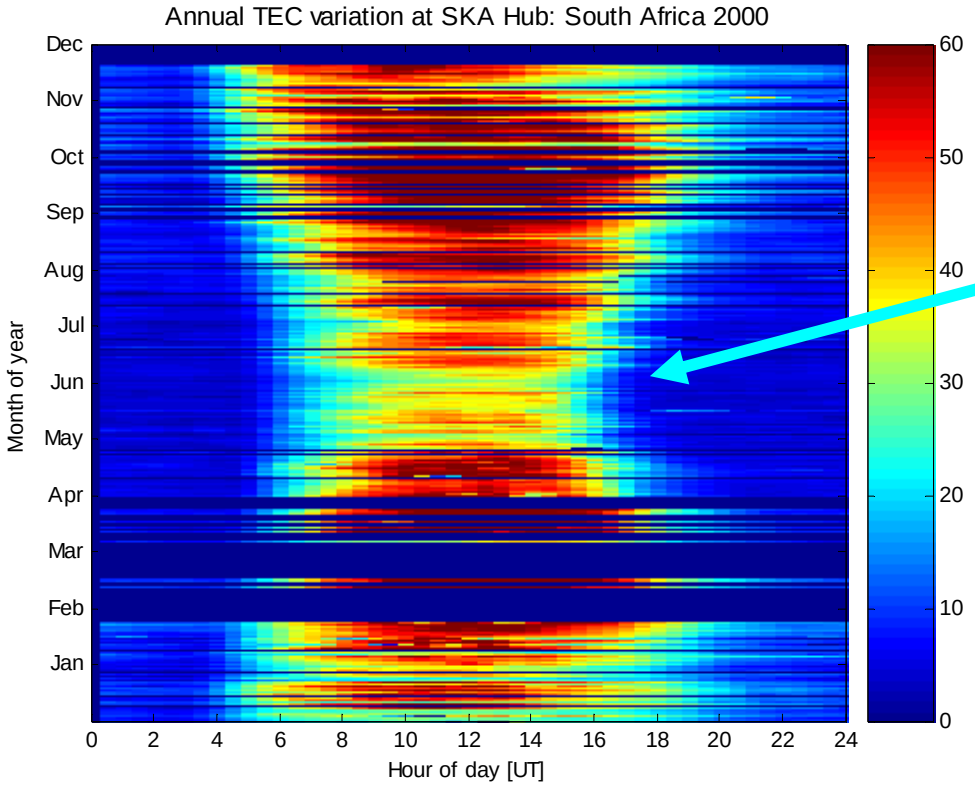
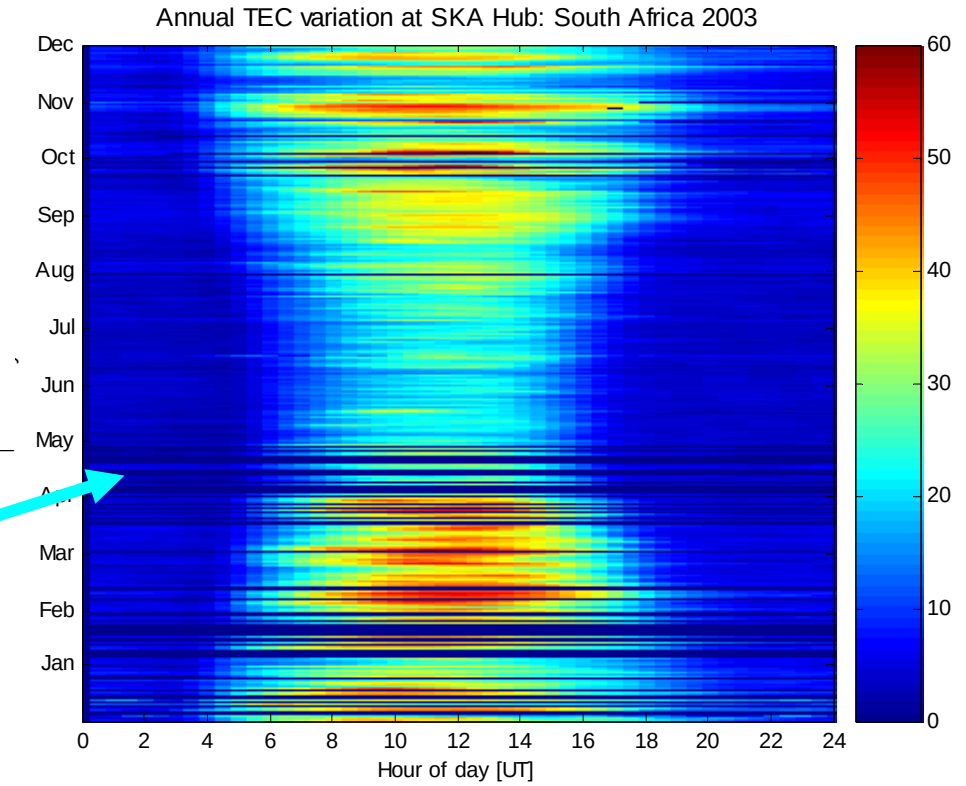


Diurnal, seasonal and solar cycle TEC variation at SKA-Hub (21.4E, 30.7S).

2000: Near Solar maximum



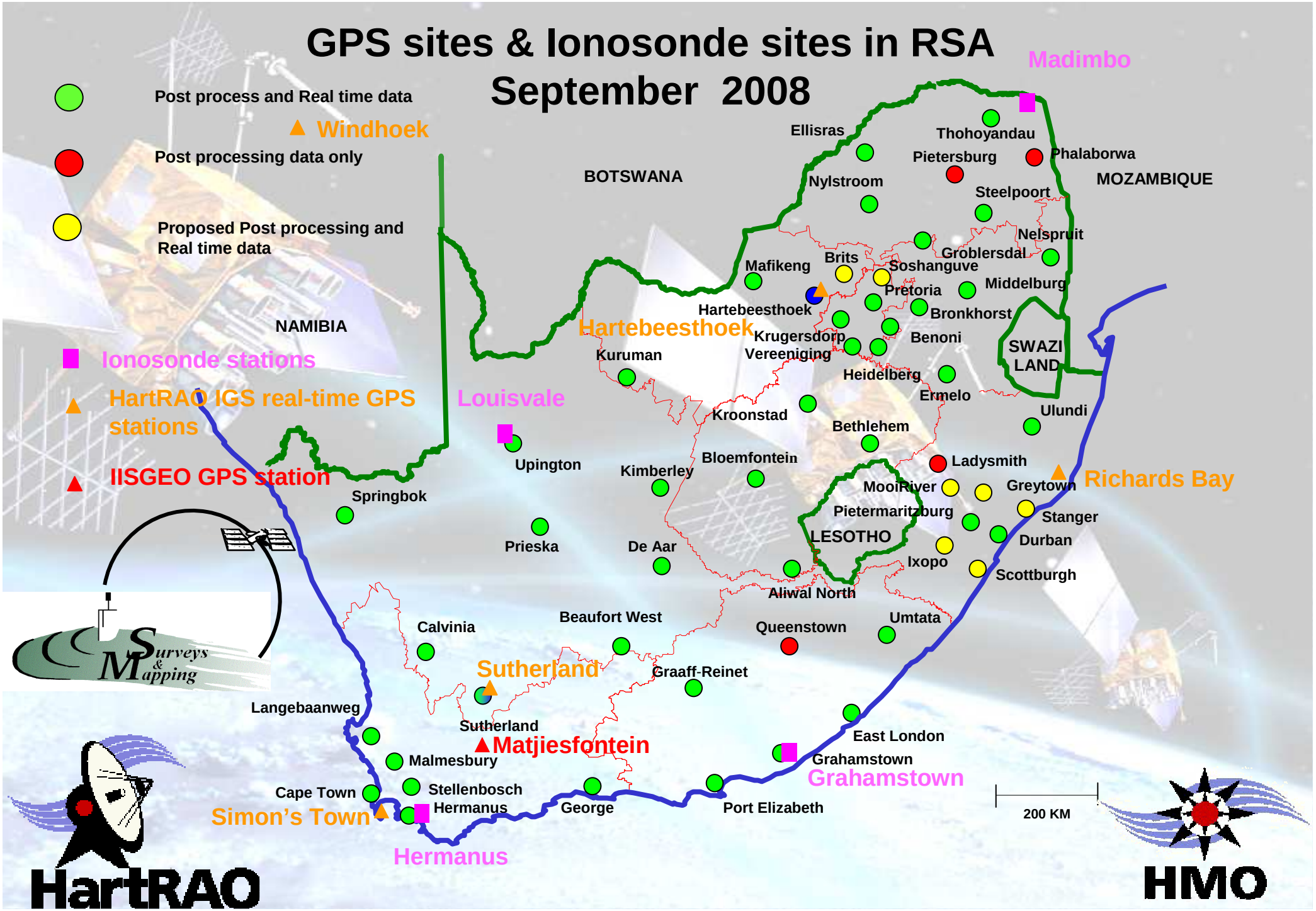
2003: Near Solar minimum

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

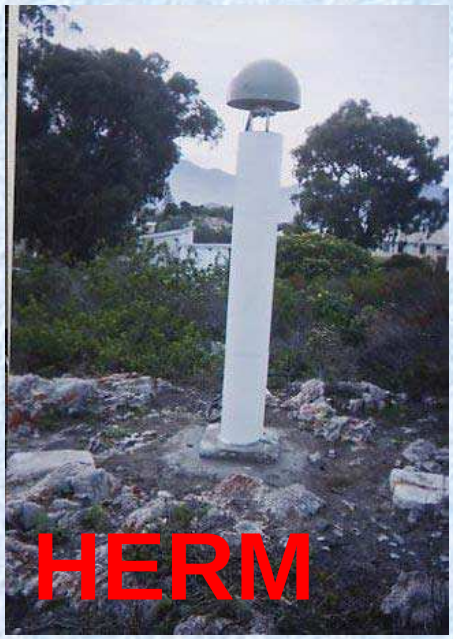
GPS-advantages for ionospheric observation

- Instantaneous global coverage
- Ionospheric measurements beyond continental borders
- Continuous 24/7 operation
- High temporal resolution (1s)
- Near real-time data acquisition
- Excellent support by international GPS user community


GPS sites & Ionosonde sites in RSA
September 2008
Post process and Real time data
Windhoek
Post processing data only
Proposed Post processing and Real time data
Ionosonde stations
HartRAO IGS real-time GPS stations
IISGEO GPS station
BOTSWANA
NAMIBIA
LESOTHO
SWAZI LAND
MOZAMBIQUE
Madimbo
Ellisras
Thohoyandau
Pietersburg
Phalaborwa
Nylstroom
Steelpoort
Nelspruit
Groblersdal
Mafikeng
Brits
Soshanguve
Middelburg
Pretoria
Hartebeesthoek
Bronkhorst
Krugersdorp
Benoni
Vereeniging
Kuruman
Heidelberg
Ermelo
Ulundi
Kroonstad
Bethlehem
Louisvale
Upington
Bloemfontein
Ladysmith
Kimberley
MooiRiver
Greytown
Richards Bay
Springbok
Pietermaritzburg
Stanger
Durban
Prieska
De Aar
Ixopo
Scottburgh
Aliwal North
Beaufort West
Calvinia
Queenstown
Umtata
Sutherland
Graaff-Reinet
Langebaanweg
East London
Matjiesfontein
Malmesbury
Grahamstown
Cape Town
Stellenbosch
Simon's Town
Hermanus
George
Port Elizabeth
200 KM
Surveys & Mapping
HartRAO
HMO

CDSM GPS Receiver infrastructure

- Originally Ashtech Z12 dual frequency receivers
- Now NETR5, many real-time 24/7 @ 1s sampling rate
- All data streamed to CDSM in Cape Town
- Some data streamed to HMO

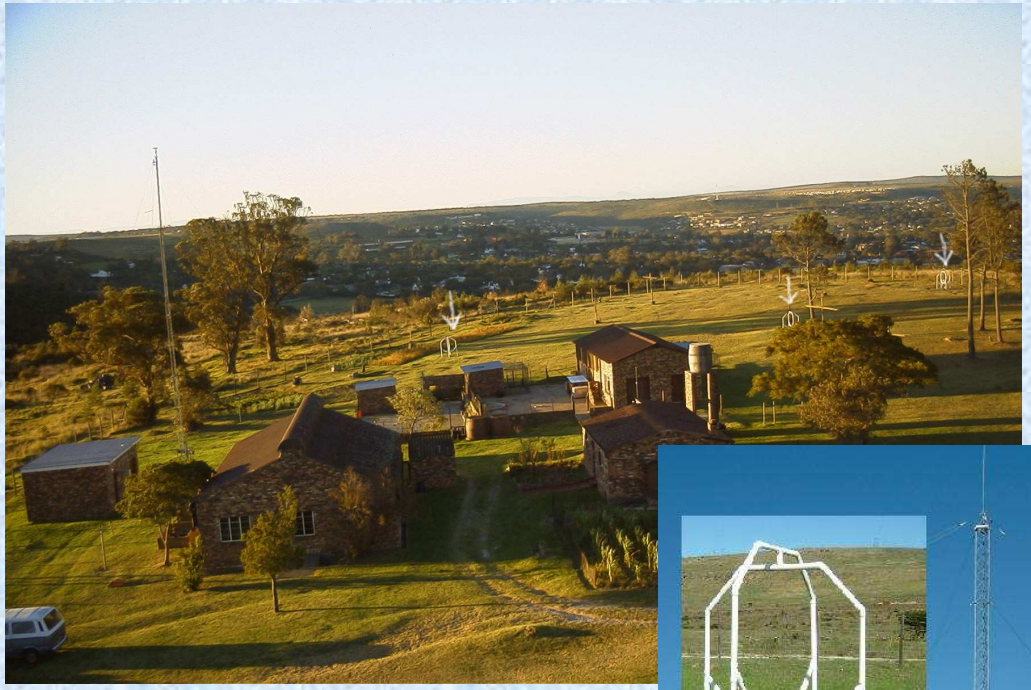


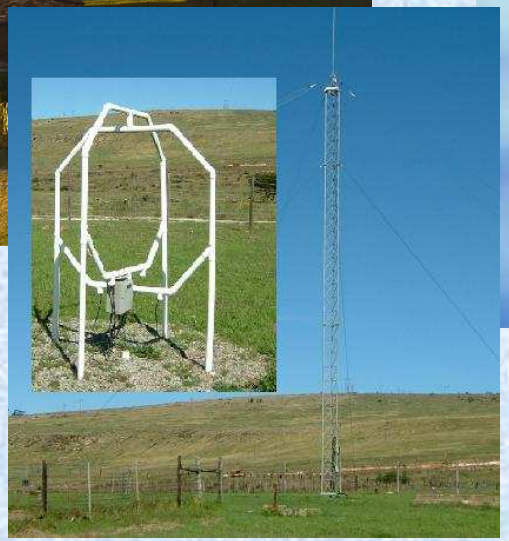
Hermanus GPS dual frequency receiver station: Established January 2000

Ashtech Z12

NETR5

CDSM GPS Receiver: Grahamstown



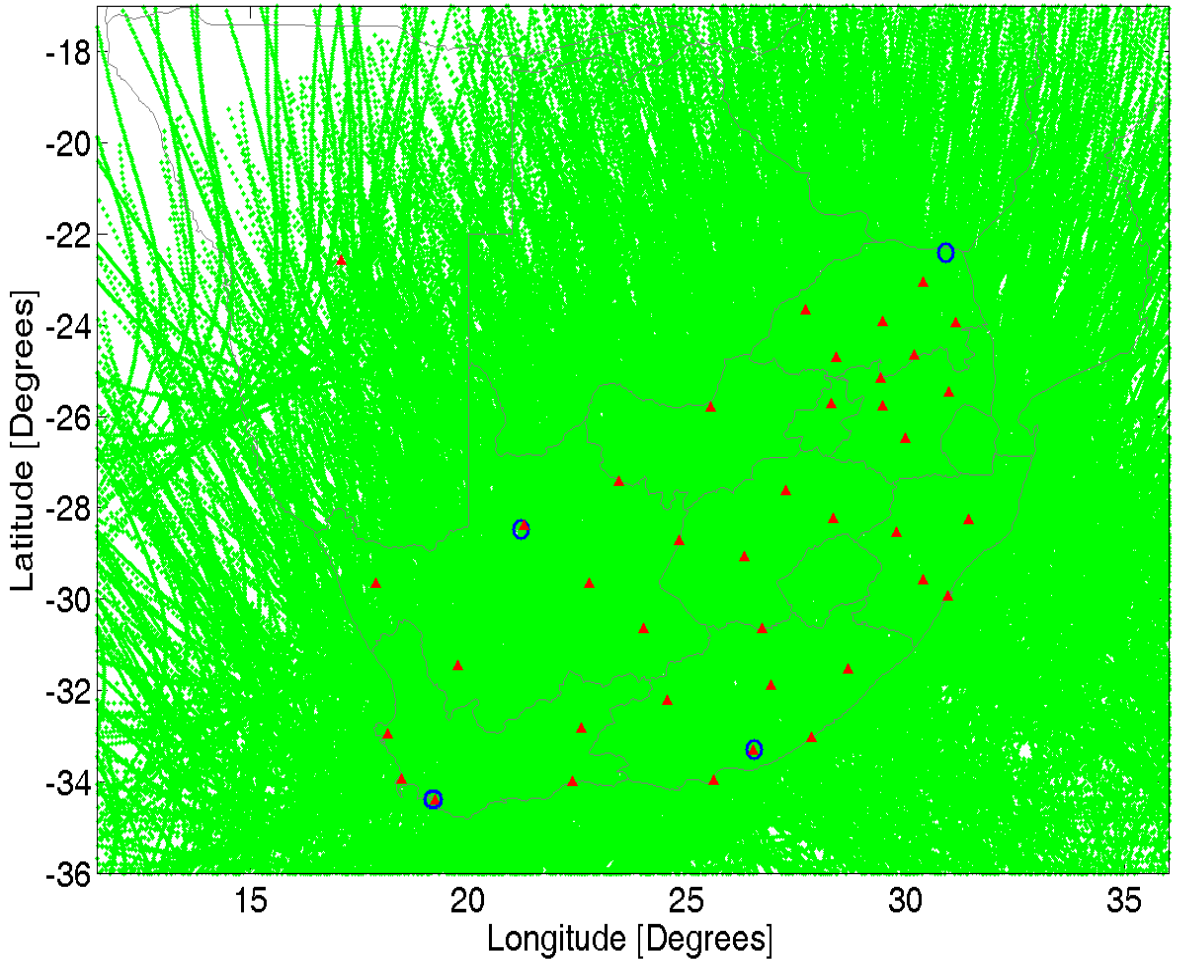


Grahamstown Ionosonde
Installed 1996

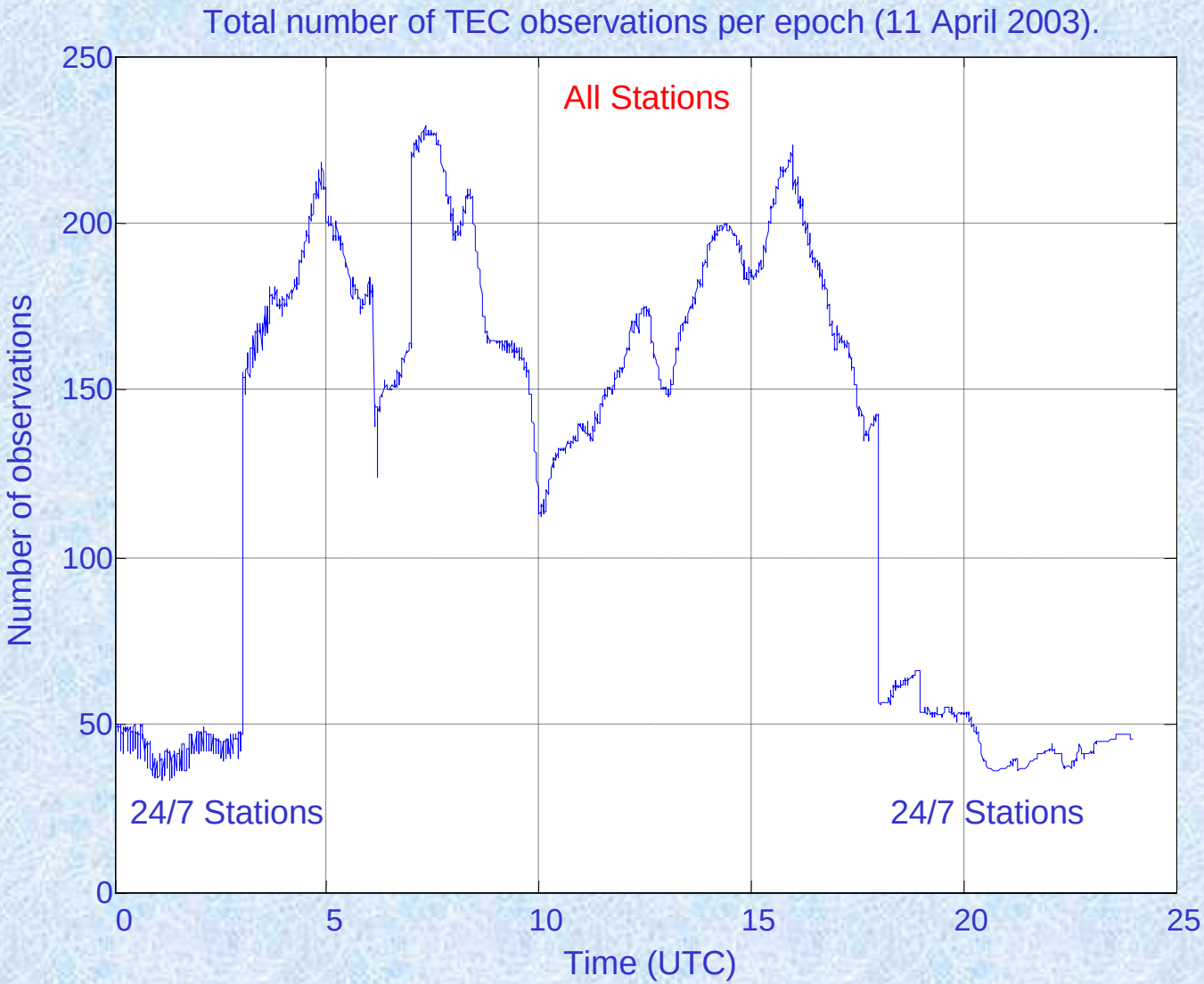
Grahamstown GPS dual frequency receiver station:
Installed February 2005

24h IPP Coverage

42 GPS receivers on 7 May 2008.

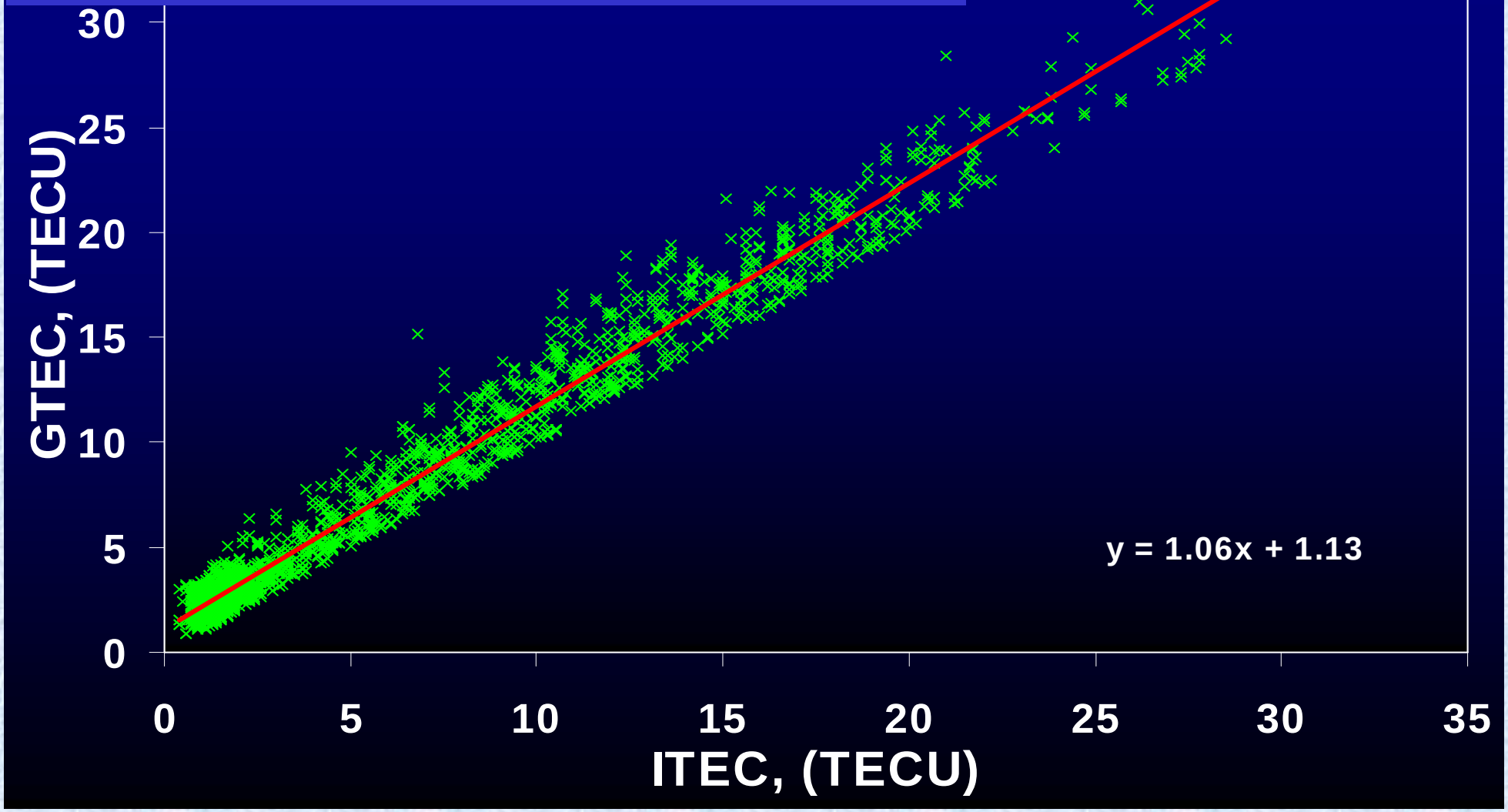


TEC observables per day

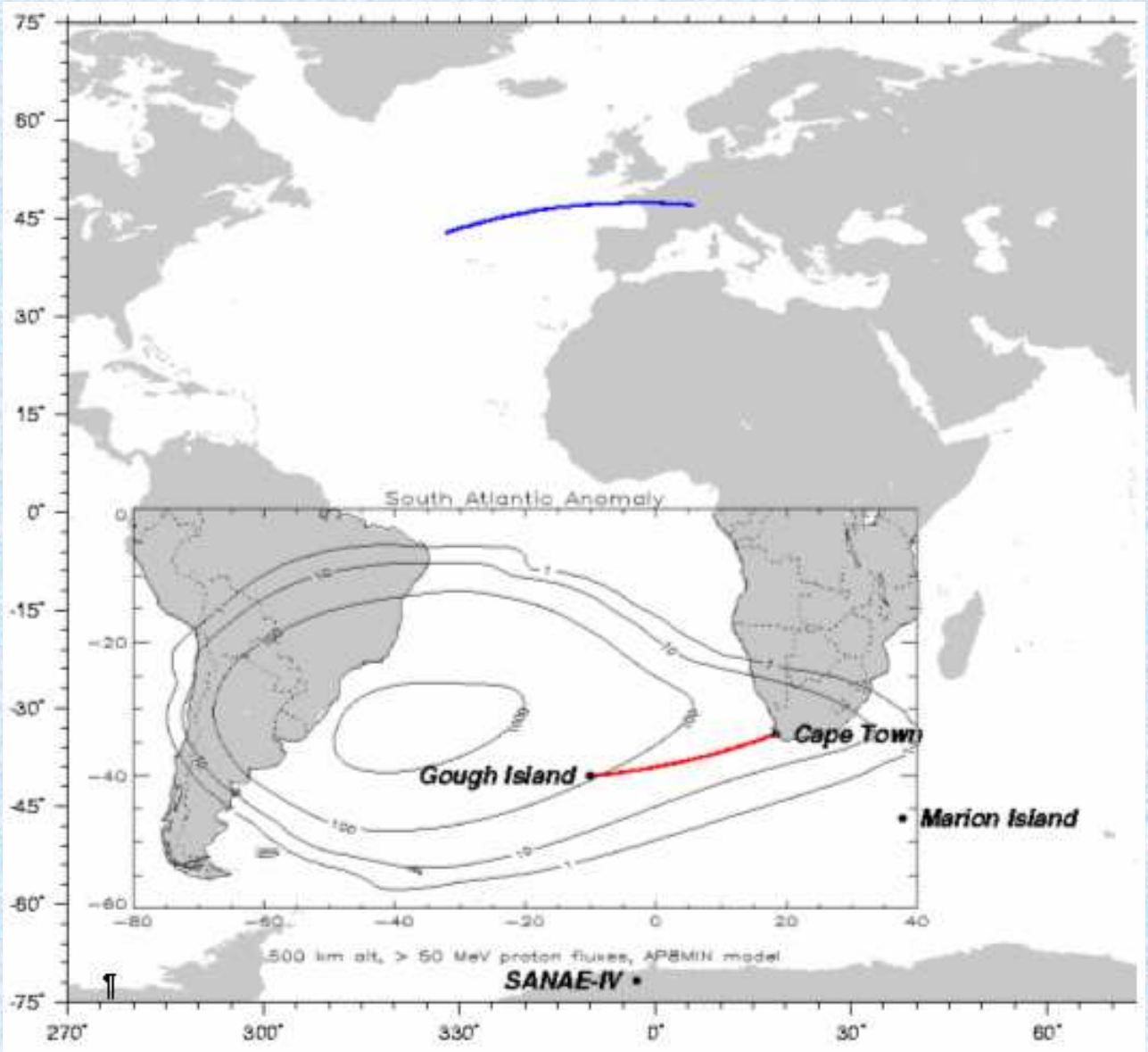


Comparison of ITEC with GTEC

ITEC = Ionosonde TEC (0 – 1000 km)
GTEC = GPS derived TEC (0 – 20200 km)



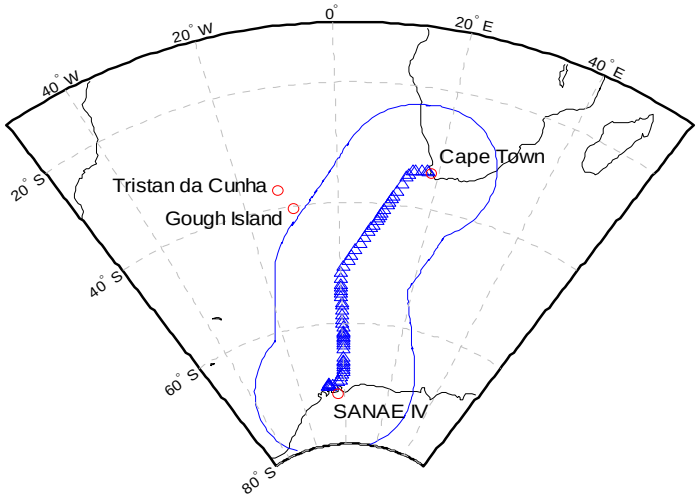
South Atlantic Anomaly

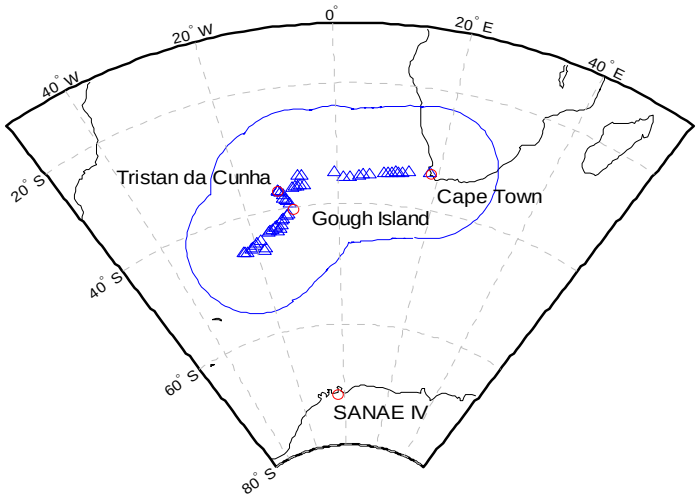


The SA Agulhas

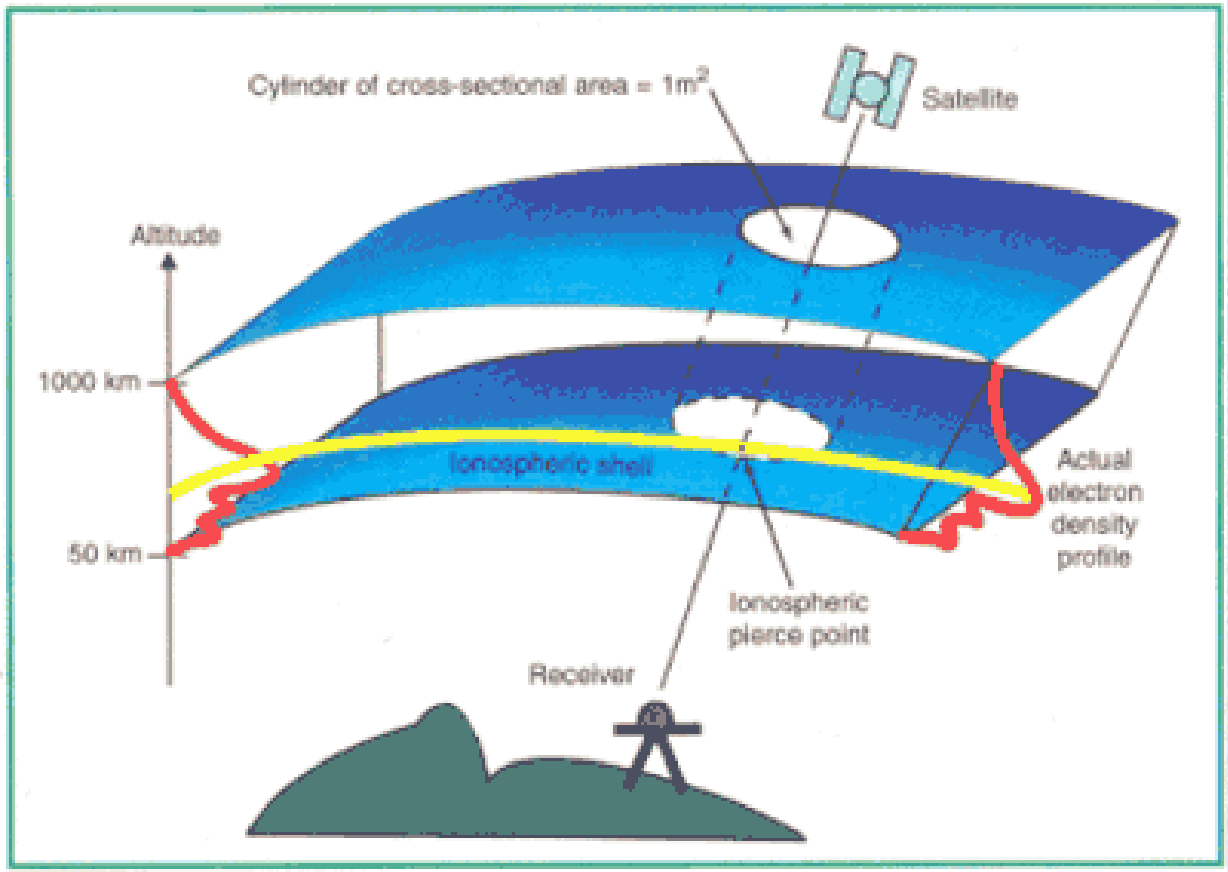
The SA Agulhas is South Africa's polar research vessel. The Agulhas is used to service the SANAP research bases in the Southern Ocean, Marion Island, Gough Island, Tristan da Cunha and Antarctica. The SA Agulhas has been equipped with a dual frequency AshTech GPS receiver for ionospheric monitoring during IPY since December 2005.

Ionospheric observations using GPS dual frequency receiver on board SA Agulhas





Total Electron Content (TEC)



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

$$\Delta\rho_{\mathrm{ion}} = c\Delta t_{\mathrm{ion}} = \frac{\alpha \cdot \mathrm{TEC}}{f_1^2}$$

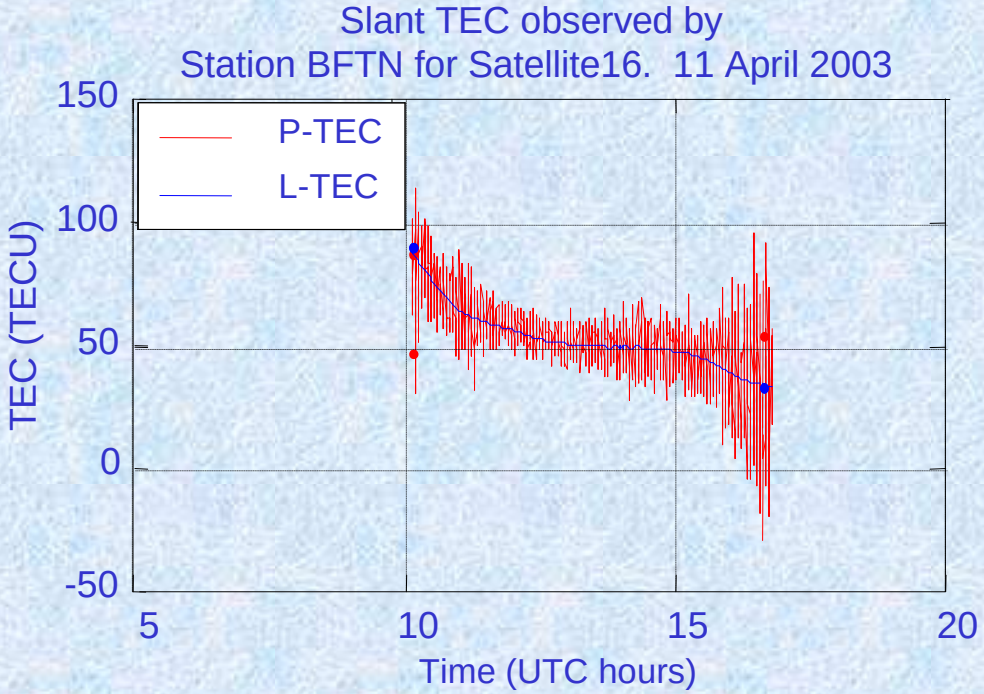
$$\alpha = 40.3 \cdot 10^{16} \left[\mathrm{ms}^{-2}\mathrm{TECU}^{-1} \right]$$

$$1\,\mathrm{TECU} = 10^{16}\ \mathrm{electrons/m}^2$$

The total electron content (TEC) is the line integral of the free electron density and equal to the total number of electrons in a 1 m^2 cylinder from satellite to receiver:

TEC measurement from GPS Observables

- Slant TEC derived from L1, L2 phase observables
- Phase ambiguity removed by comparison of L1-L2 with P1-P2



$$L_1 - L_2 = -\xi \Delta\rho_{\text{ion}} + \Delta B + \varepsilon$$

$$P_1 - P_2 = \xi \Delta\rho_{\text{ion}} + DCB + \varepsilon$$

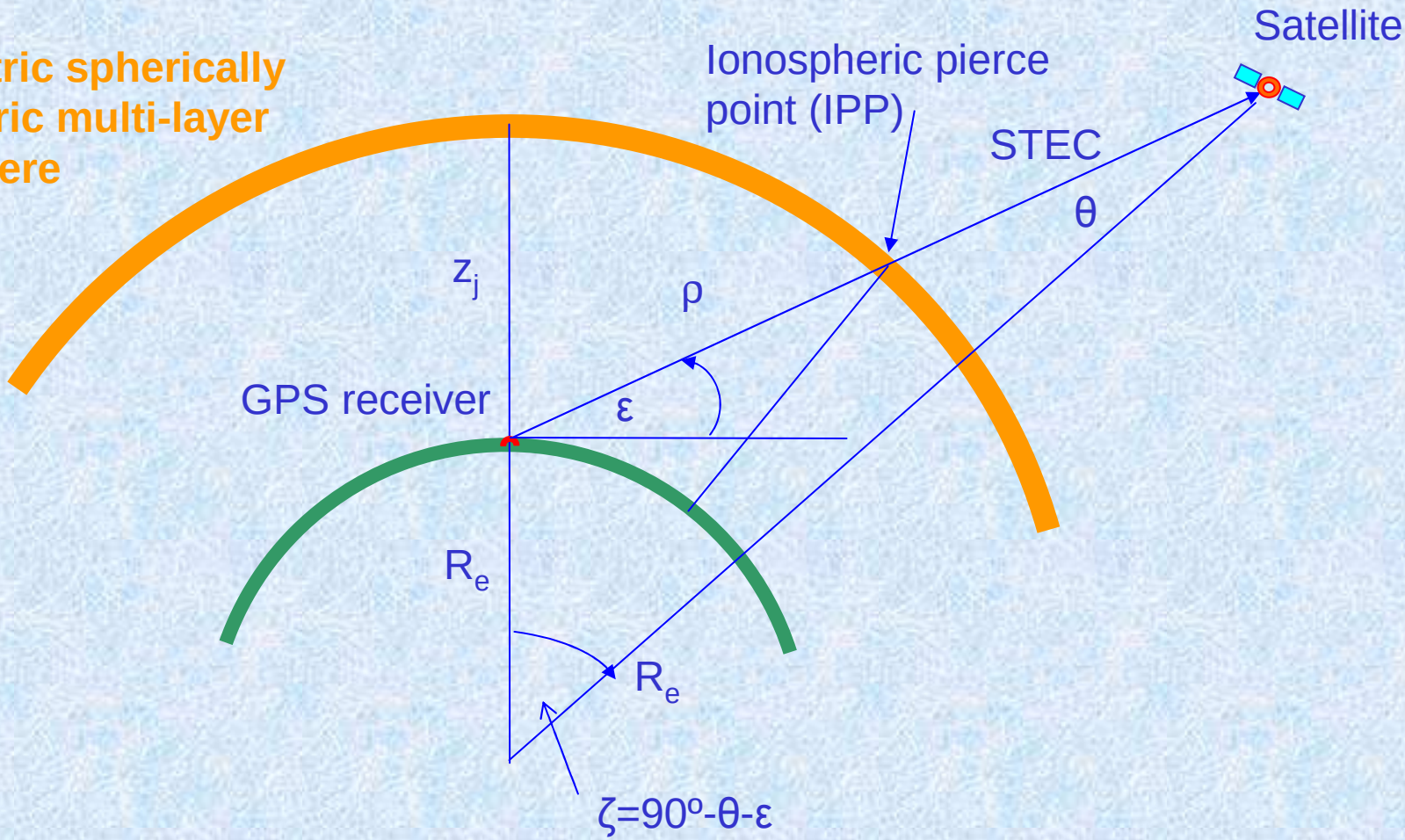
$$\xi = 1 - f_1^2 / f_2^2 = -0.647$$

ΔB = Carrier Phase ambiguity

DCB = Differential Clock Bias

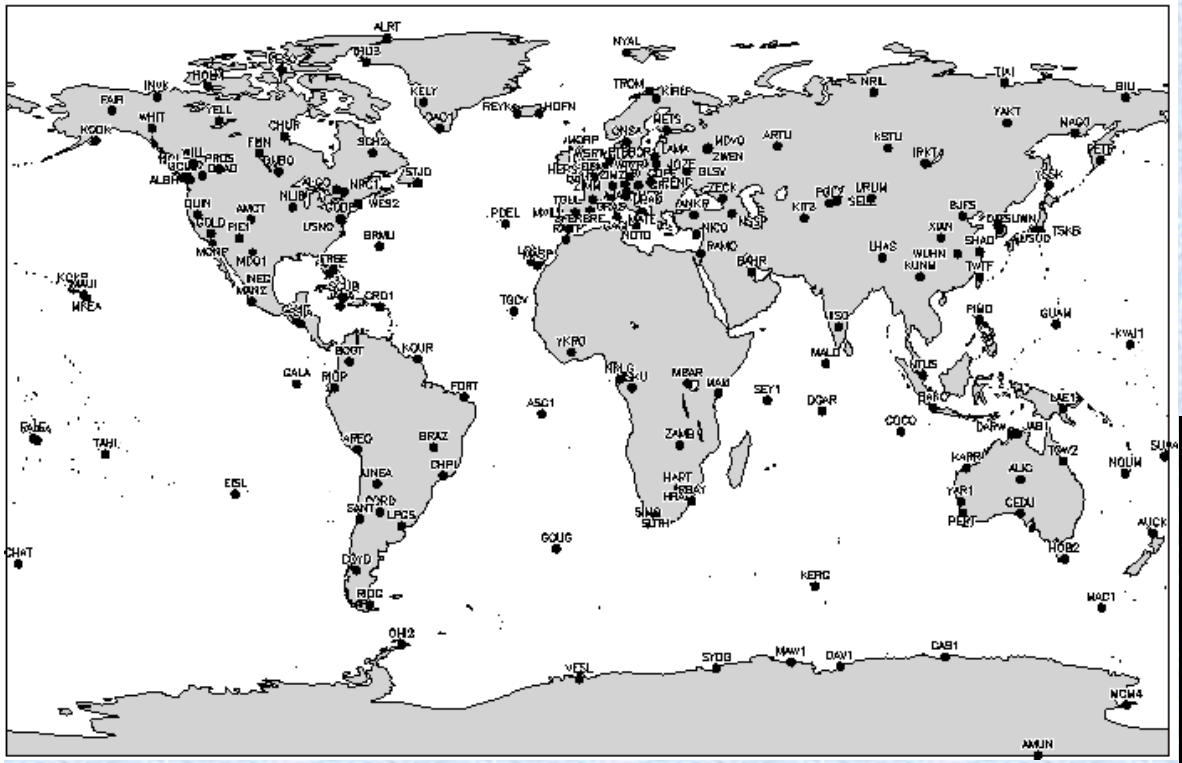
GPS TEC
Ionospheric Pierce Points

Concentric spherically symmetric multi-layer Ionosphere

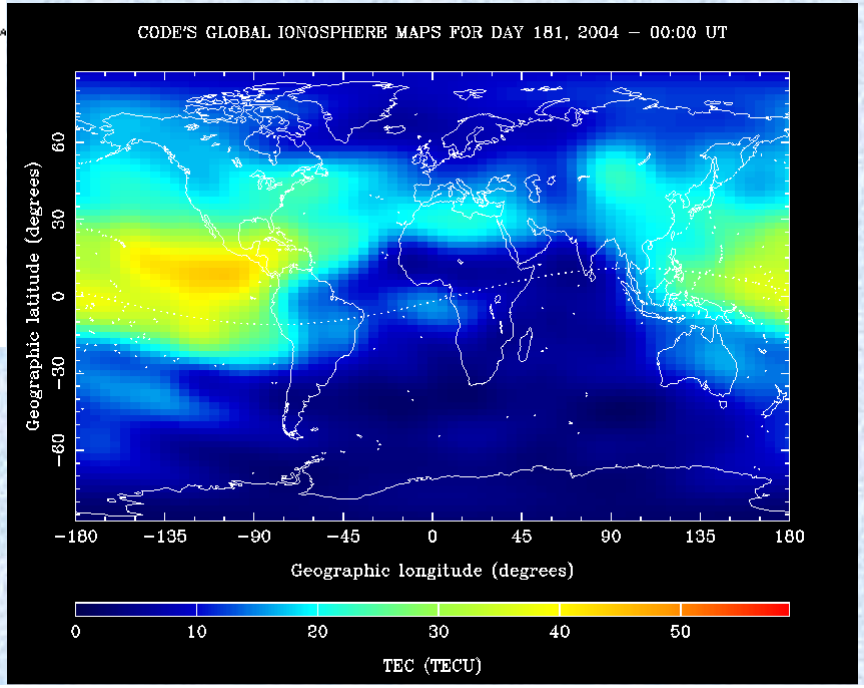


Global TEC maps

GPS Tracking Ground Stations Considered at CODE

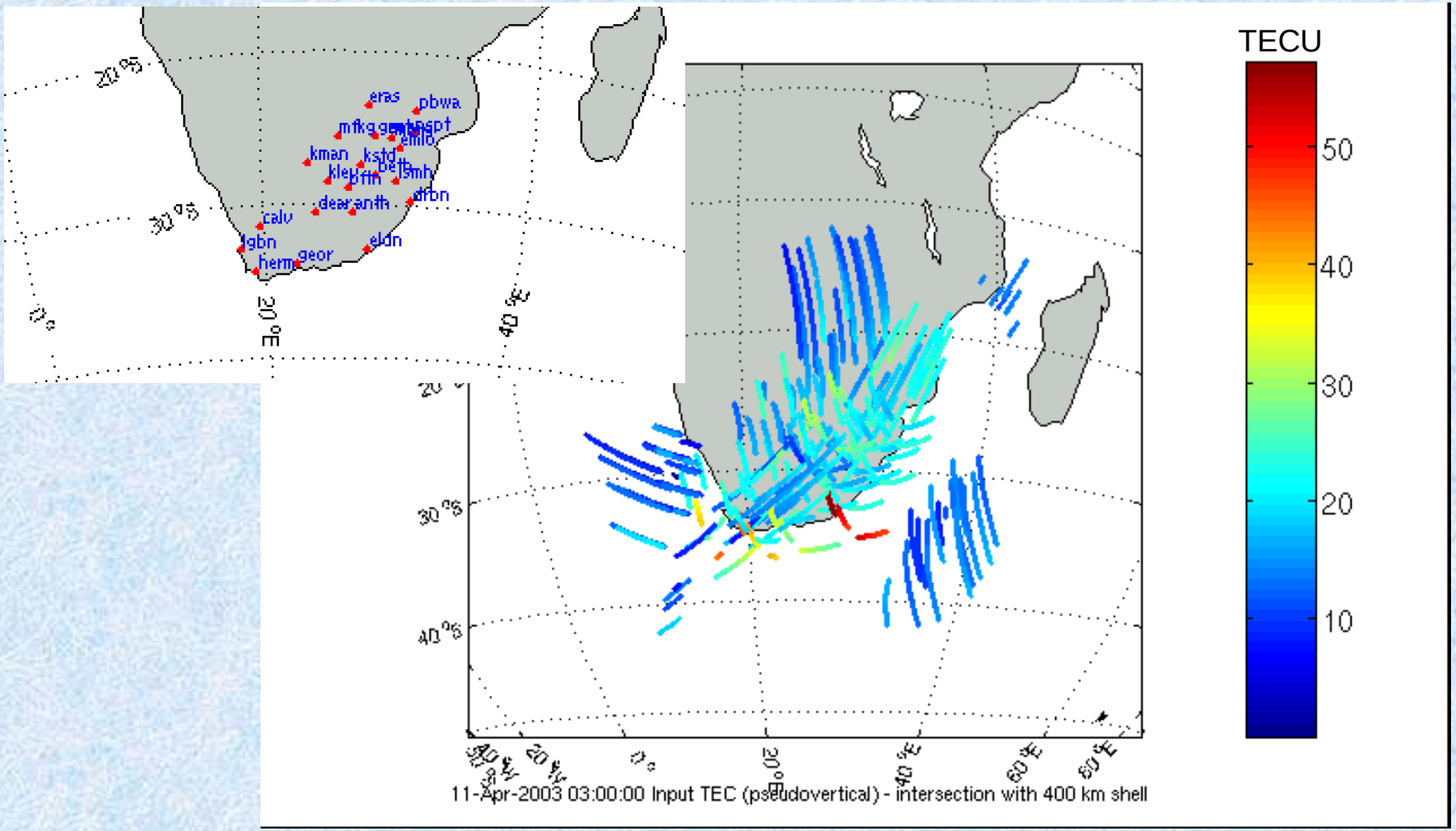


- Global Ionospheric Maps (GIMs) are produced daily by Centre for Orbit Determination in Europe (CODE)
- 200 GPS receivers worldwide
- 5 RSA Receivers used:
  - 2 @ Sutherland,
  - 2@ HartRAO
  - Richardsbay
- 13 maps per day, 2h intervals
- Limited resolution



CODE GIMs (http://www.cx.unibe.ch/aiub/ionosphere.html)

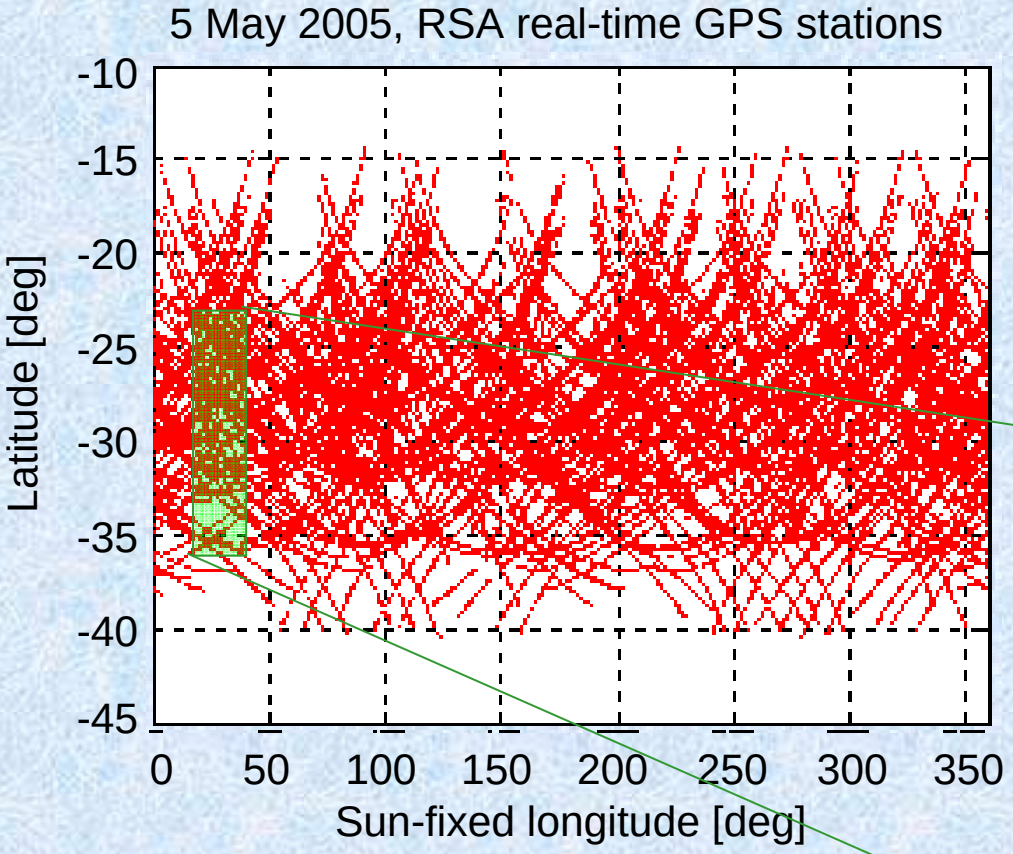
GPS-TEC processing using MIDAS
Raw data 03:00-04:00 UT

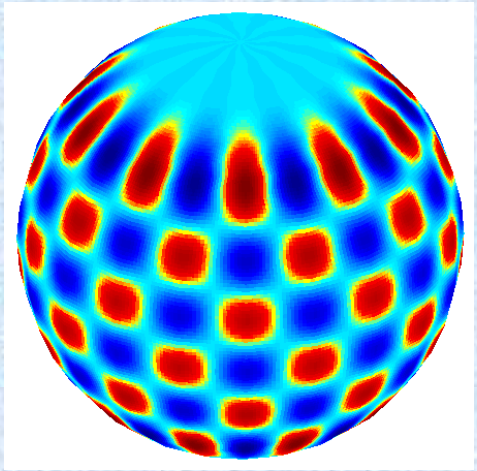


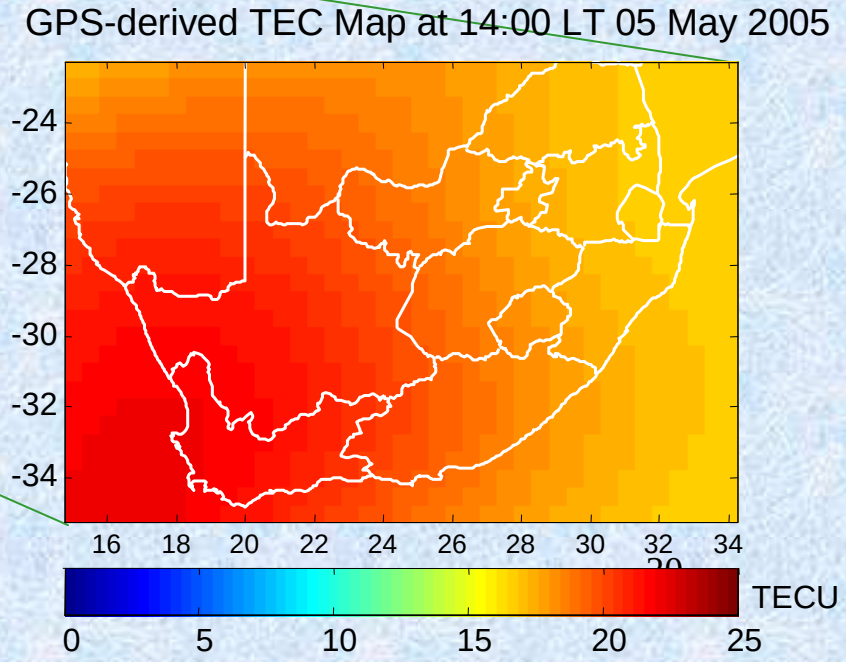
11-April-2003 TEC at IPPs at 400 km of ray paths to 21 CDSM GPS receivers .

http://www.hmo.ac.za

2D GPS TEC map using SHM

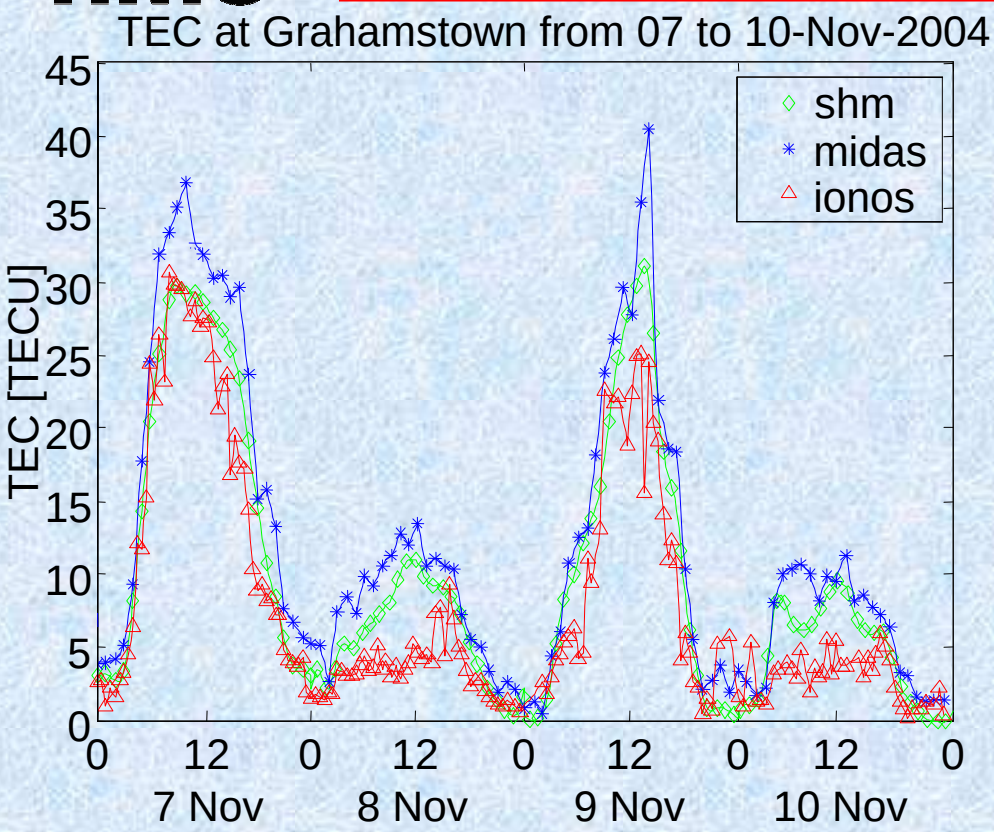


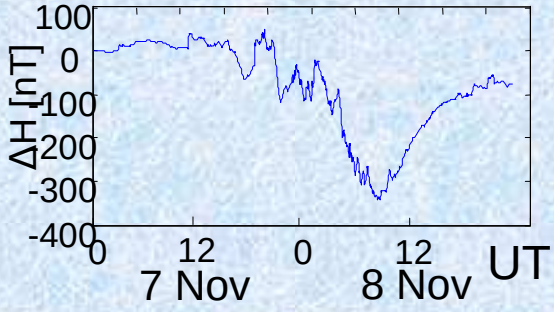


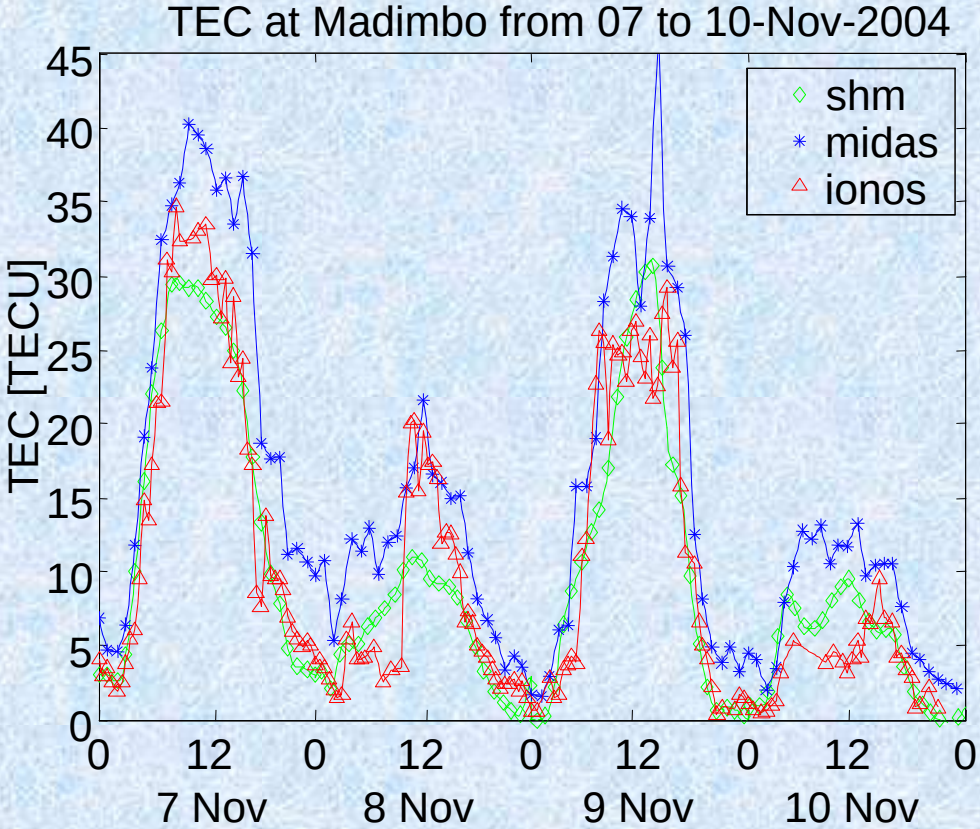


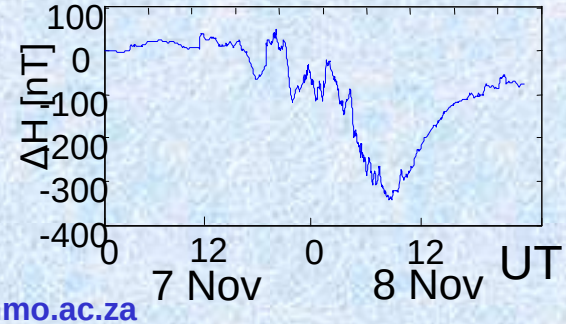
http://www.hmo.ac.za

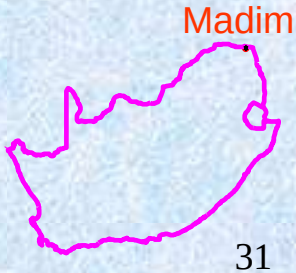
Total Electron Content during geomagnetic storm











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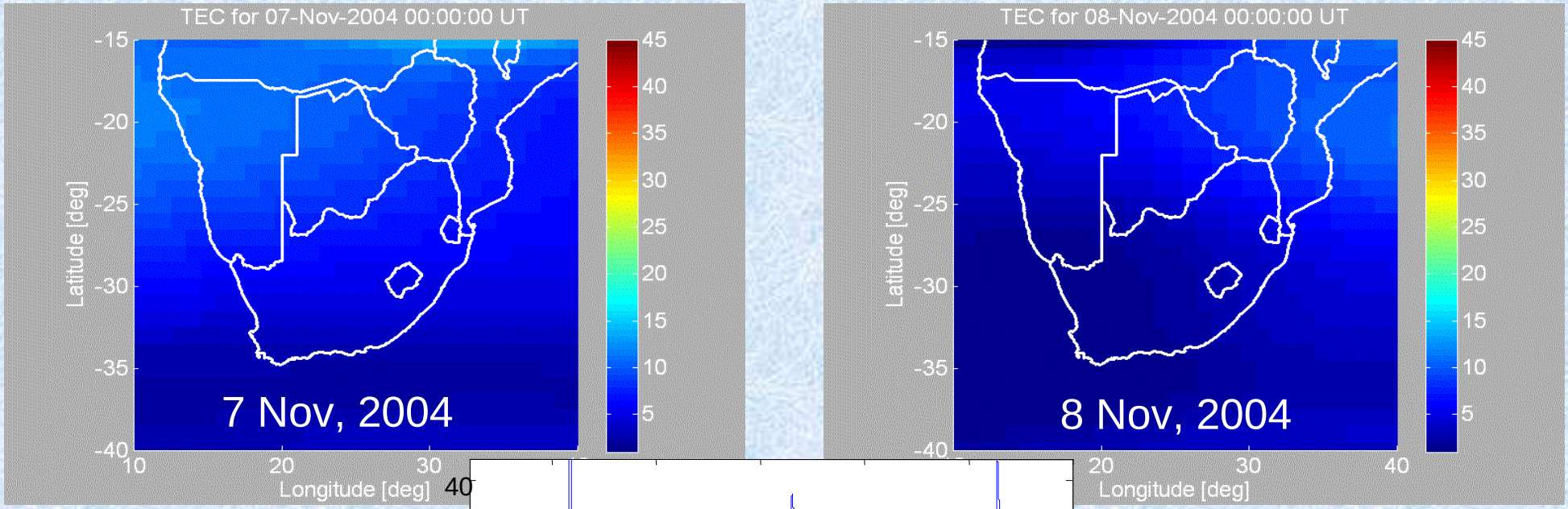
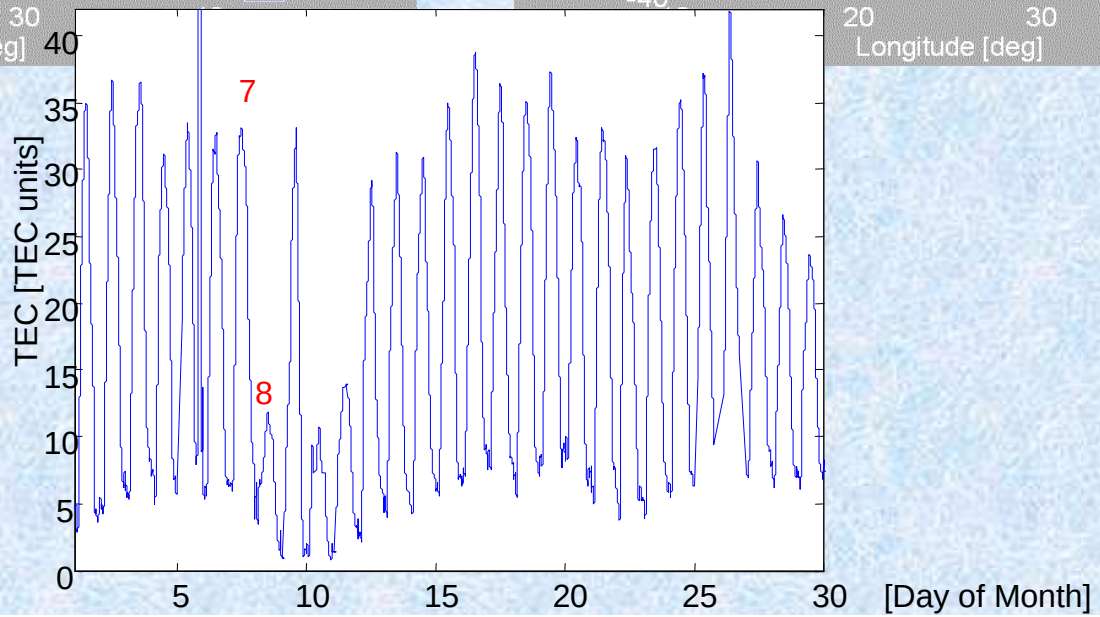
Geomagnetic storm 7-8 Nov 2004



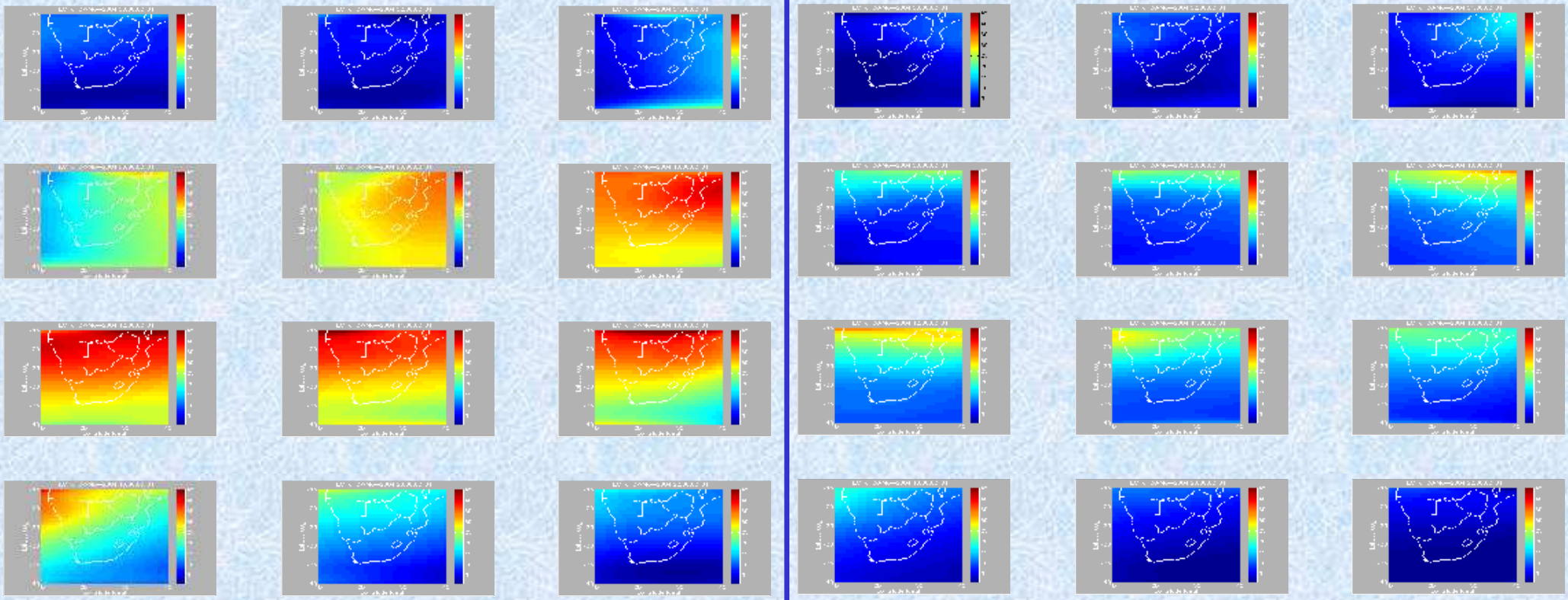


GPS TEC maps in 2 hour increments

Spherical Harmonic Interpolation over 24 hours

7 Nov, 2004

8 Nov, 2004

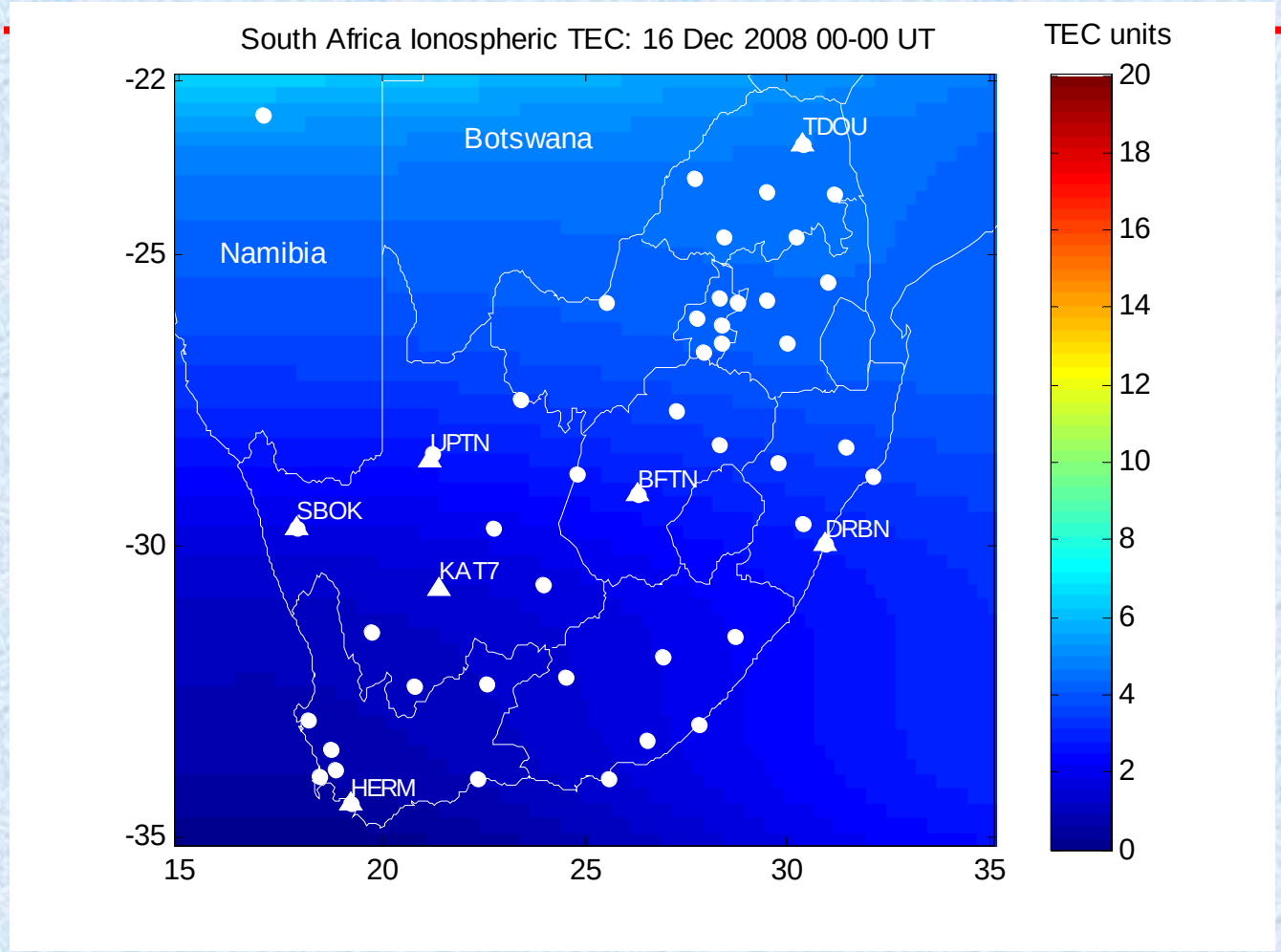


TEC maps determined from 24 hours of GPS data decimated to 60 s, and interpolated using a 12th order Spherical Harmonic Model. Maps shows snapshots at 2 hour intervals.

Real-time Ionospheric TEC mapping

CDSM TEC processor: Cape Town

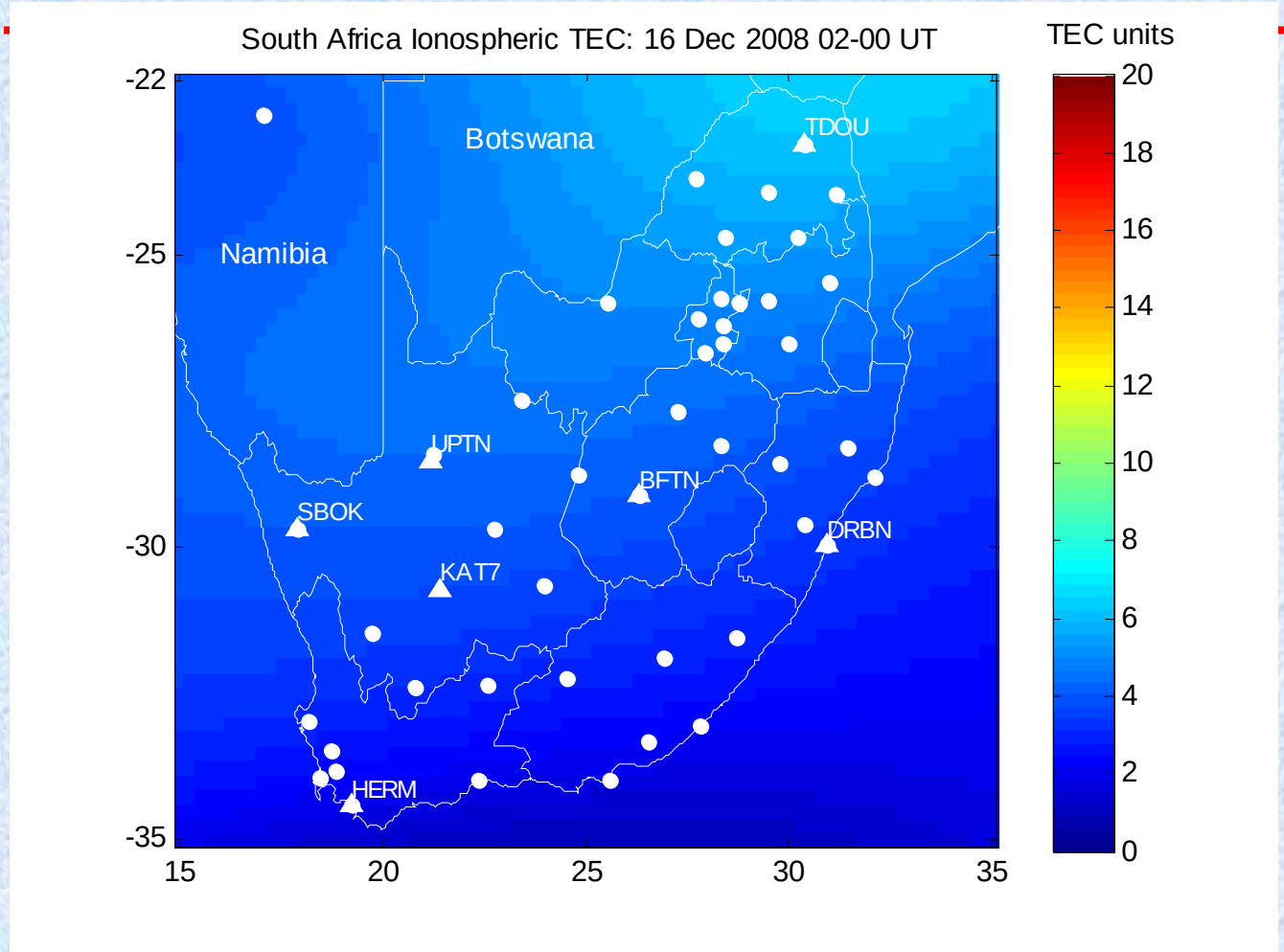
Real-time (1-hour) GPS TEC maps
using HERMION Algorithm



TEC maps determined from 1 hour of GPS data decimated to 60 s, and interpolated using the MIDAS algorithm developed at the University of Bath, UK

http://www.hmo.ac.za

Real-time (1-hour) GPS TEC maps
using HERMION Algorithm



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Real-time (1-hour) GPS TEC maps
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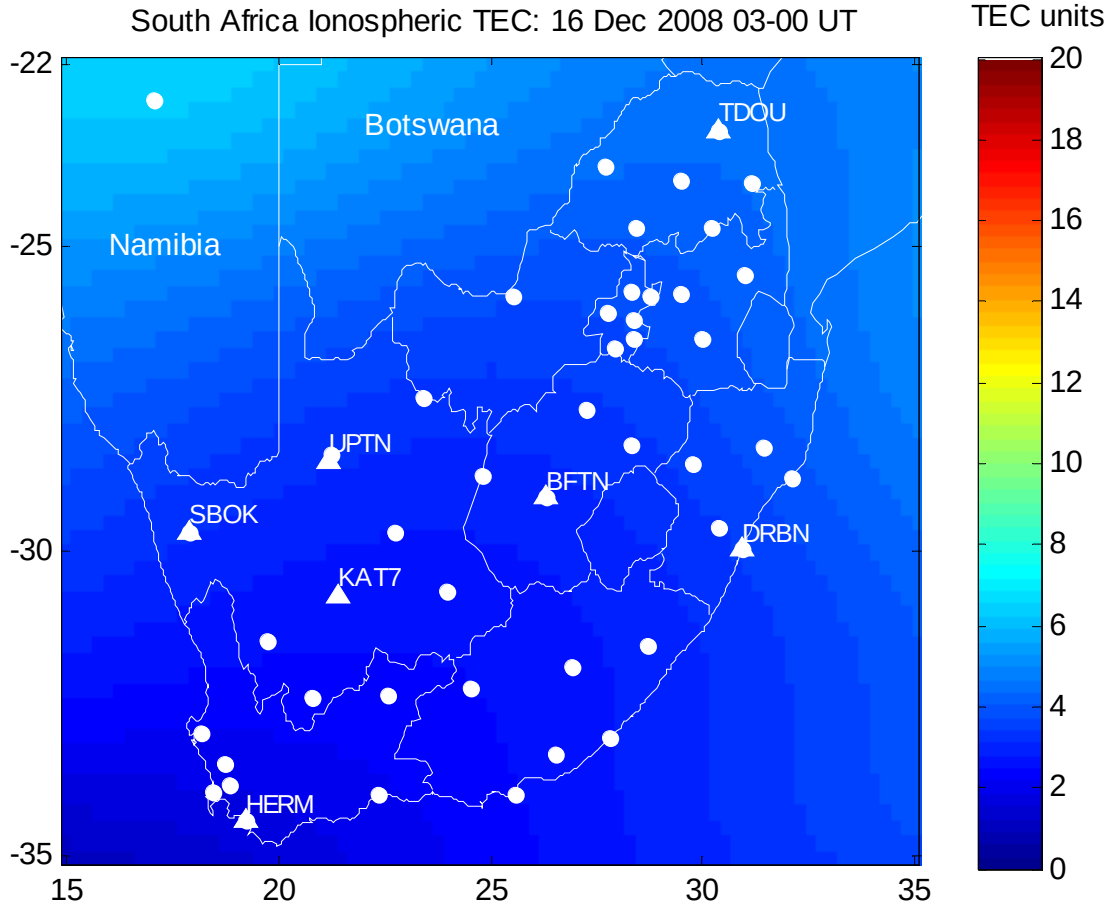

TEC maps determined from 1 hour of GPS data decimated to 60 s, and interpolated using the MIDAS algorithm developed at the University of Bath, UK

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Real-time (1-hour) GPS TEC maps
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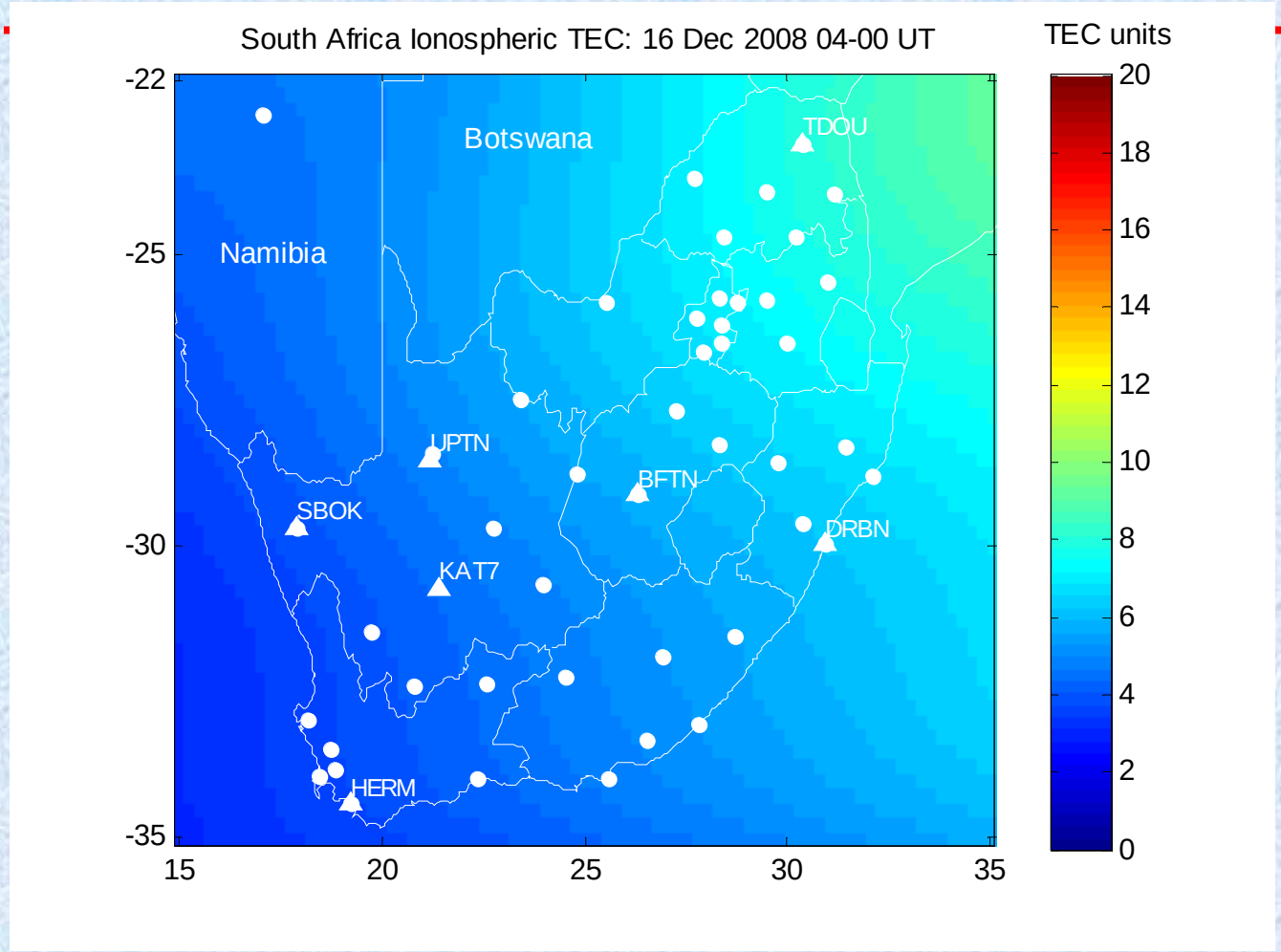

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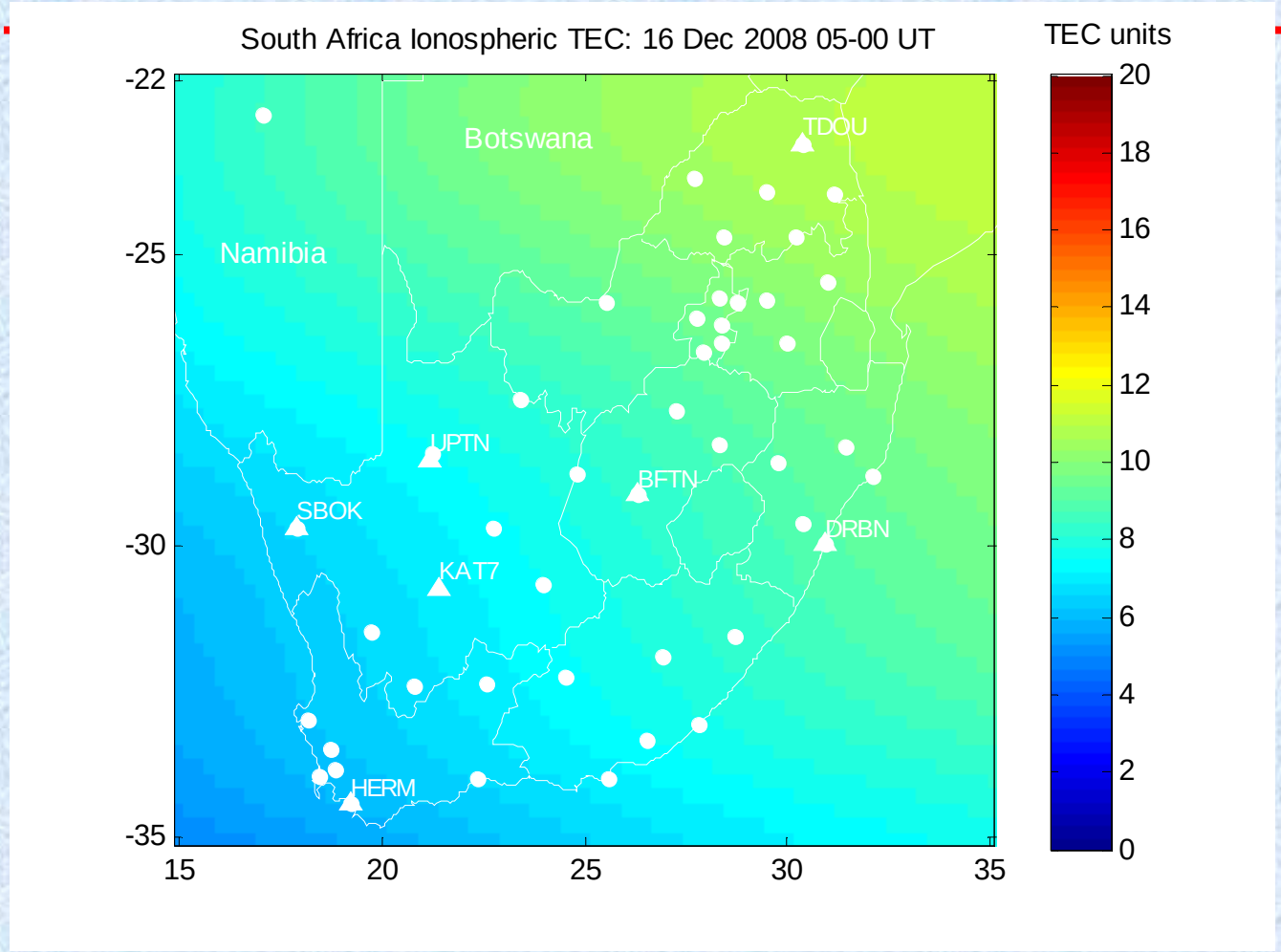
Real-time (1-hour) GPS TEC maps
using HERMION Algorithm



TEC maps determined from 1 hour of GPS data decimated to 60 s, and interpolated using the MIDAS algorithm developed at the University of Bath, UK

http://www.hmo.ac.za

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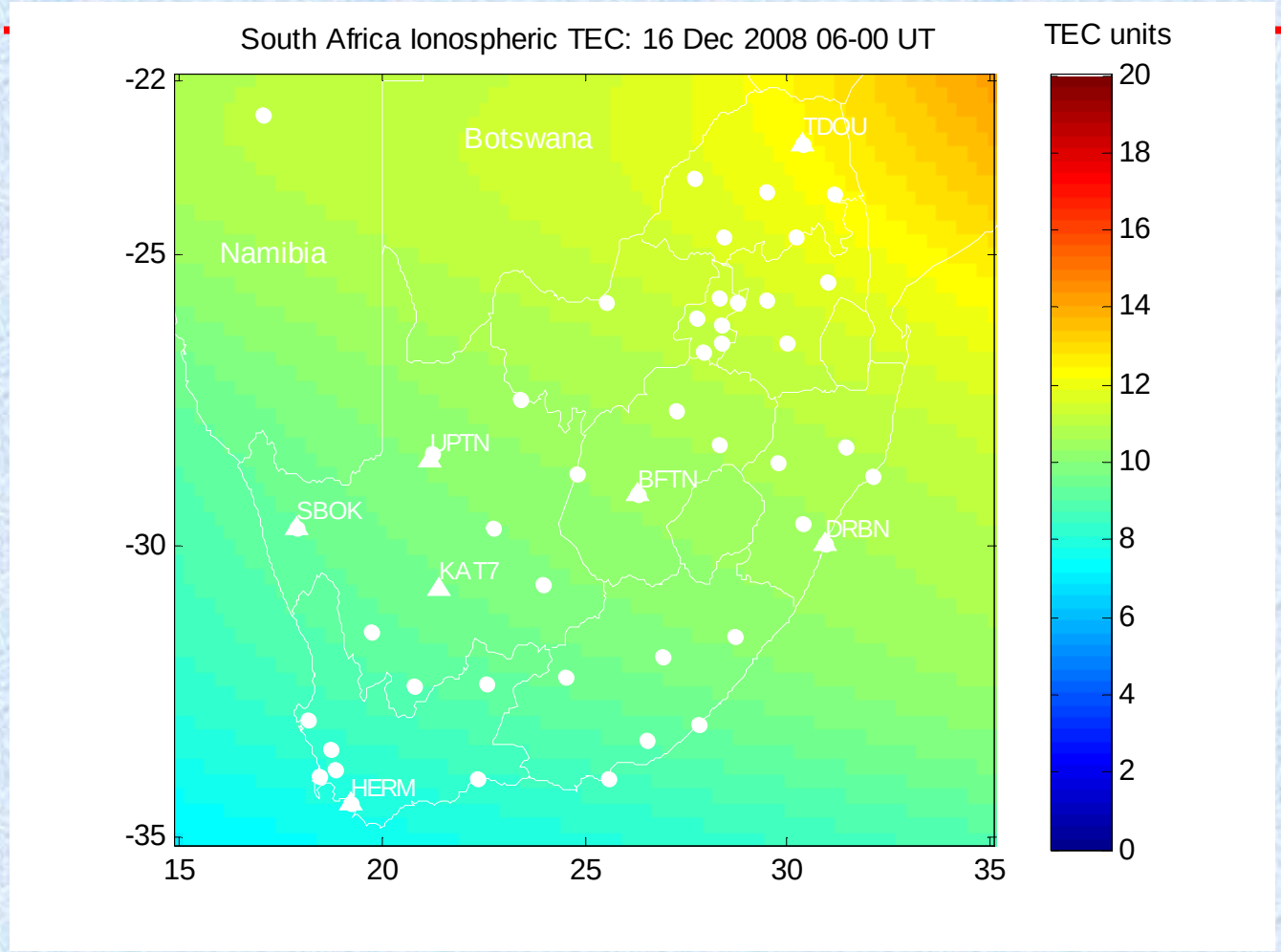

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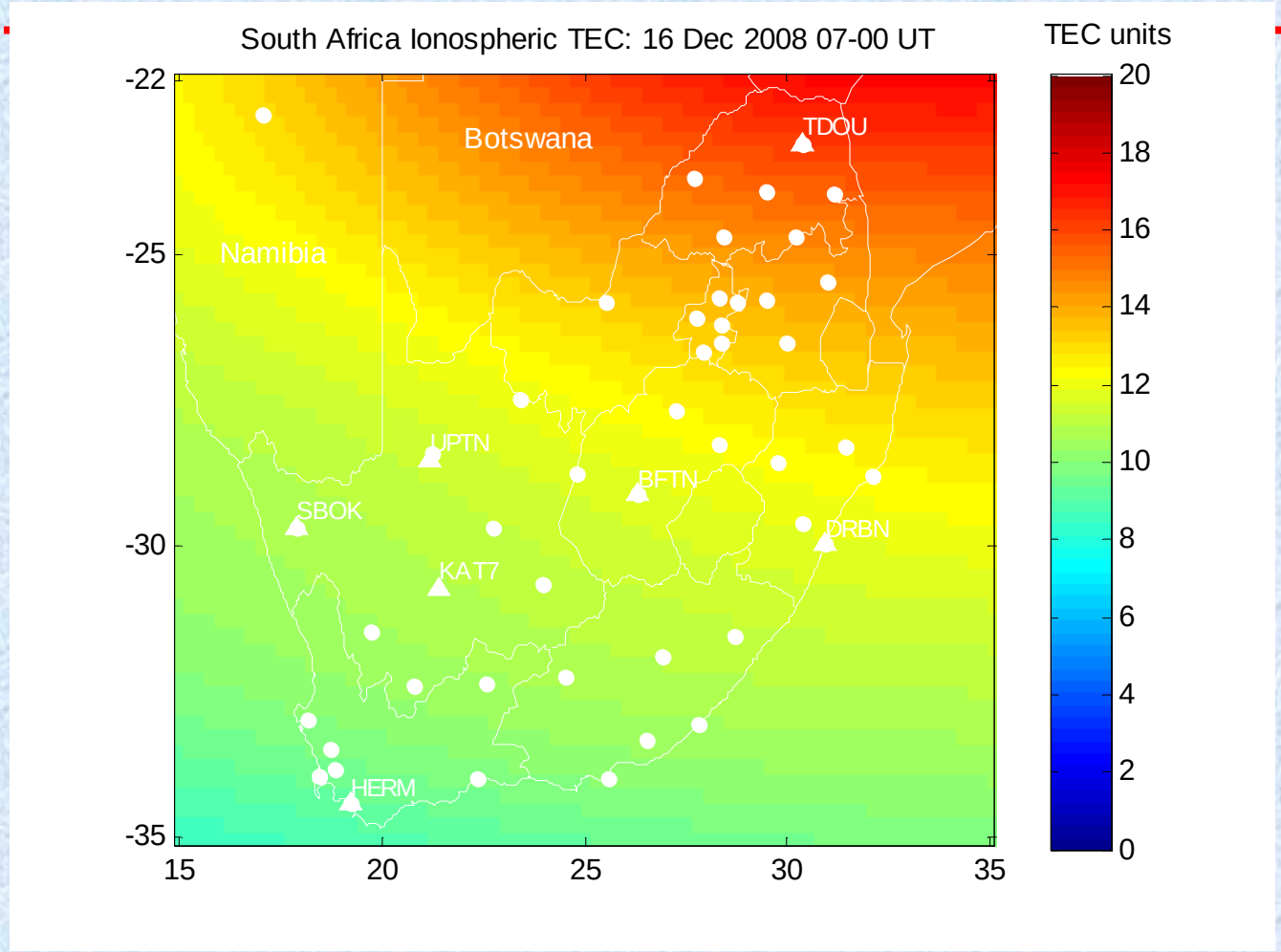

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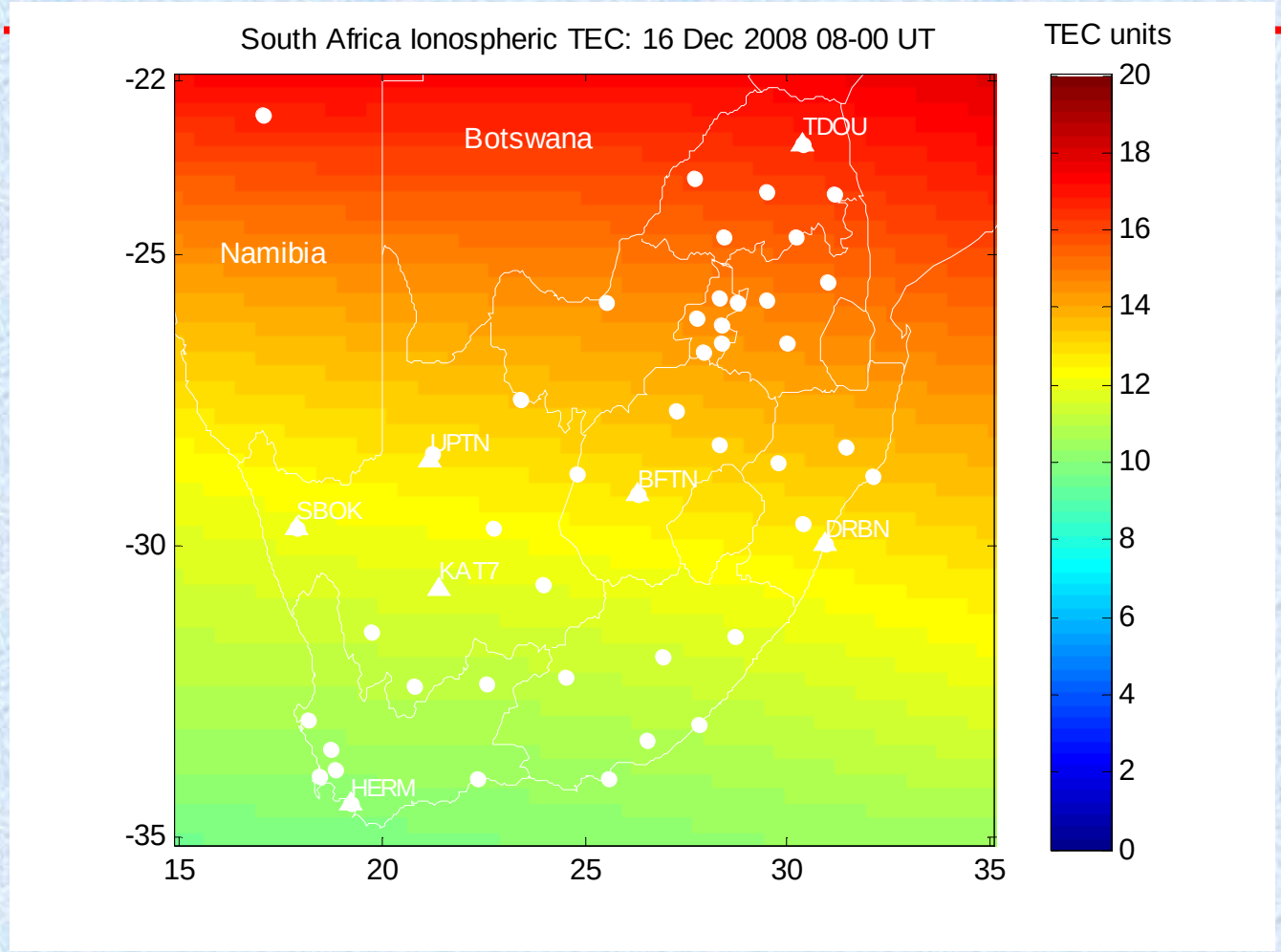

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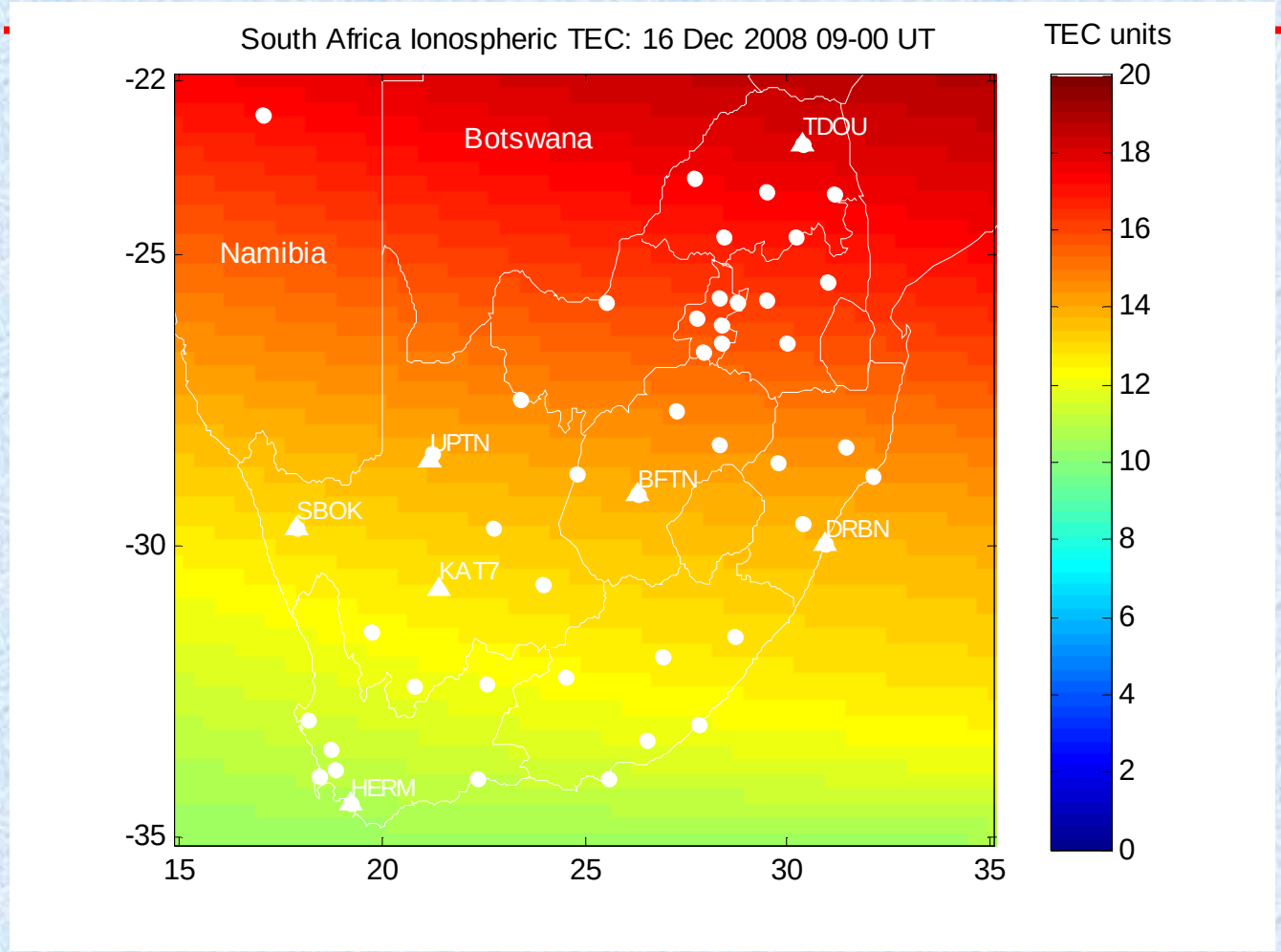

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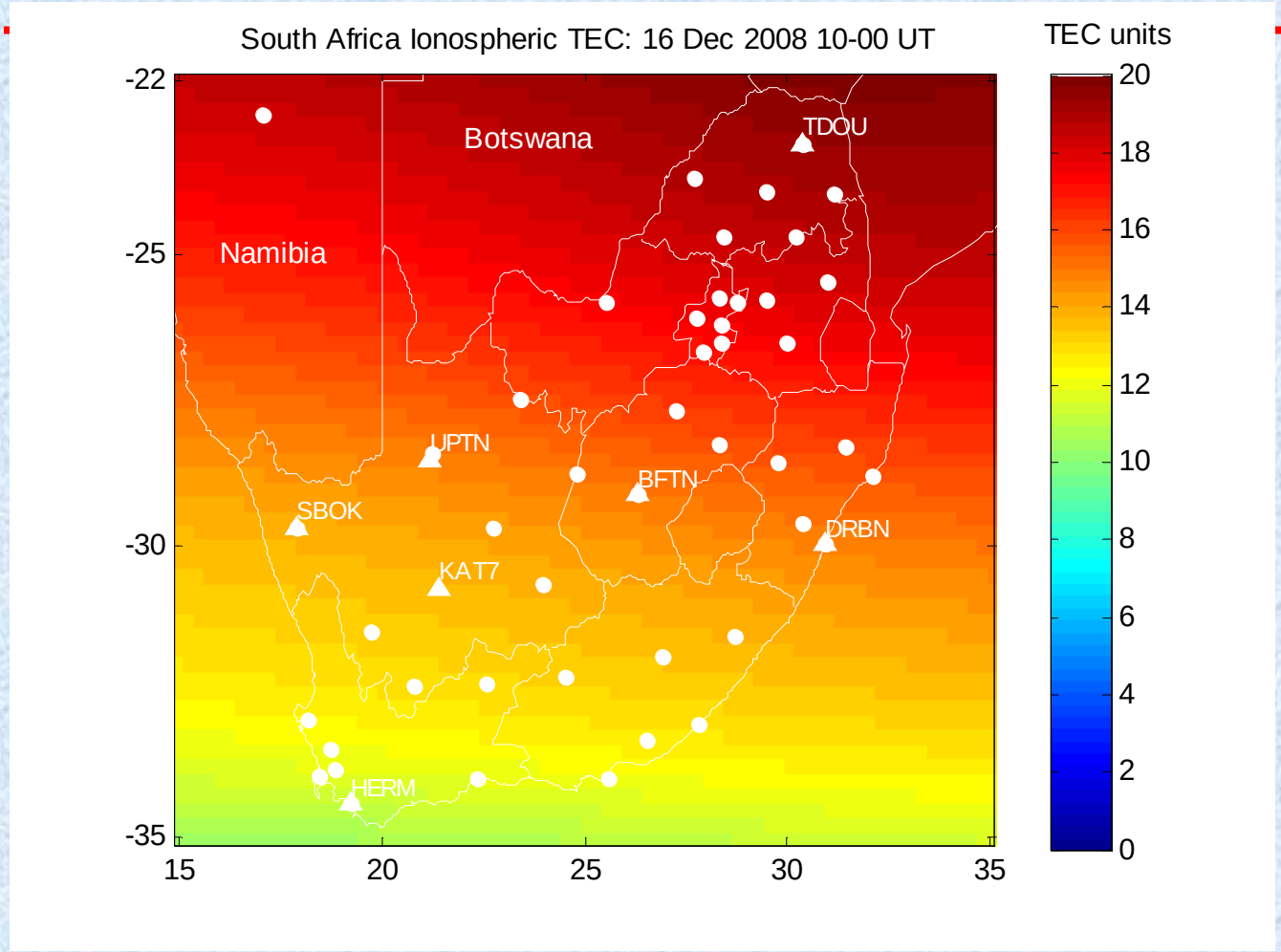

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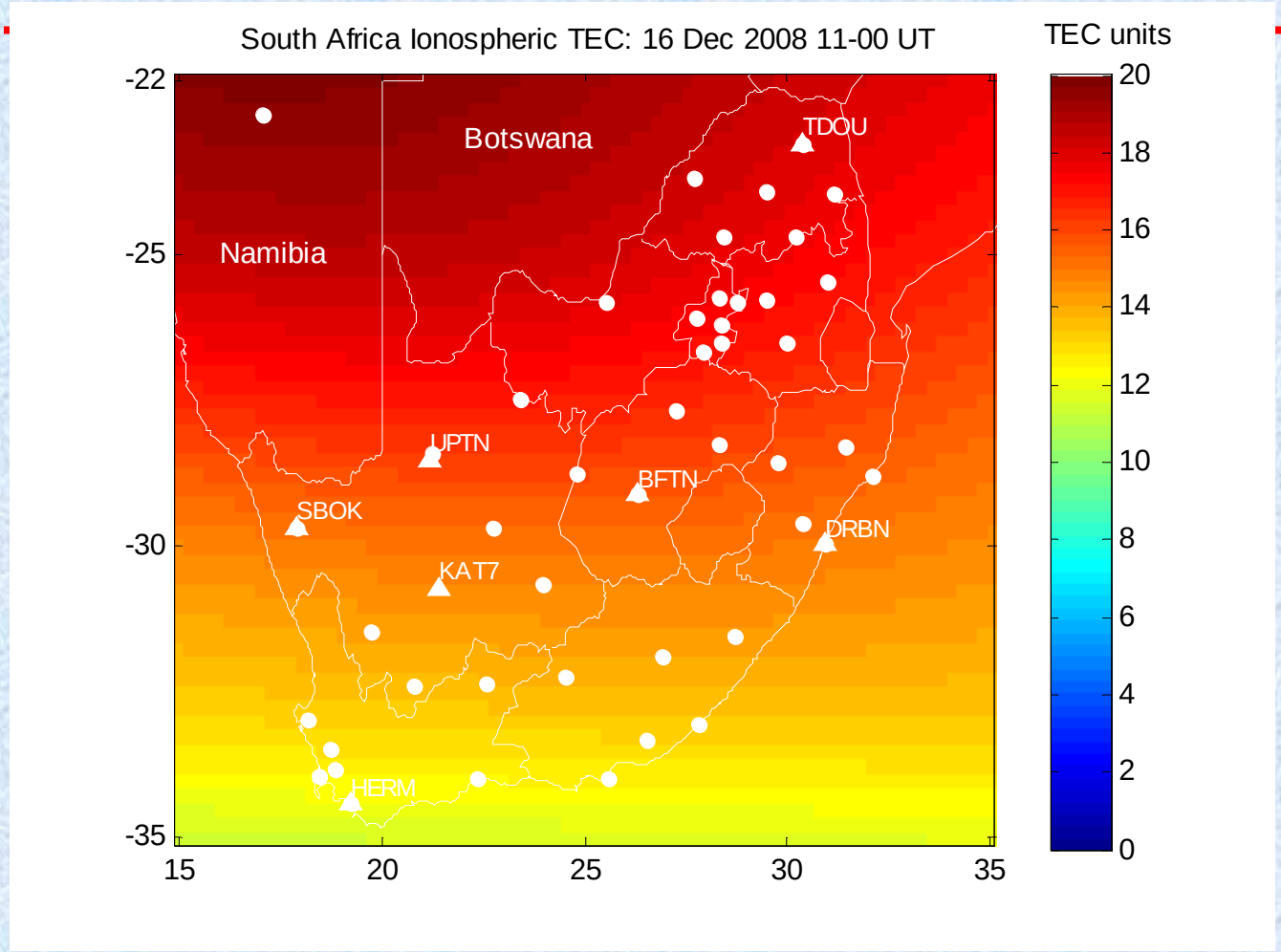

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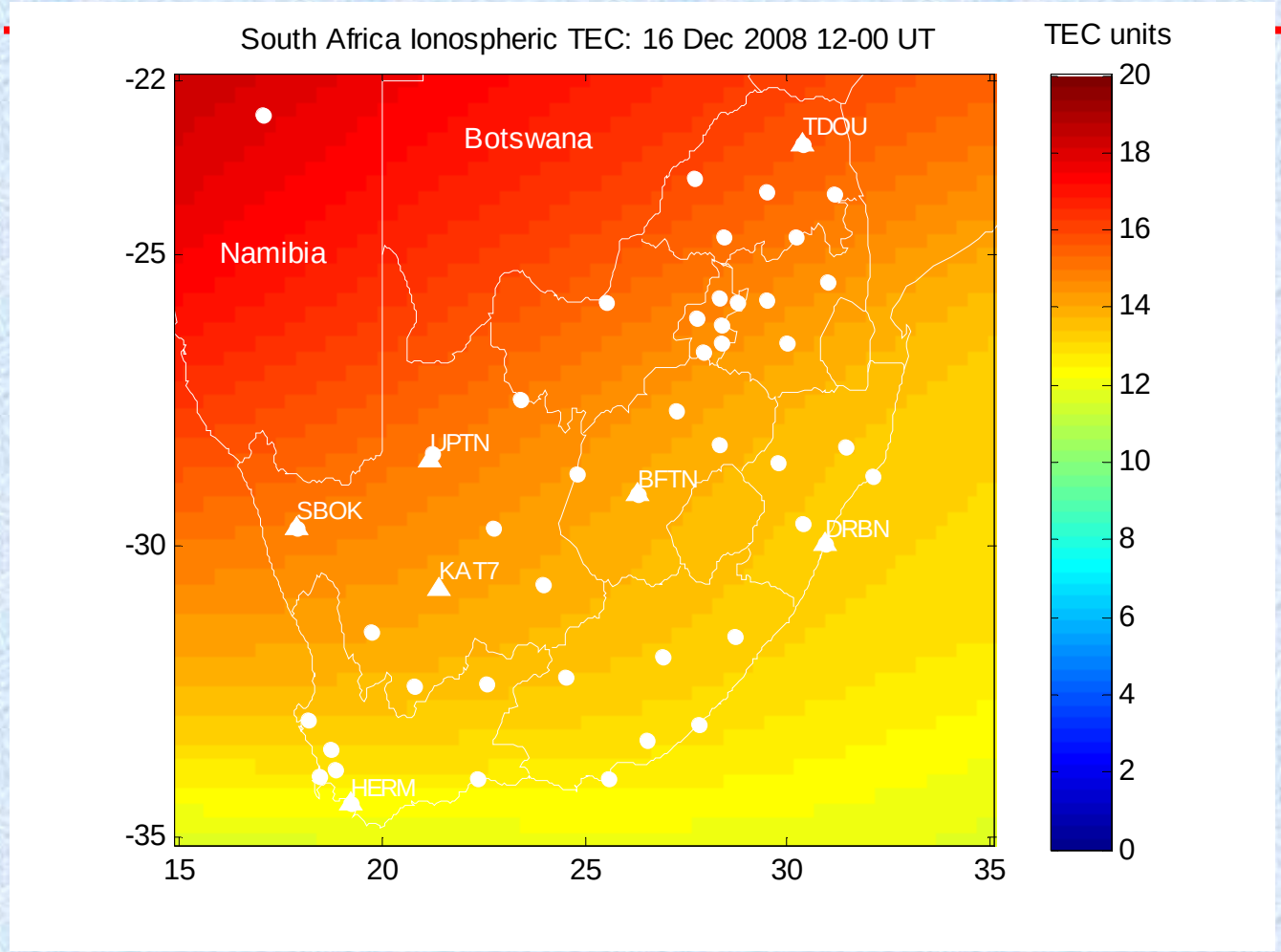

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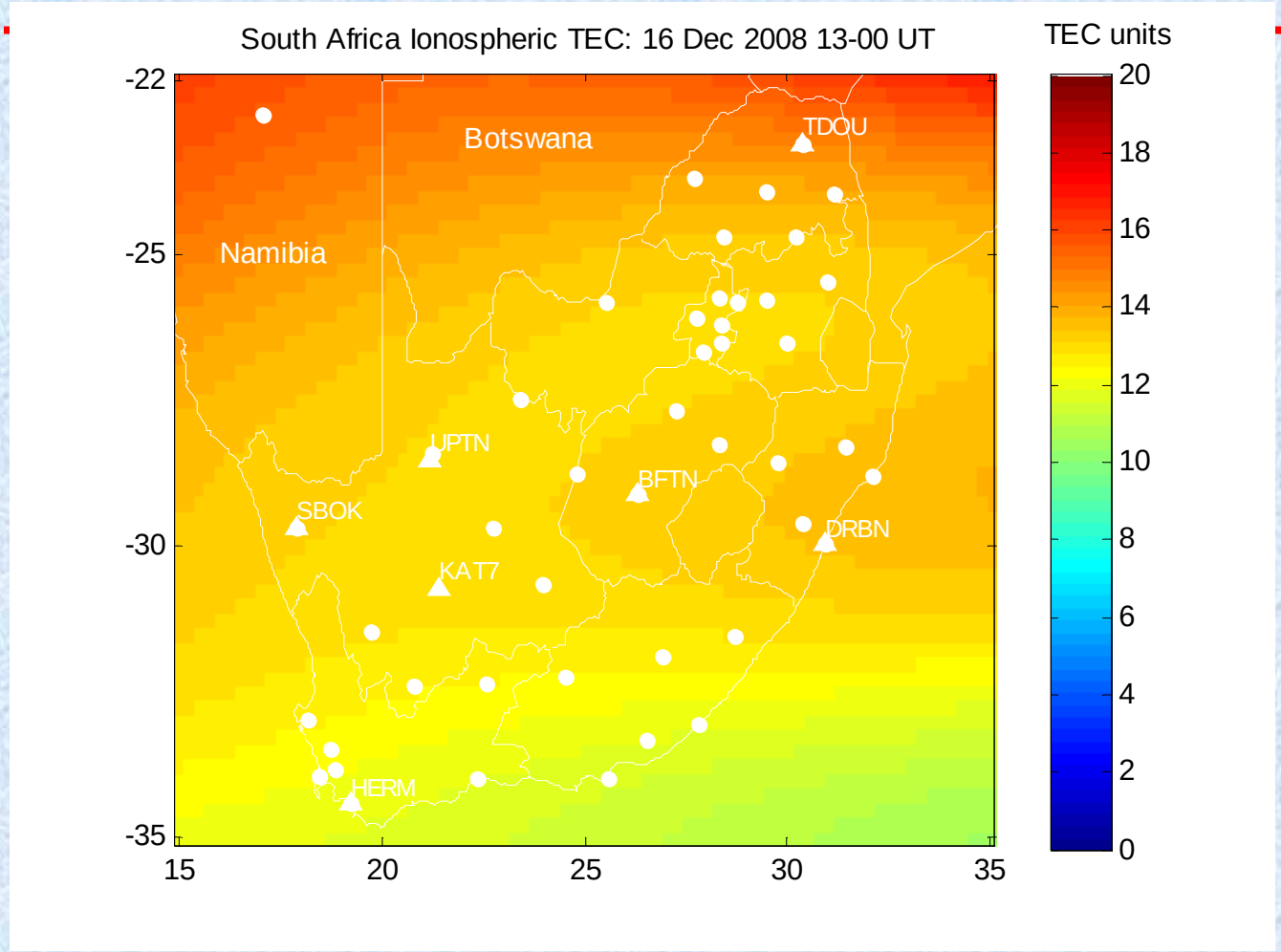

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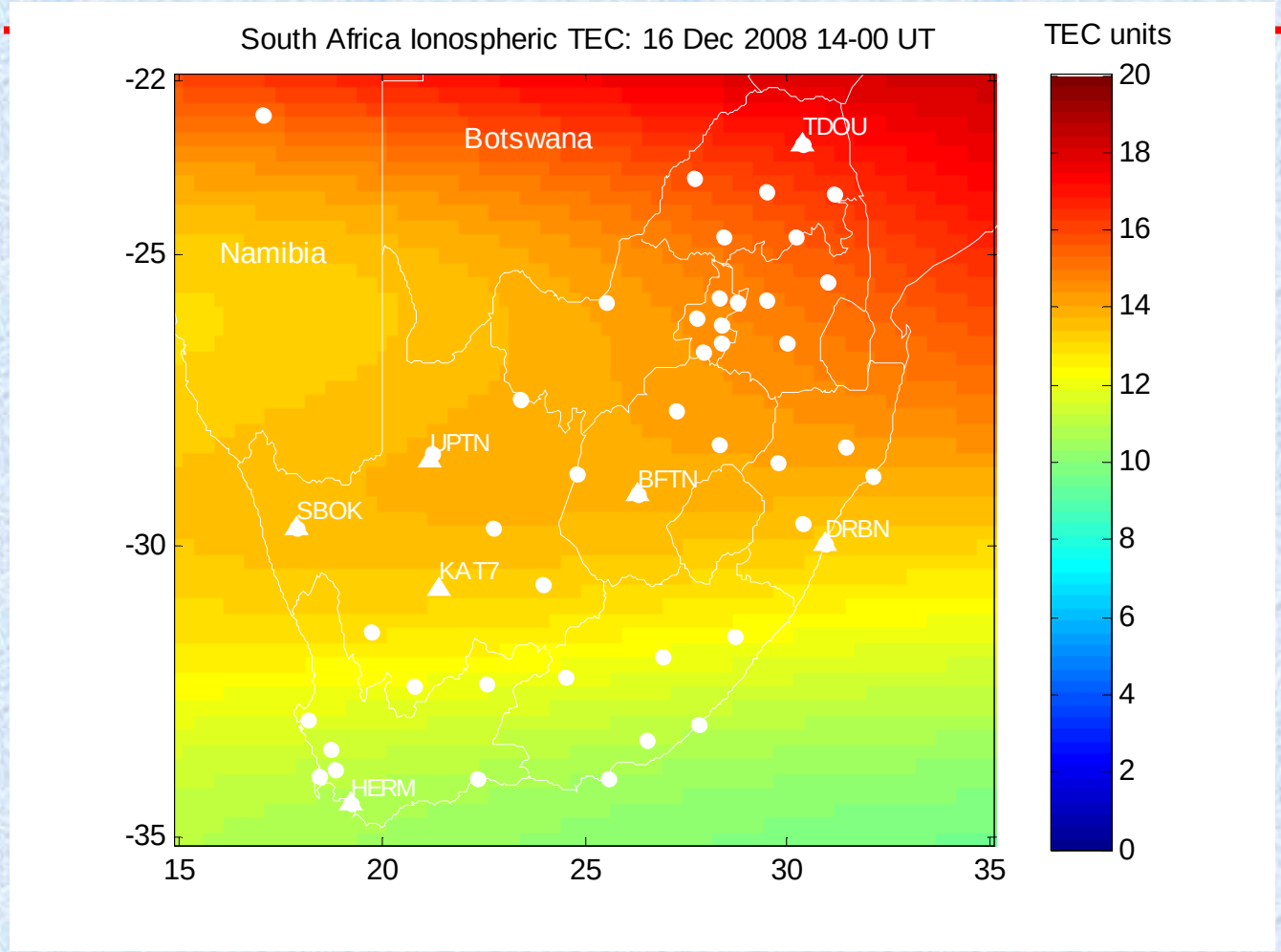

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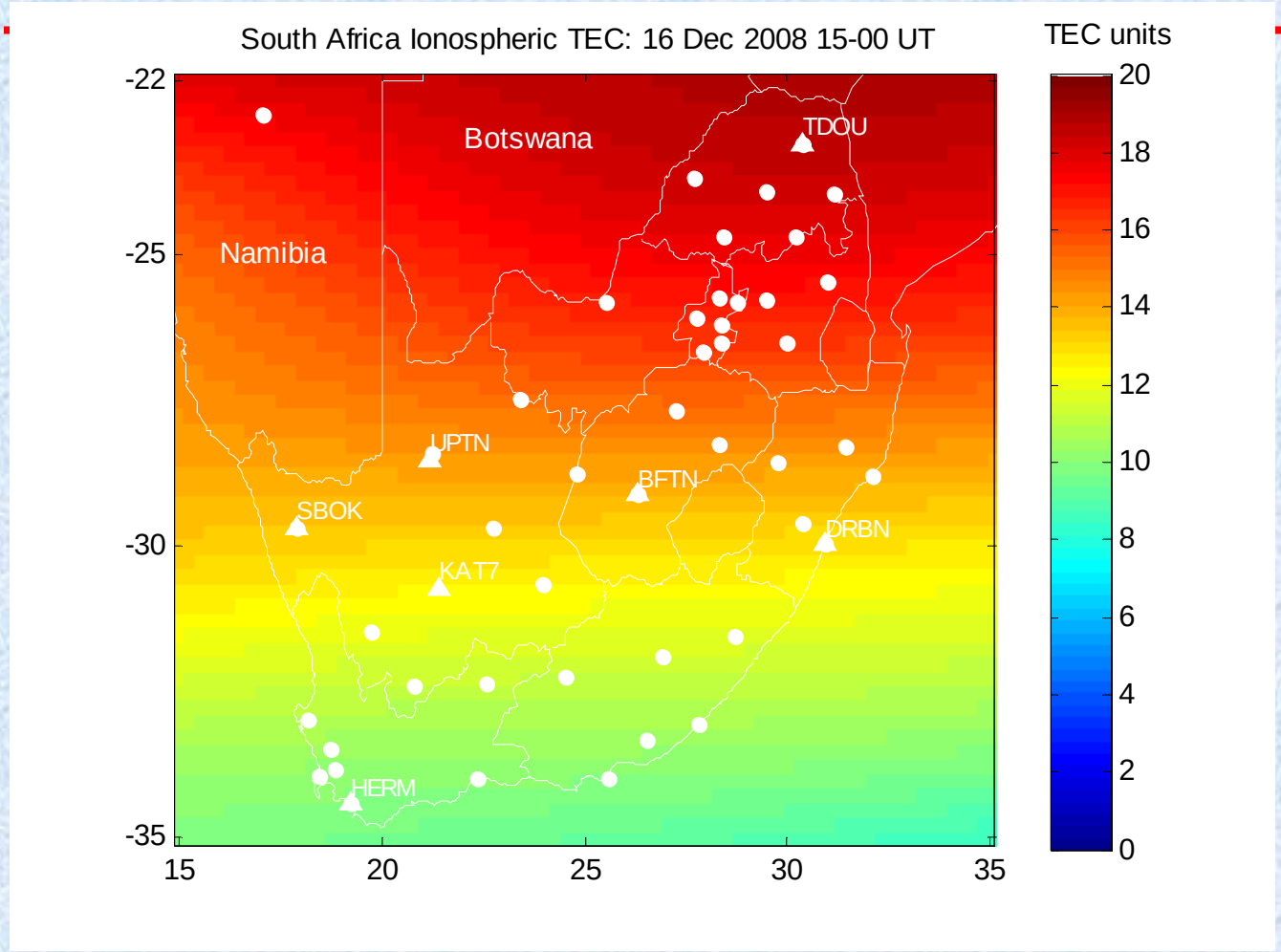

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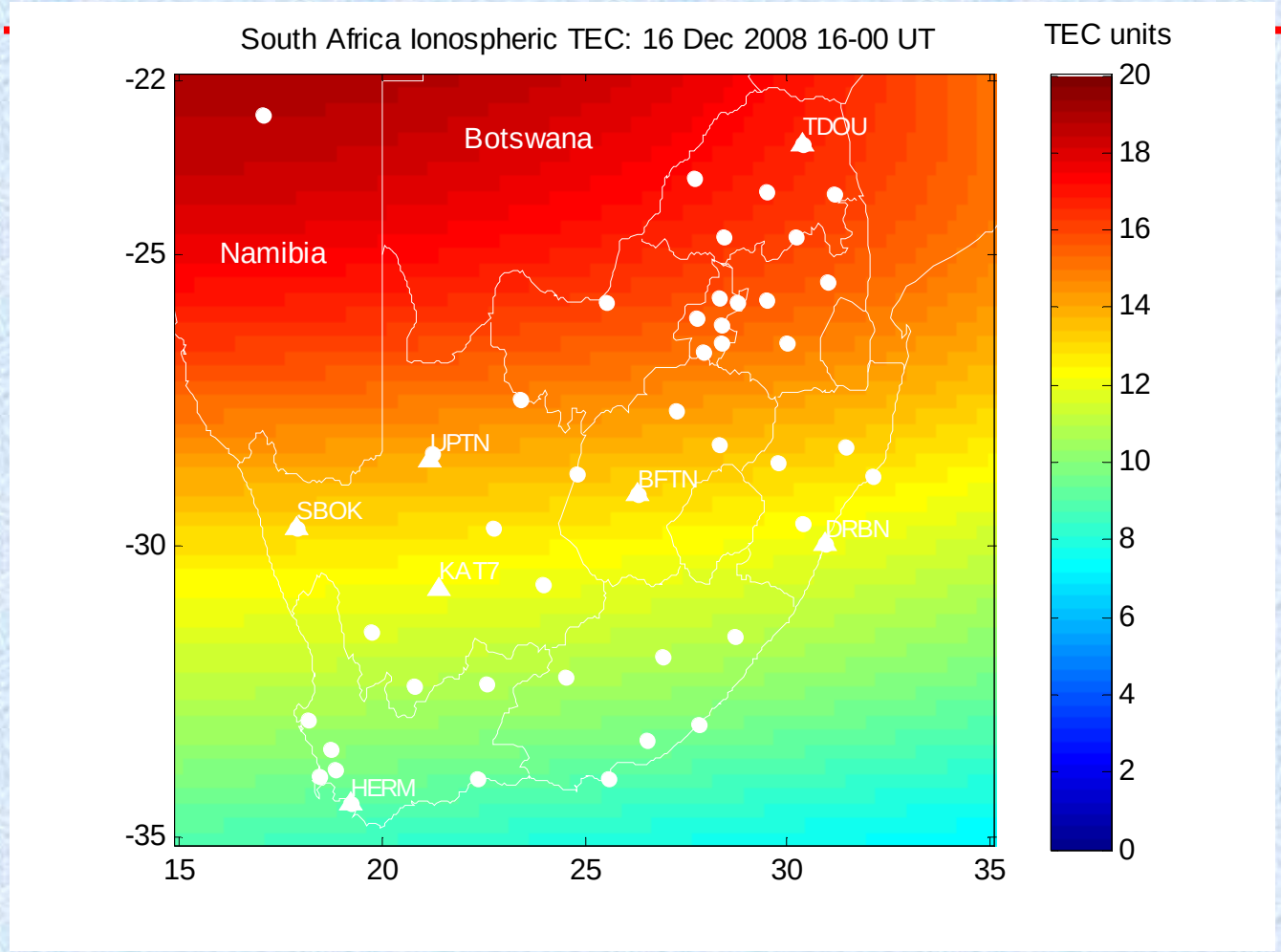

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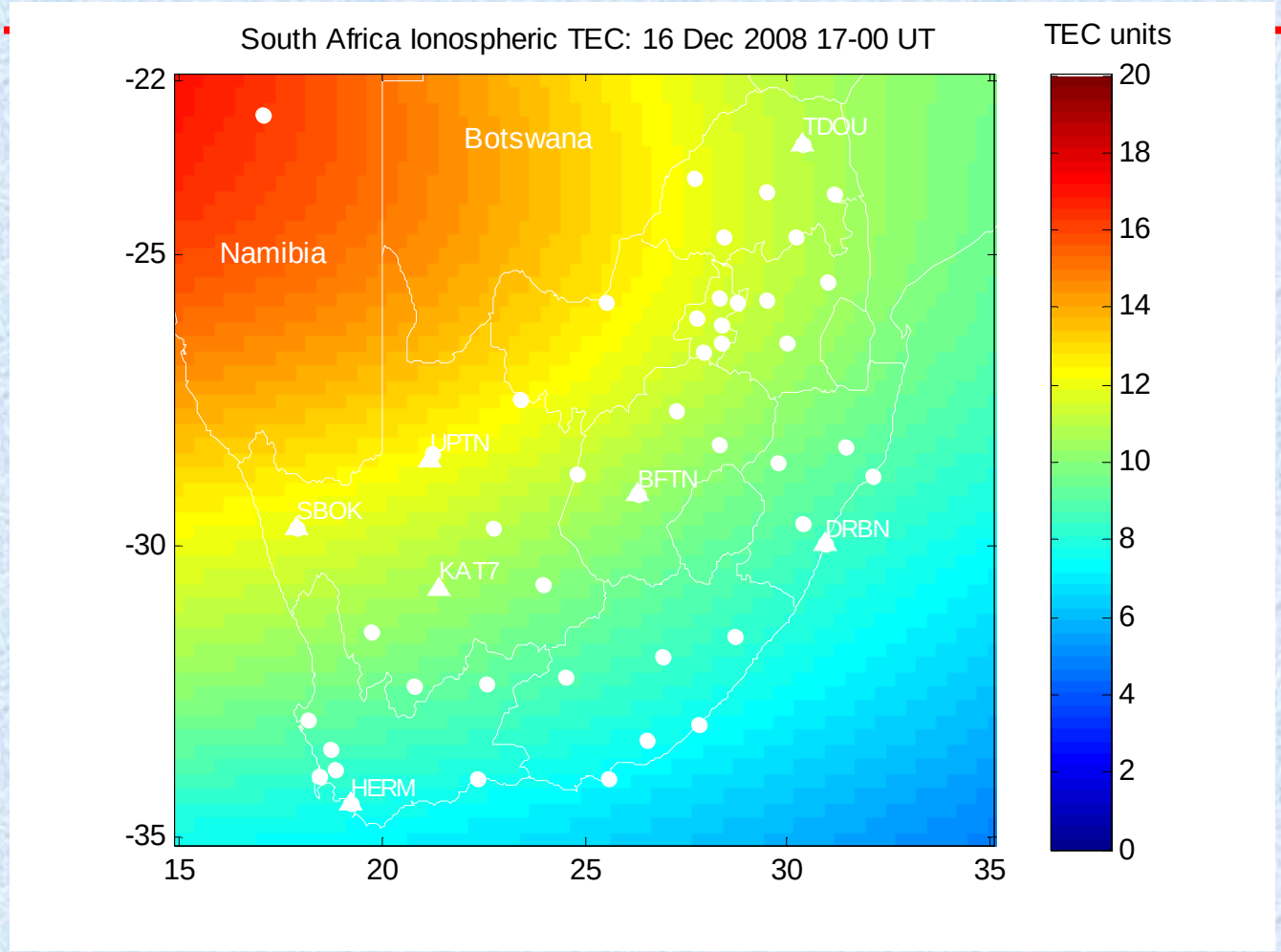

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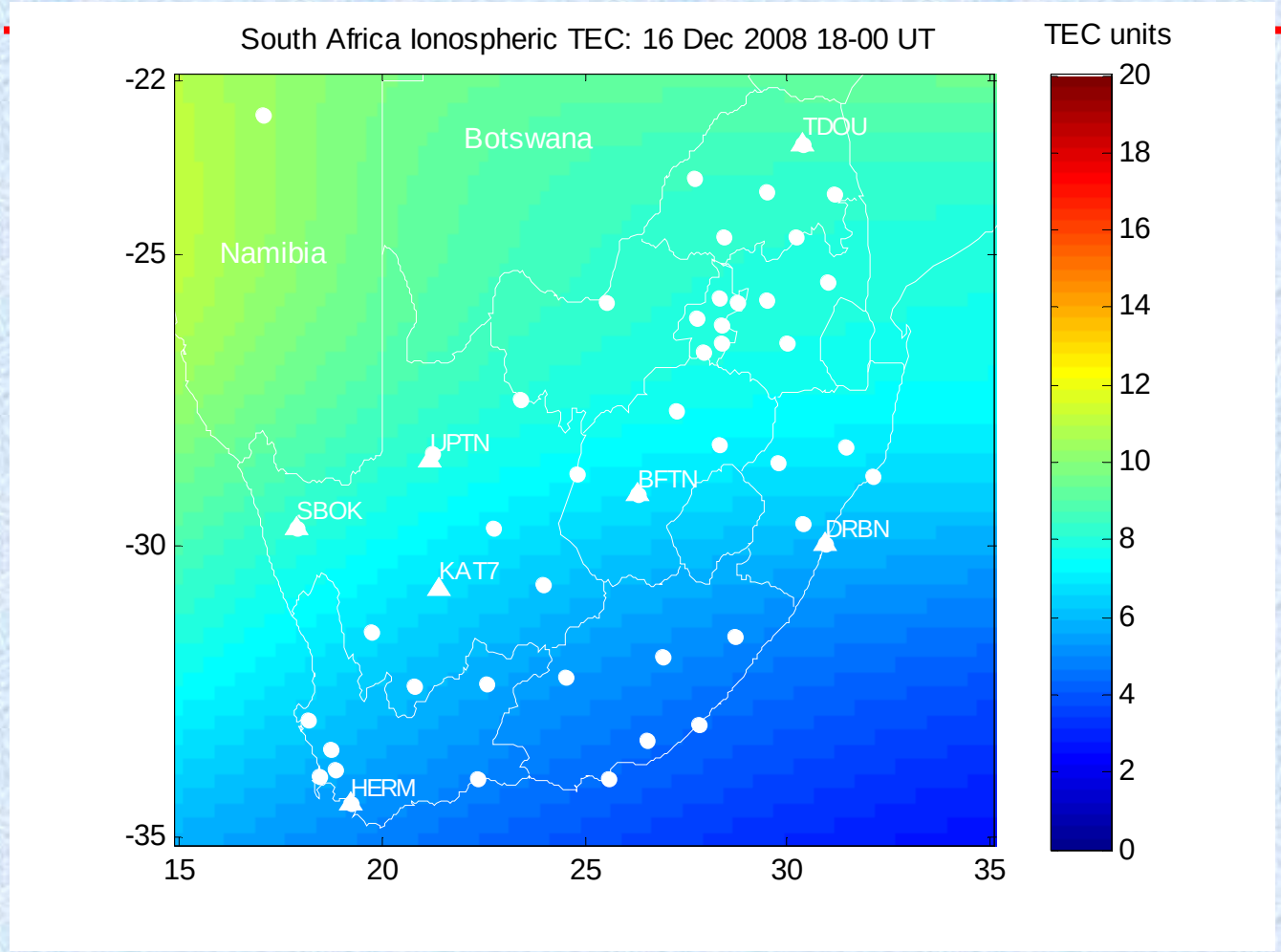

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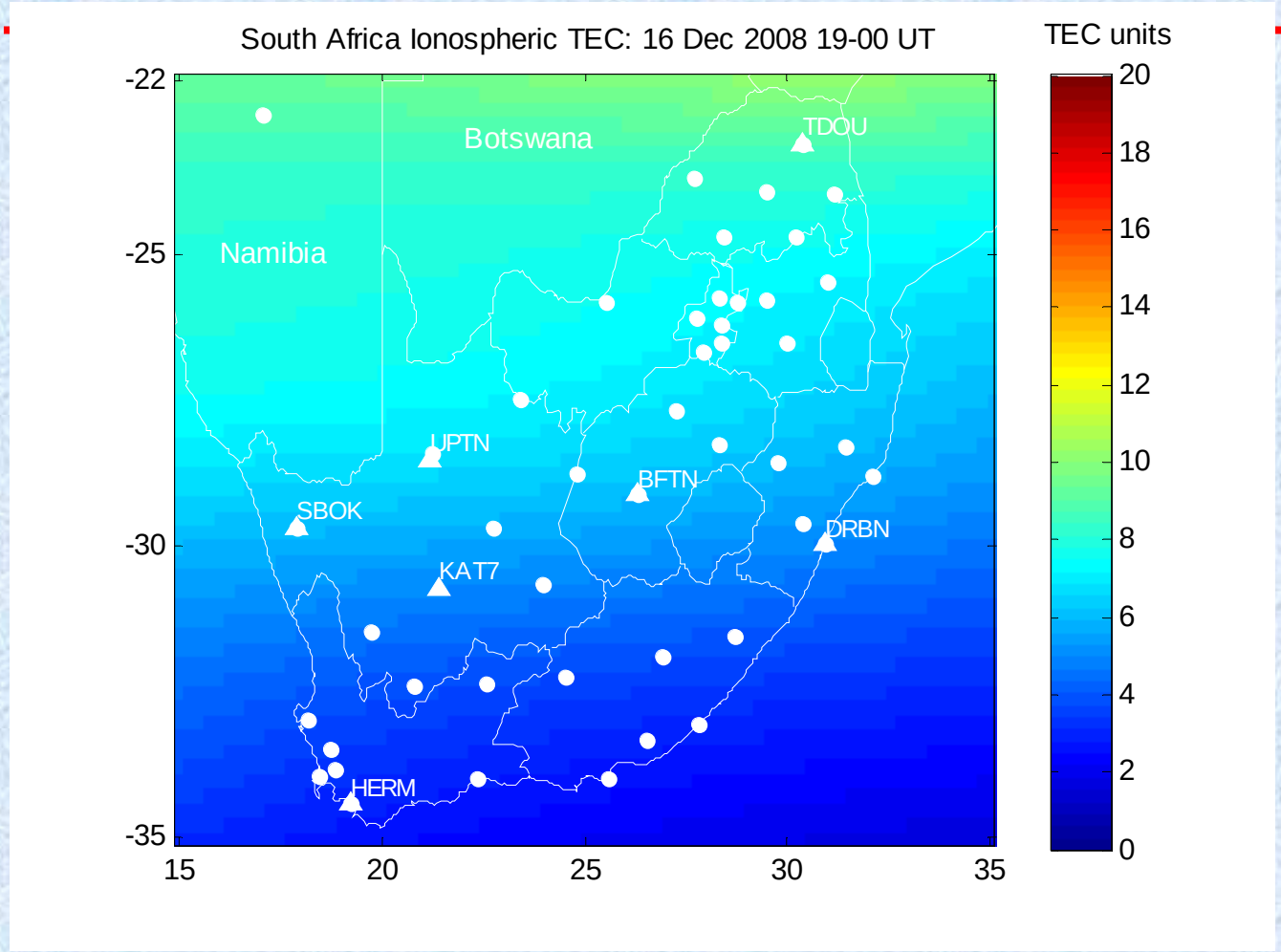

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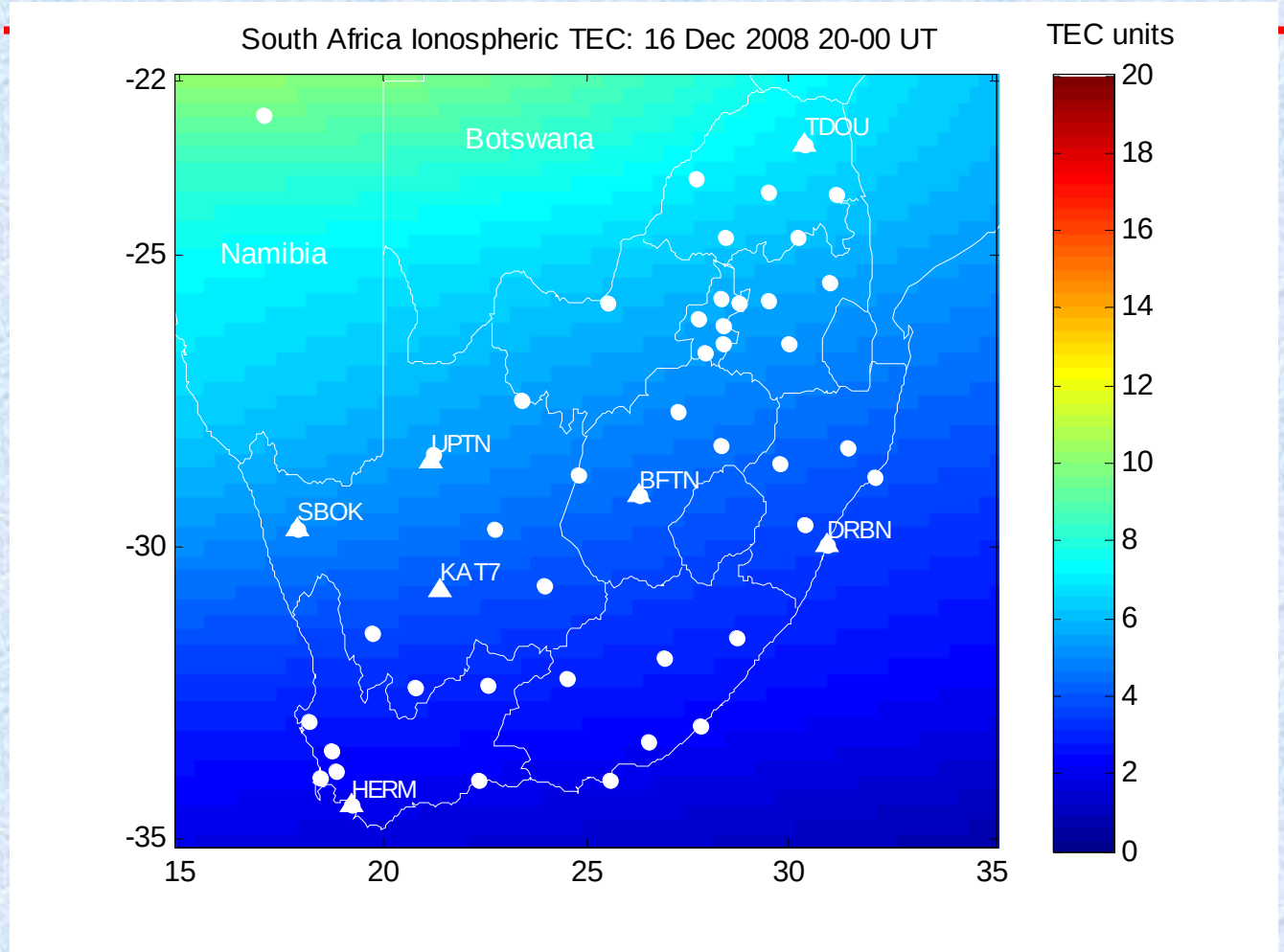

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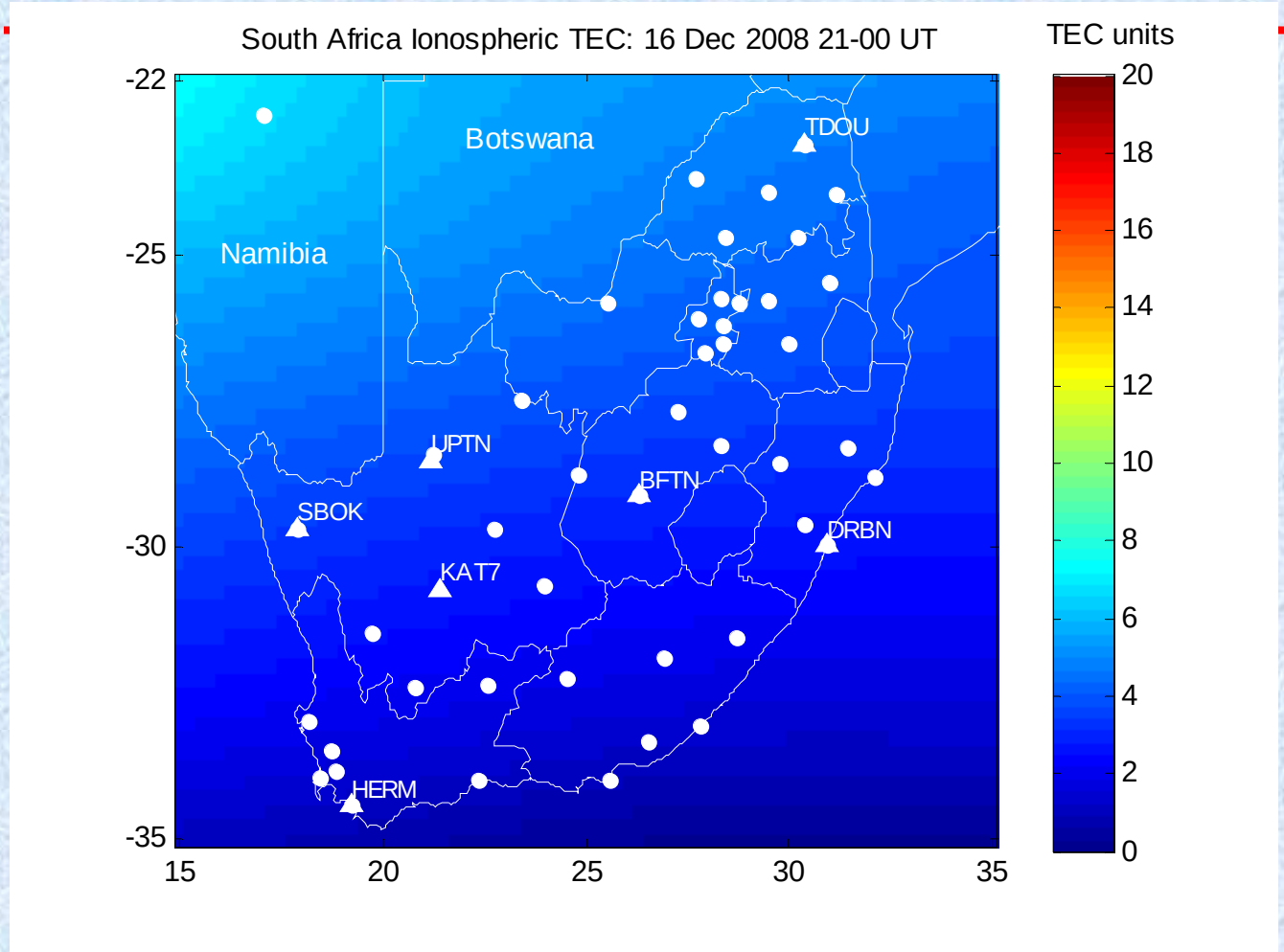

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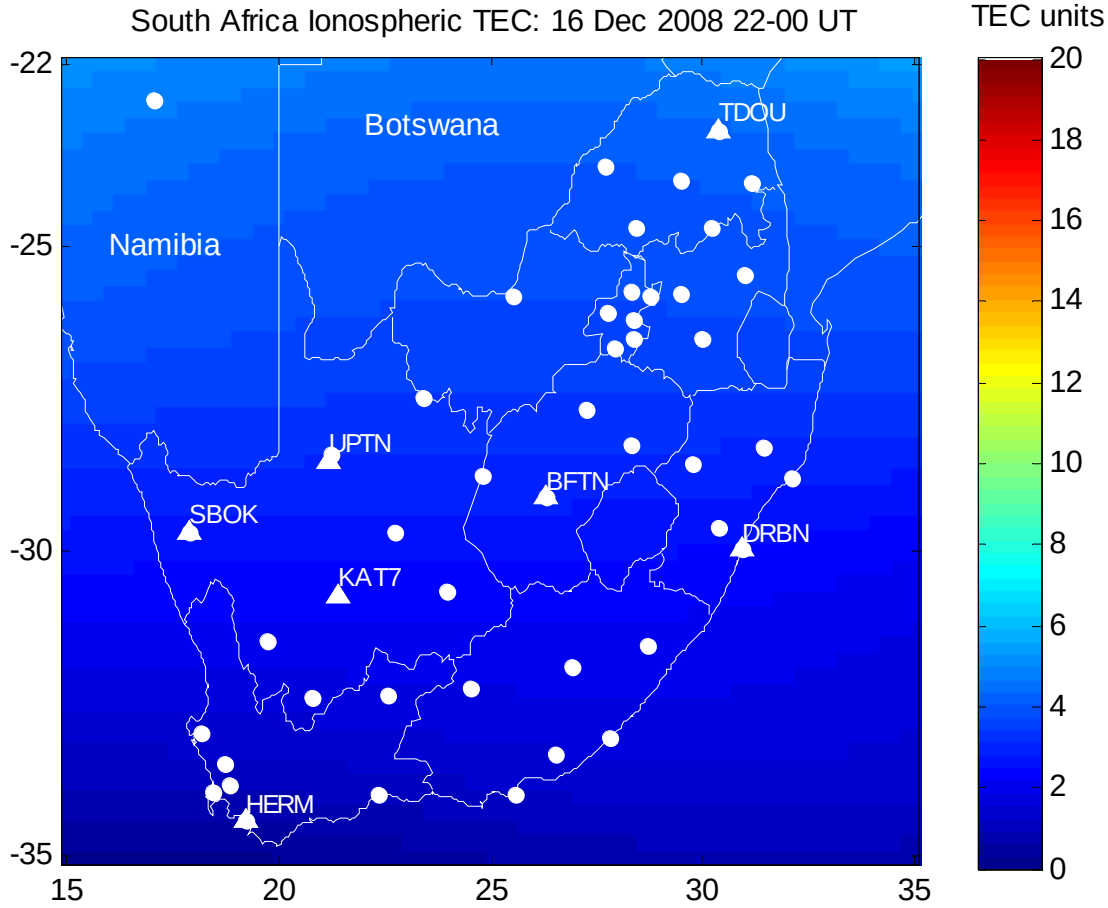

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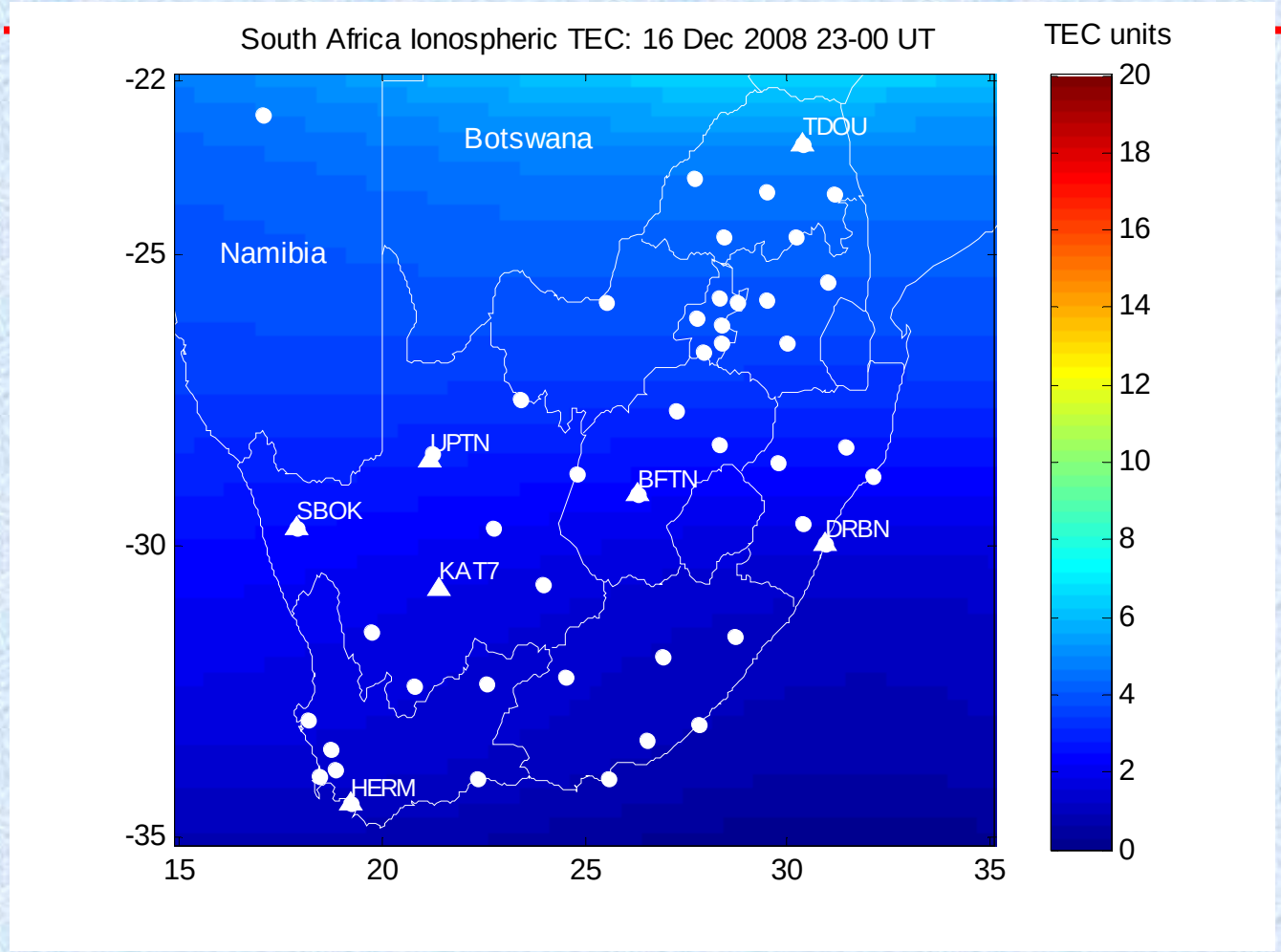

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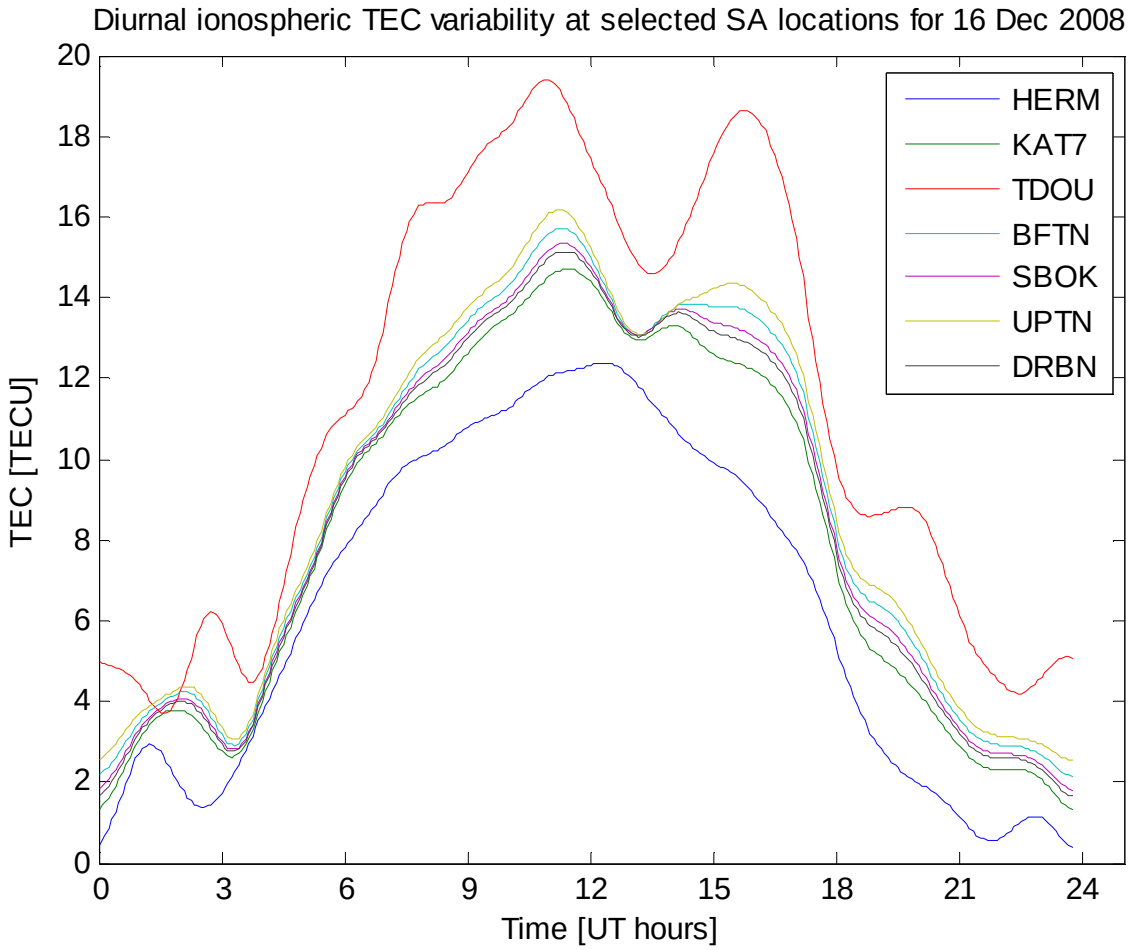

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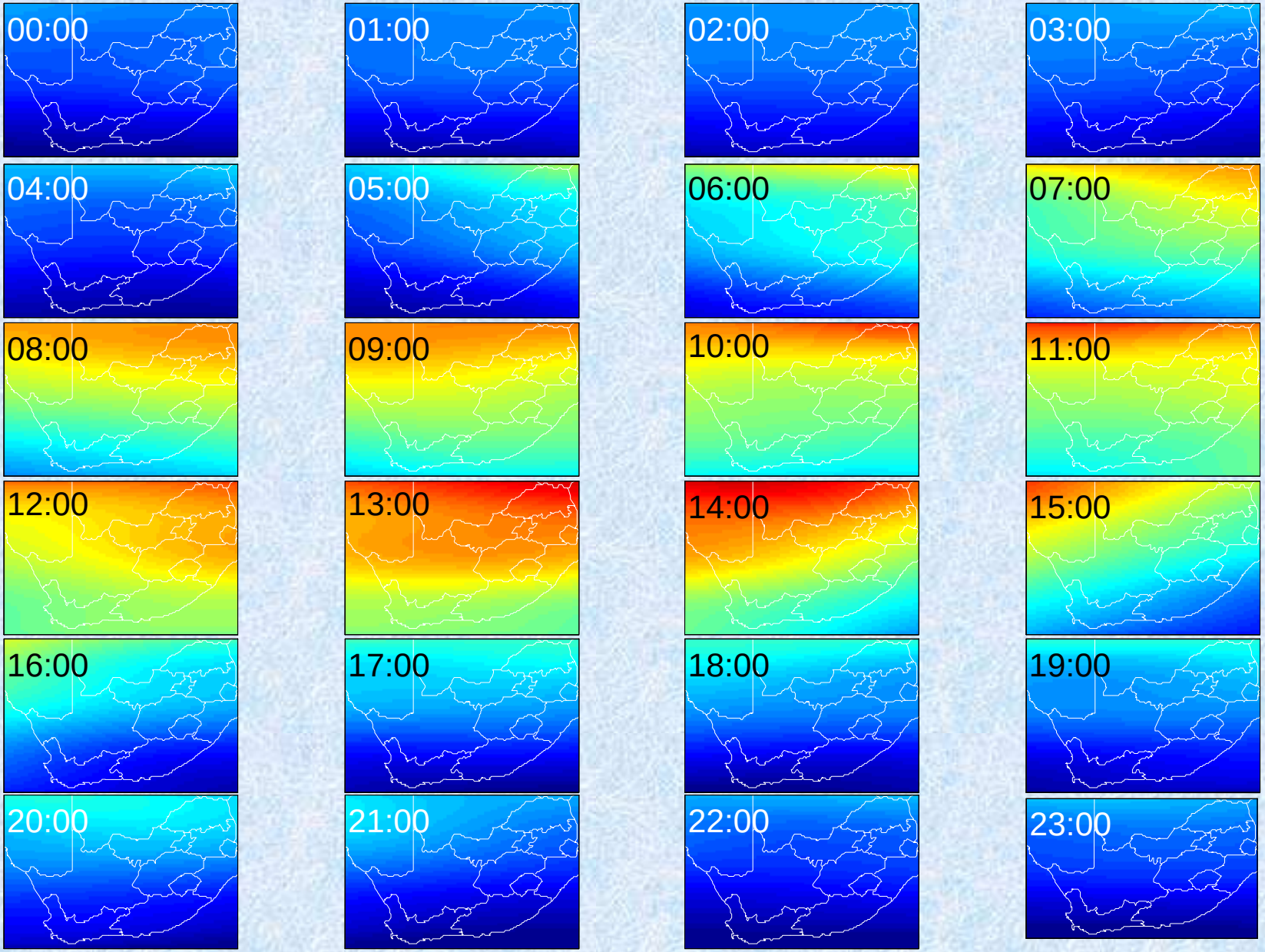
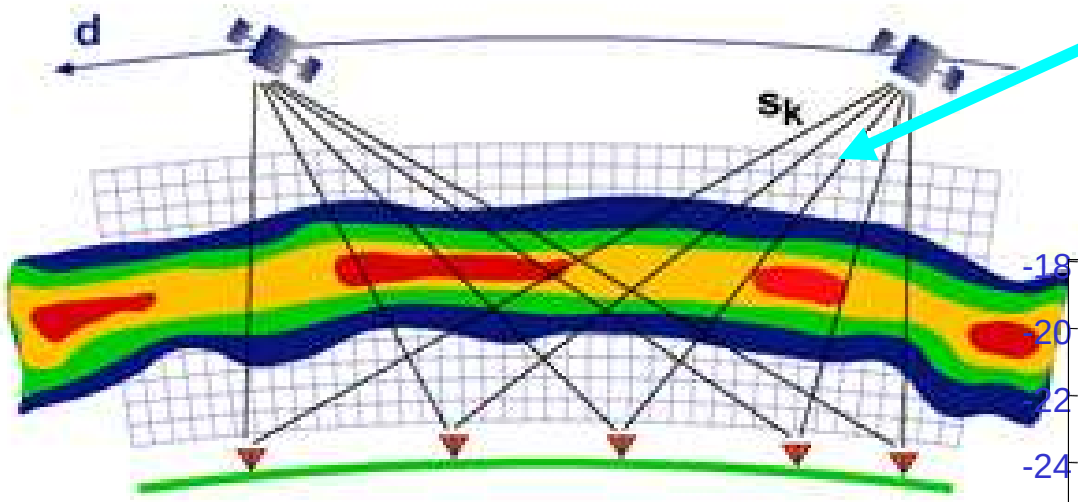


GNSS-derived 2D TEC images over South Africa for 7 May 2008.

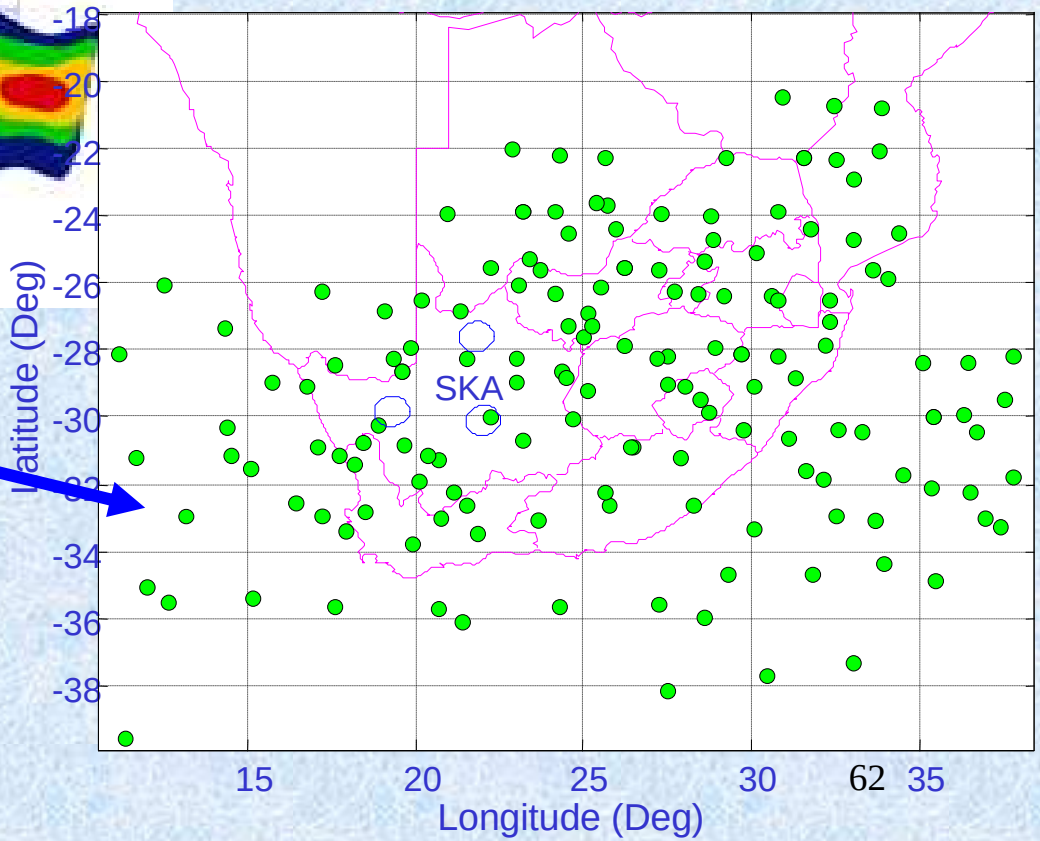
Ionospheric Tomography

Computerised Ionospheric Tomography (CIT)



Multiple ray paths through ionosphere

IPP distribution, 30 CSDM GPS receivers. 11 April 2003
158 TEC Observations at 12:00 UTC



Multiple observations per second

$$N_e(z) = \sum_{j=1}^{N} x_j f_j(z)$$

$$[TEC] = [A][X]$$

$$[X] = [A]^{-1}[TEC]$$

Computerised Ionospheric Tomography (CIT)

$$N_e(z) = \sum_{j=1}^{N} x_j f_j(z)$$

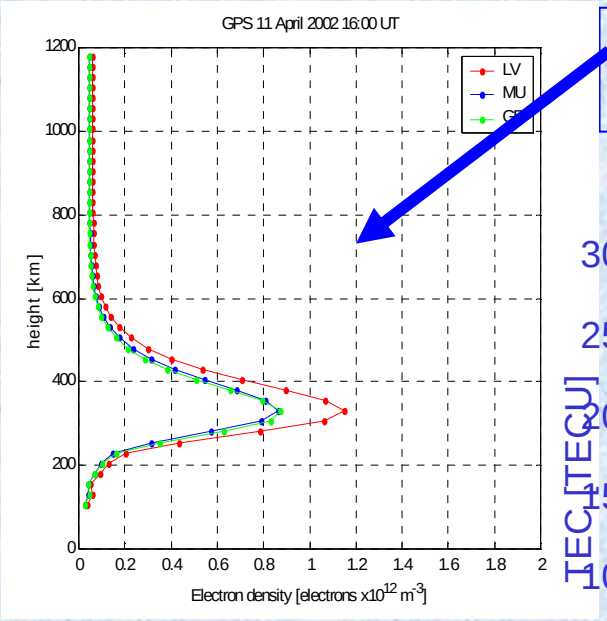
$$f_j(z) = \begin{cases} 1, & z_j - \Delta z/2 < z < z_j + \Delta z/2; \quad z_{\min} < z_j < z_{\max} \\ 0, & otherwise \end{cases}$$

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

$$[TEC] = [A][X]$$

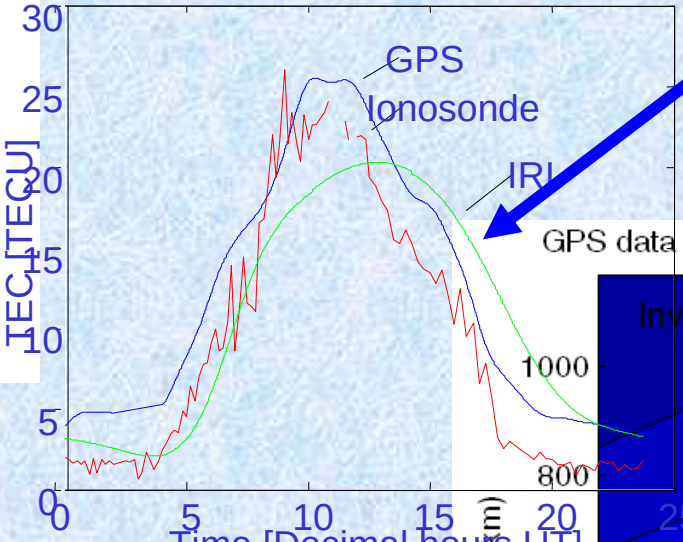
$$[X] = [A]^{-1}[TEC]$$

Computerised Ionospheric Tomography (CIT)

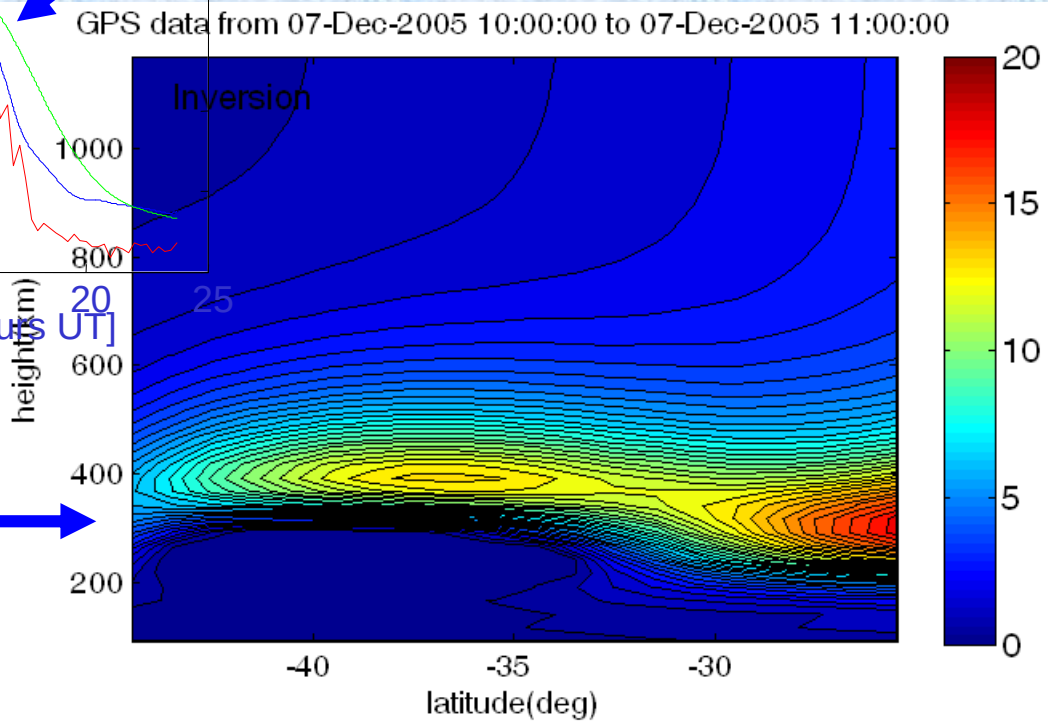


1D Electron density profiles vs height at a particular location

TEC variability at GPS Receiver(s) in :
Grahamstown Day 64 of 2005

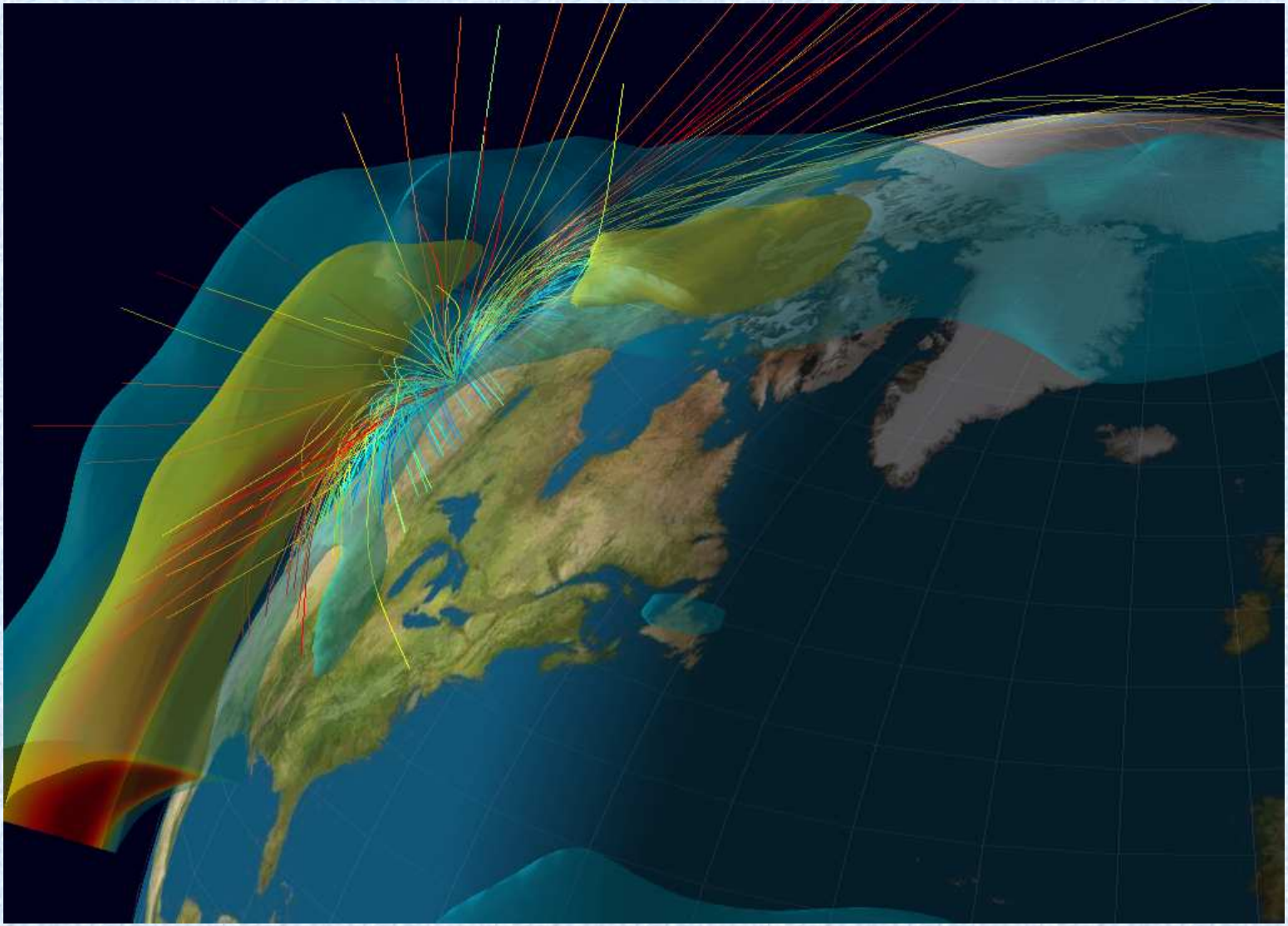


Total electron content vs time of day



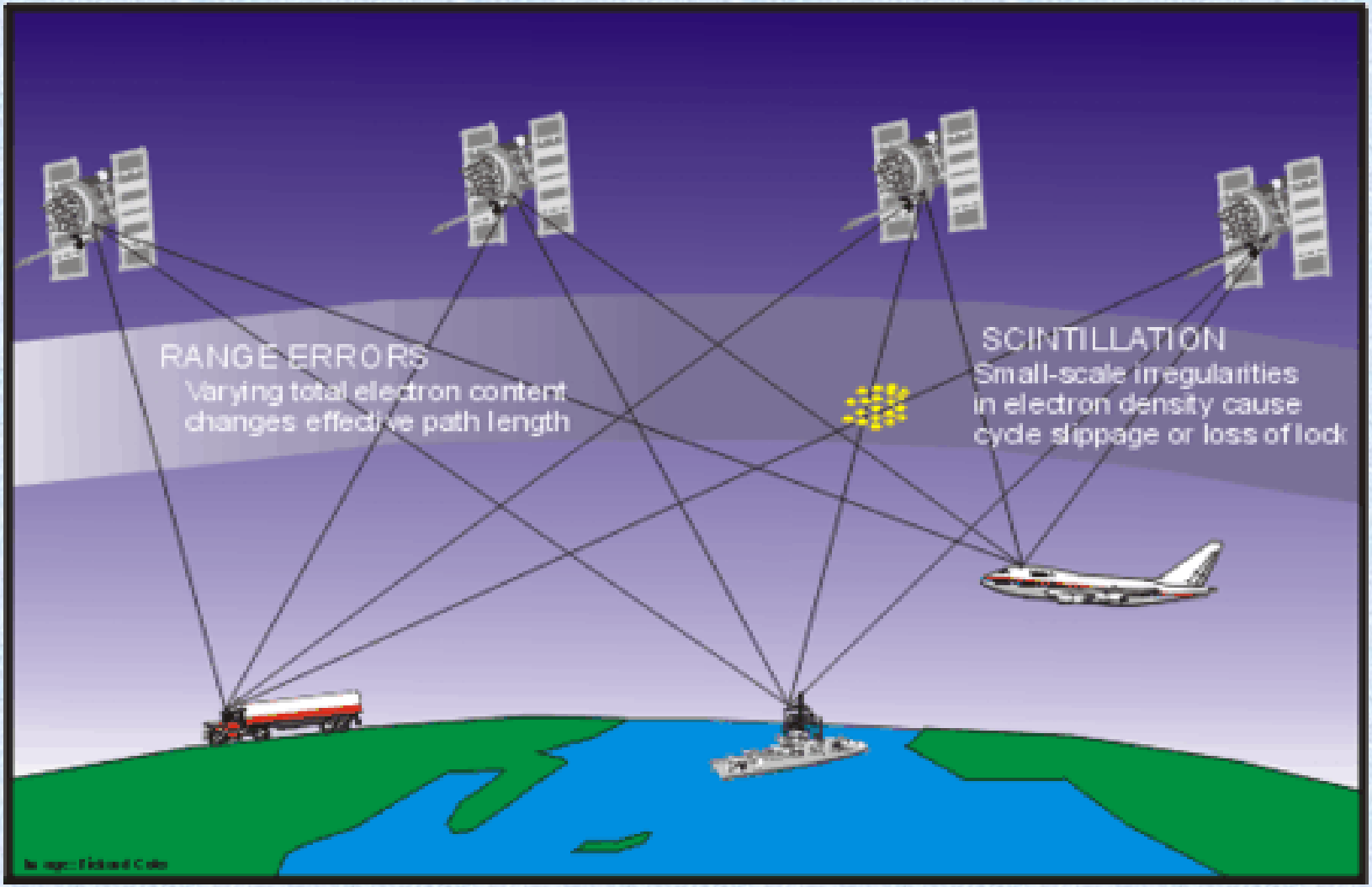
2D Electron density distribution:

Computerised Ionospheric Tomography (CIT)



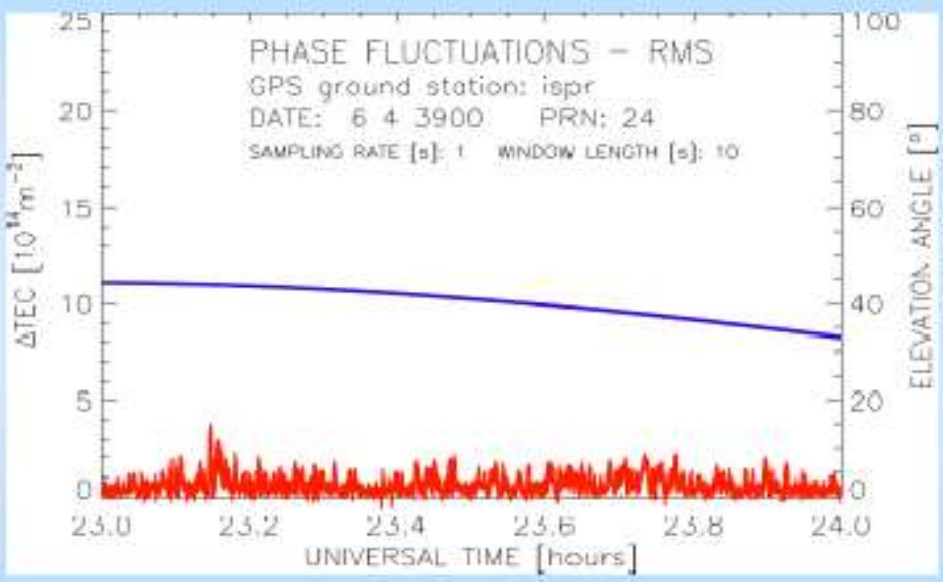
GPS Ionospheric Scintillation

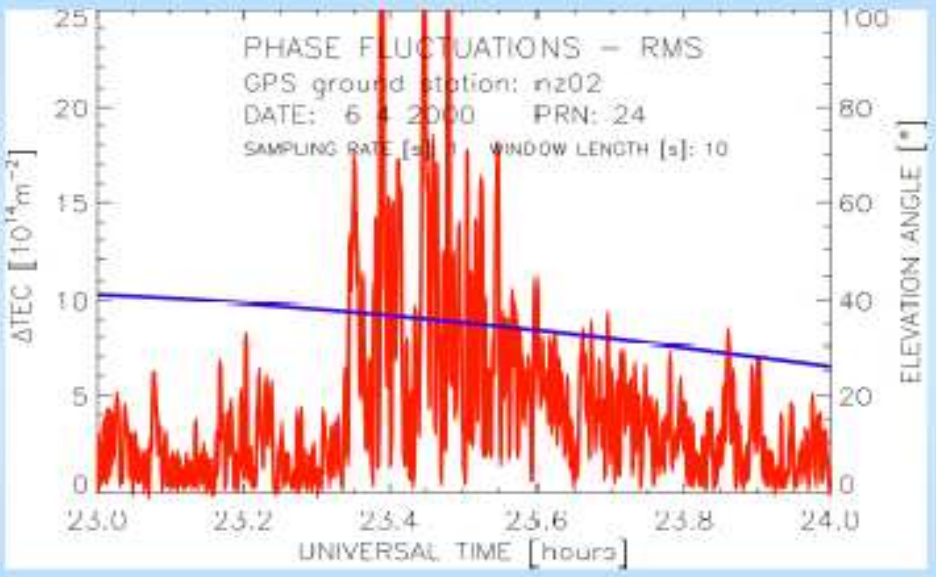
Ionospheric Scintillation



Ionospheric Scintillation
Failure of the GPS positioning system

Variability of GPS carrier phase of PRN 24 at different sites
6 April 2000, 23 - 24 UT, Sampling Rate: 1 Hz, 10s-window





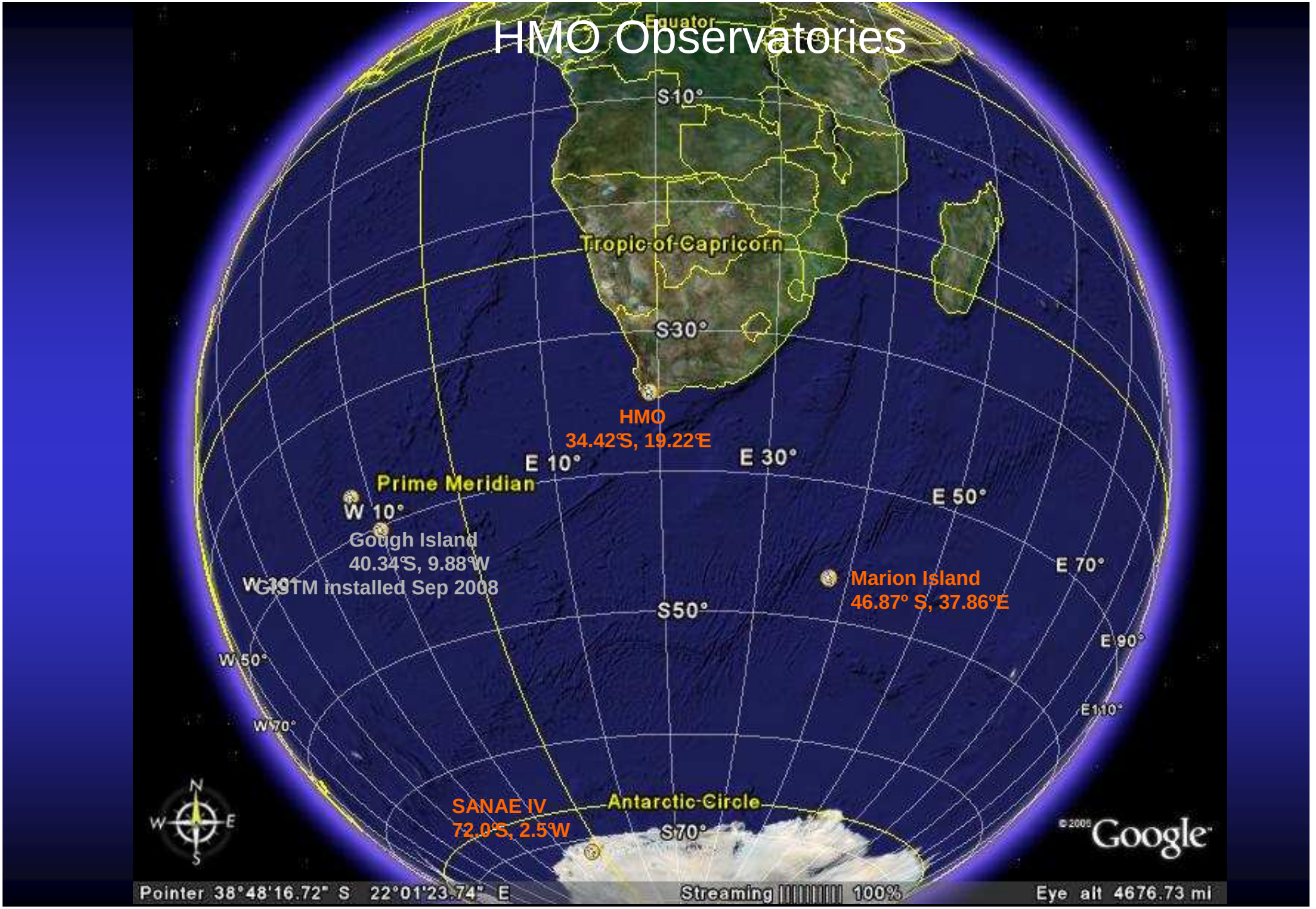
mean noise level

TEC= 2×10^{14}m^{-2} ⟺ 3.2 mm

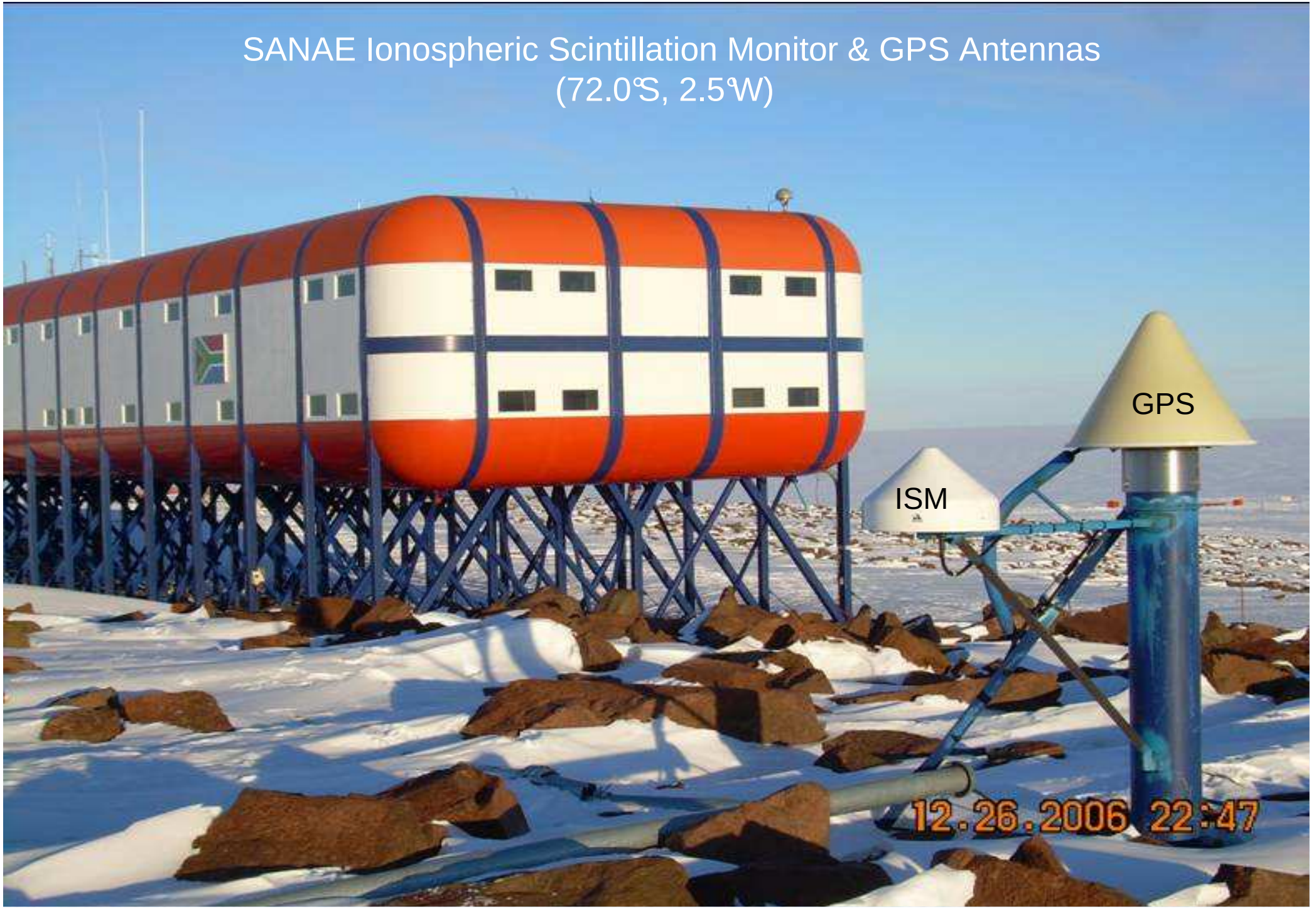
Perturbed noise level ⇨ 5 cm

problems in resolving wave length ambiguities

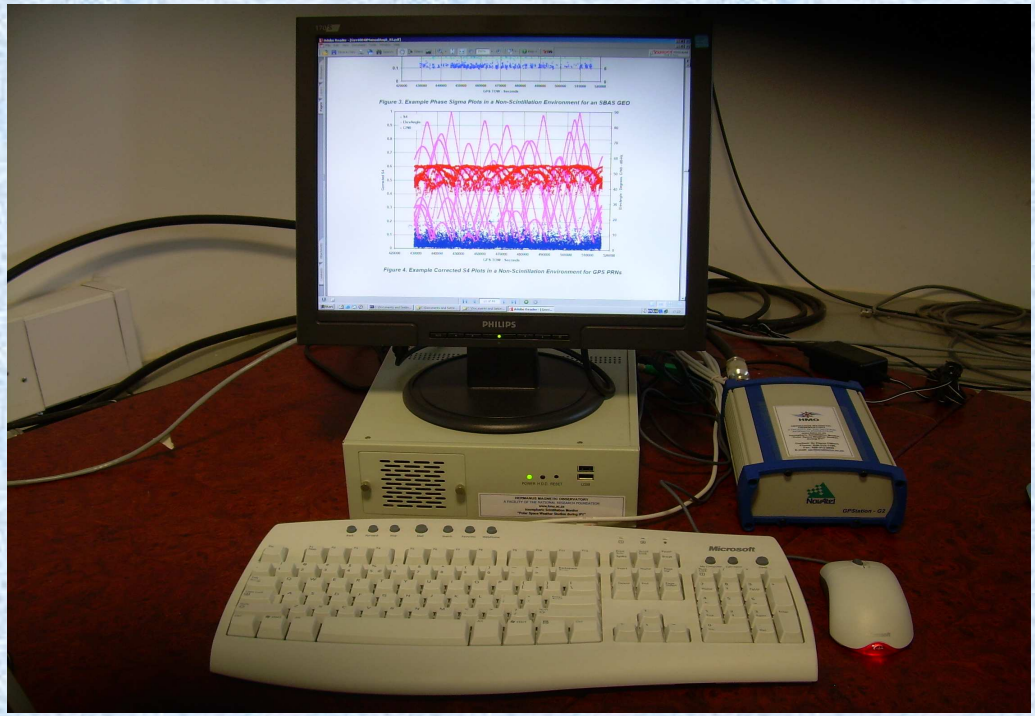
HMO Observatories

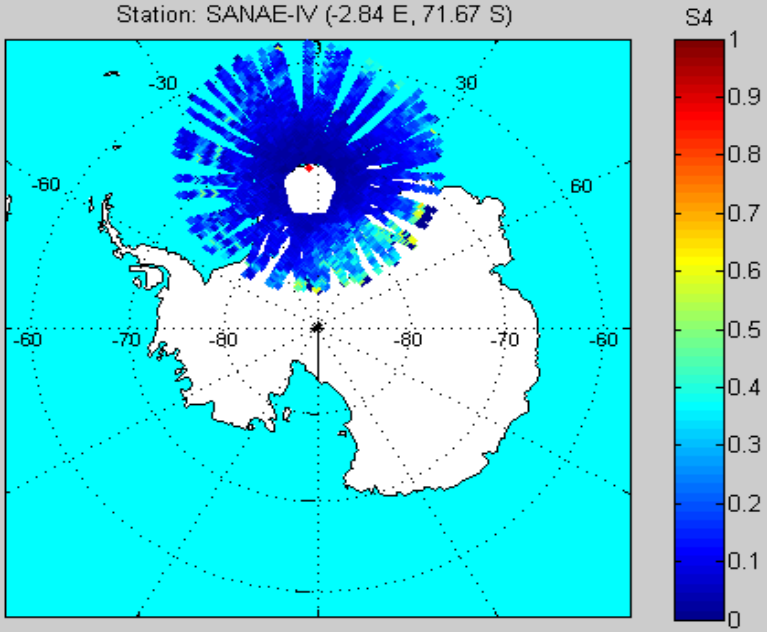


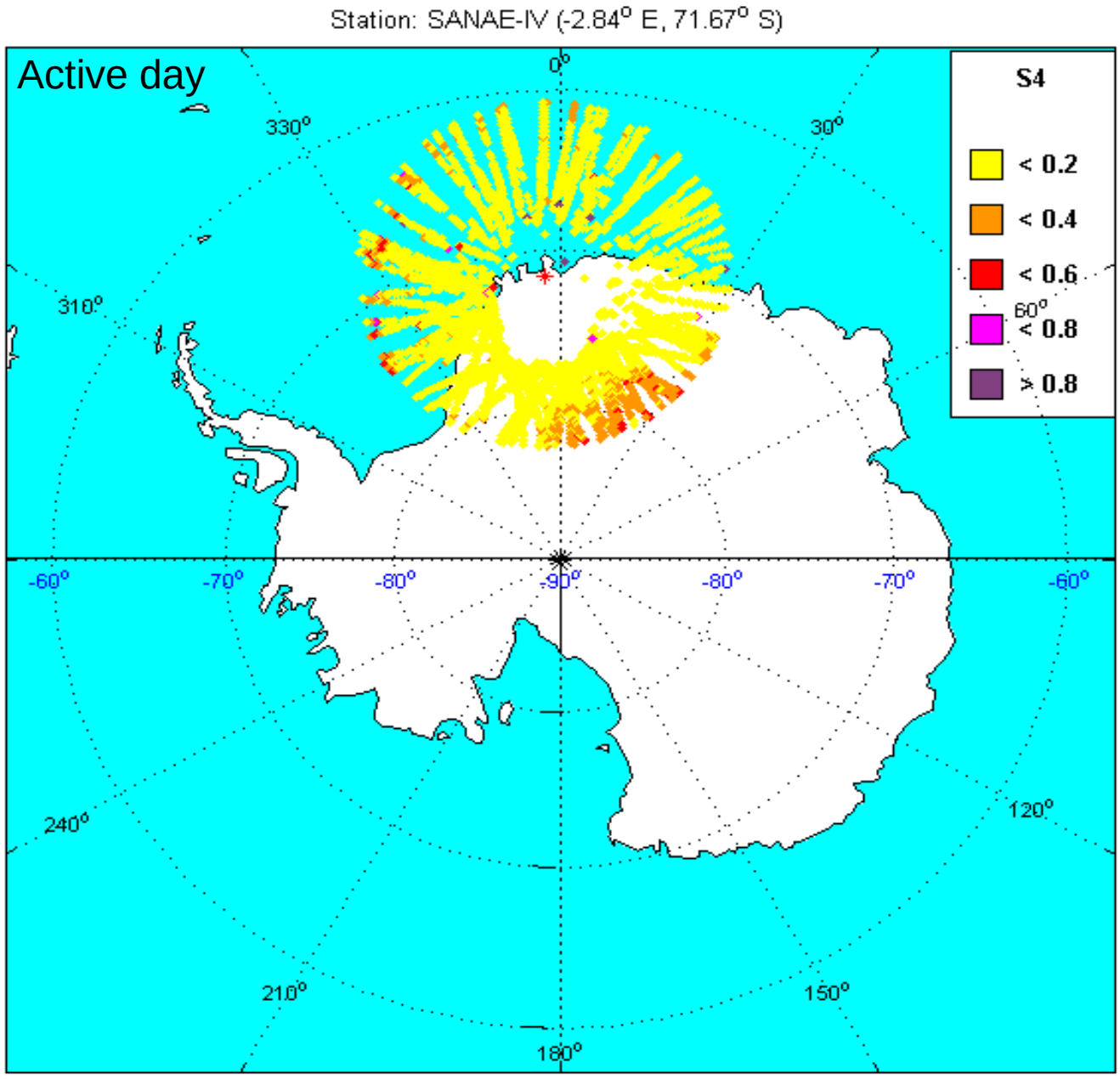
GPS Ionospheric Scintillation and TEC Monitor (GISTM) at SANAE-IV

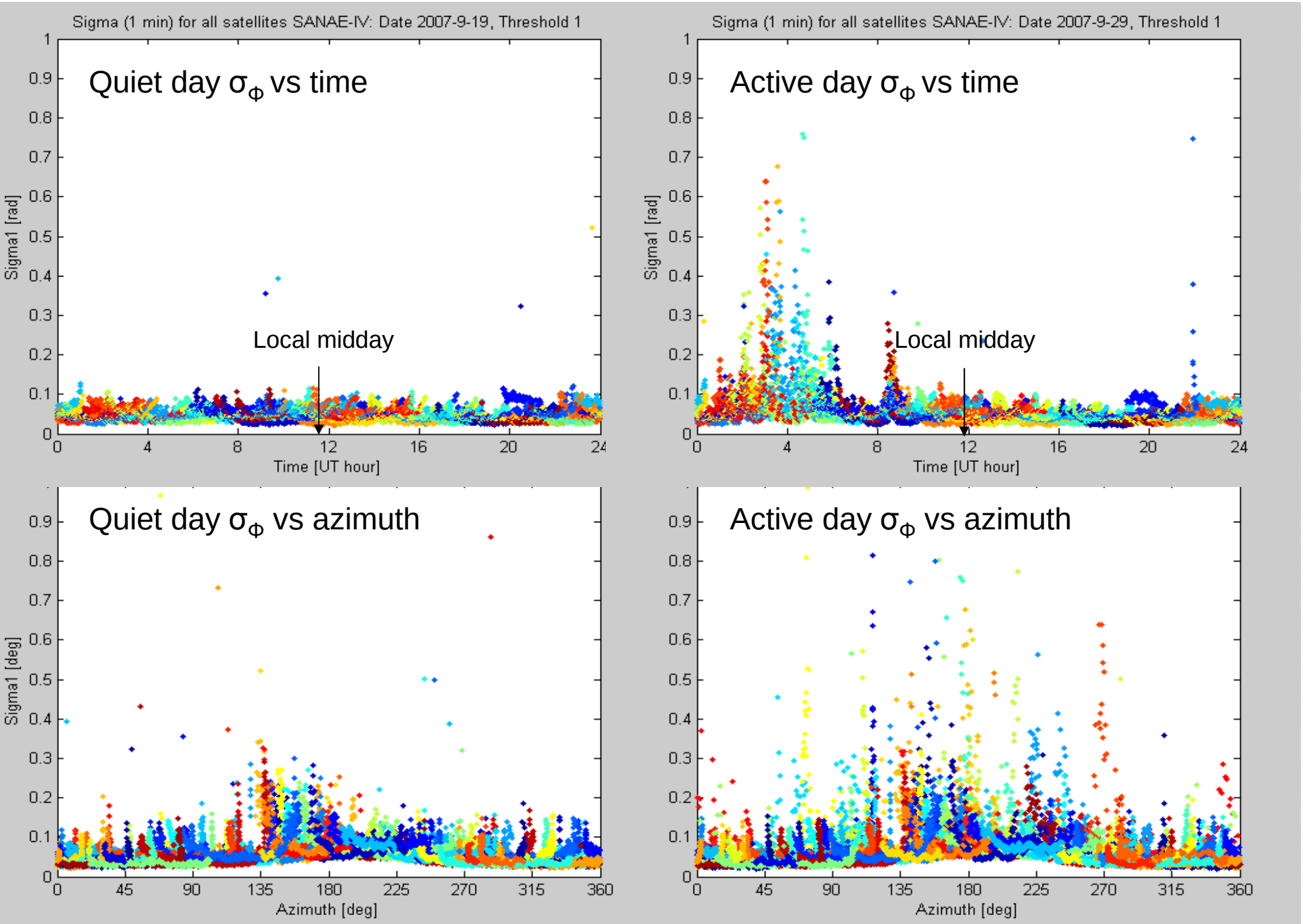

SANAE Ionospheric Scintillation Monitor & GPS Antennas
(72.0°S, 2.5°W)
GPS
ISM
12.26.2006 22:47

- **Ionospheric Scintillation Monitor (ISM)**
- Antenna: Novatel N355
- Receiver: Novatel GSV4004B
- Owner: HMO
- Availability: 1 minute data uploaded daily to HMO via ftp from 25 Dec 2006
- Source: http://ipy.hmo.ac.za






Station: SANAE-IV (-2.84° E, 71.67° S)
Active day
S4
< 0.2
< 0.4
< 0.6
< 0.8
> 0.8
0°
30°
60°
120°
150°
180°
210°
240°
270°
300°
330°
-60°
-70°
-80°
-90°
29-Sep-2007 from 00:00 to 23:58 UT; Satellite elevation threshold = 10°


Sigma (1 min) for all satellites SANAE-IV: Date 2007-9-19, Threshold 1
Quiet day σΦ vs time
Local midday
Sigma1 [rad]
Time [UT hour]
Sigma (1 min) for all satellites SANAE-IV: Date 2007-9-29, Threshold 1
Active day σΦ vs time
Local midday
Sigma1 [rad]
Time [UT hour]
Quiet day σΦ vs azimuth
Sigma1 [deg]
Azimuth [deg]
Active day σΦ vs azimuth
Azimuth [deg]

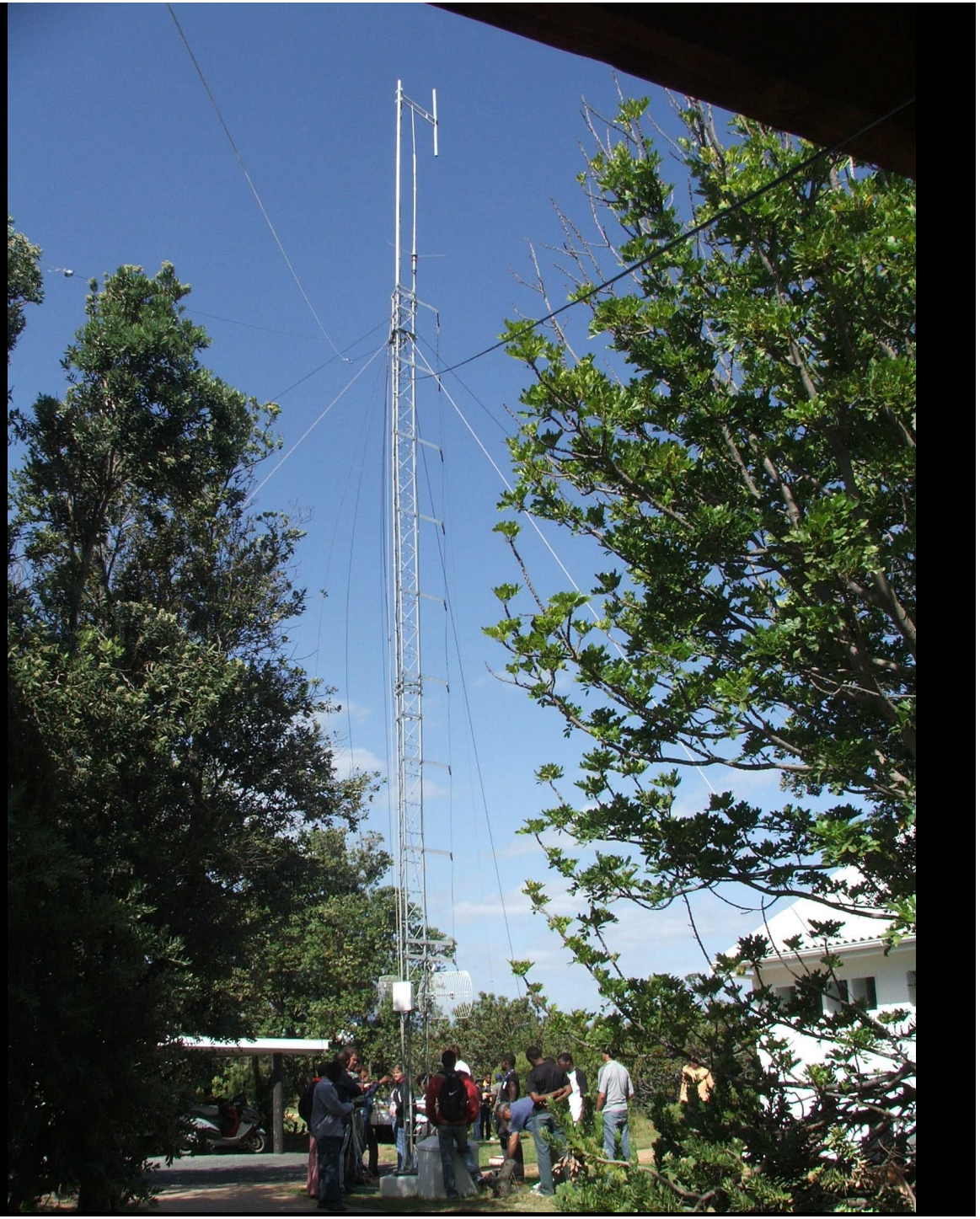
Other non-magnetic ionospheric observation instruments managed by HMO:
HF Ionosondes, HF Radio Beacon project

GRAHAMSTOWN IONOSONDE

Grahamstown field station Ionosonde receiver antennas

Hermanus
Ionosonde transmitter antenna

HF Beacon project
Receiver antenna
in Hermanus



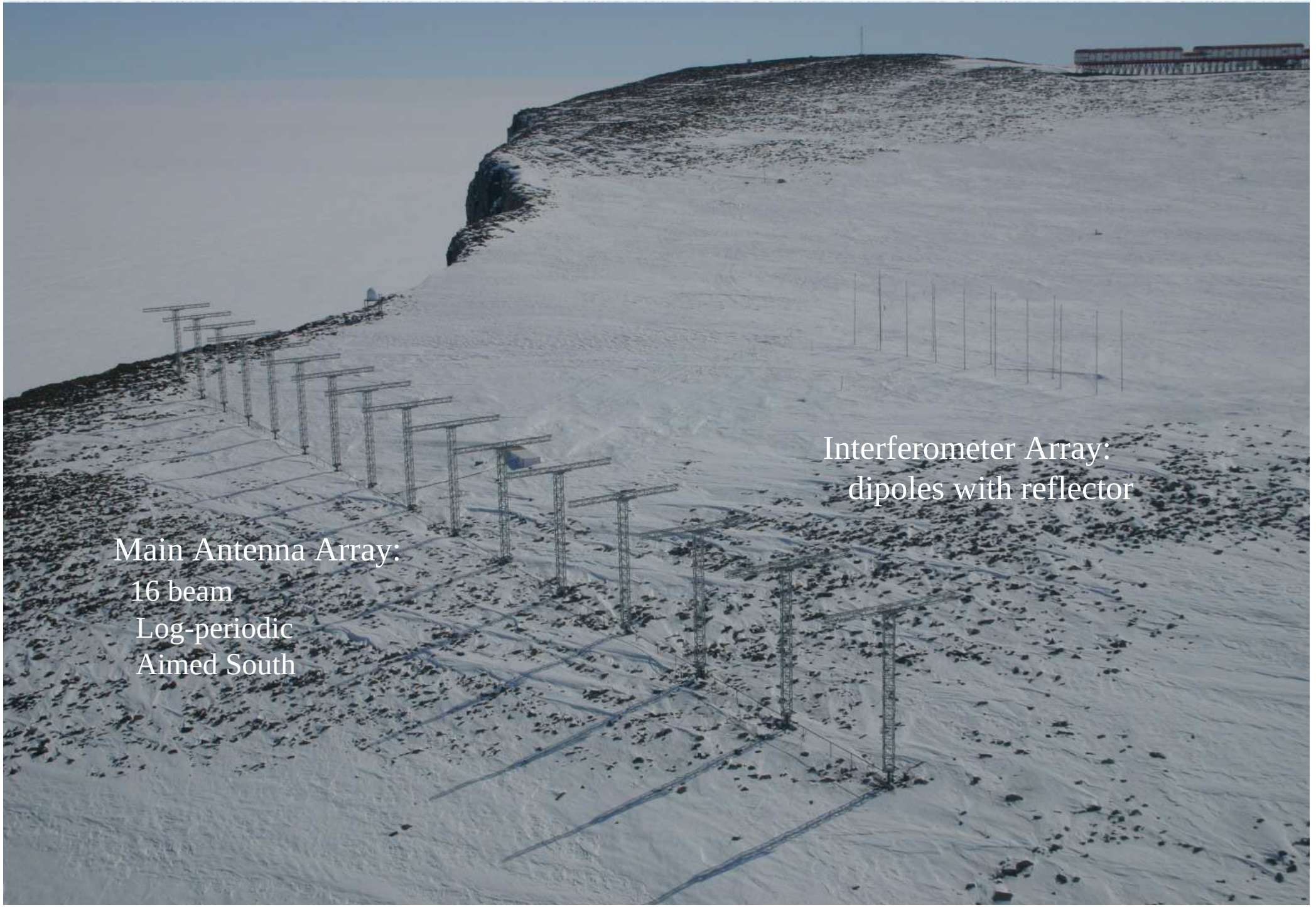
Ionospheric Instruments at SANAE-IV


SANAE-IV Antarctica (72.0°S, 2.5°W)
Magnetically quiet area
HF Radar

Physical Science Instrumentation at SANAE-IV

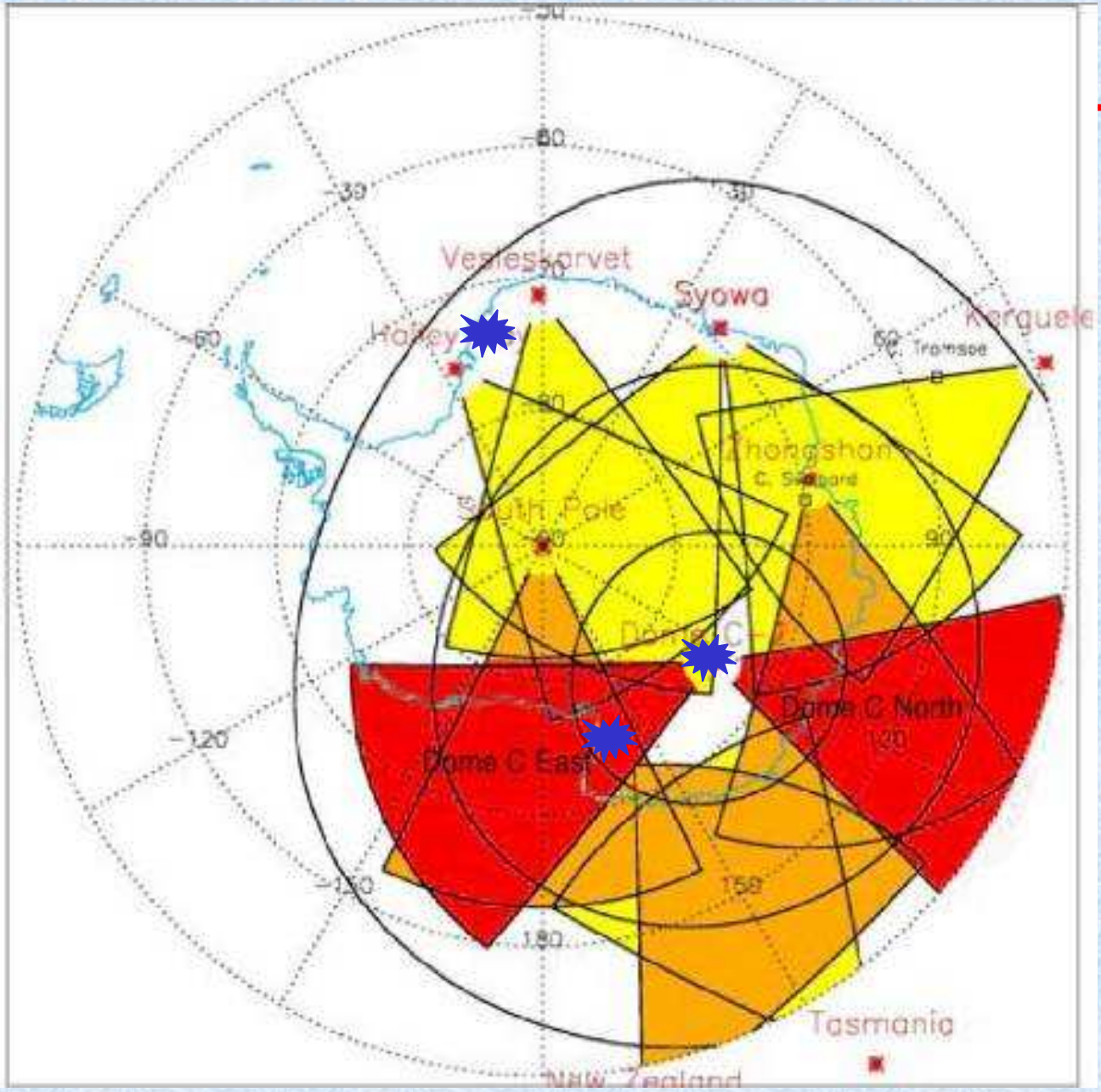
- HF radar
- Aurora cameras
- Riometers
- Magnetometers
- Neutron Monitors
- VLF-receiver
- GPS receiver
- Seismometer
- Meteorology

HF Radar SANAE-IV


Interferometer Array:
dipoles with reflector
Main Antenna Array:
16 beam
Log-periodic
Aimed South

16 HF Radio Transmitters with digital sequence modulation

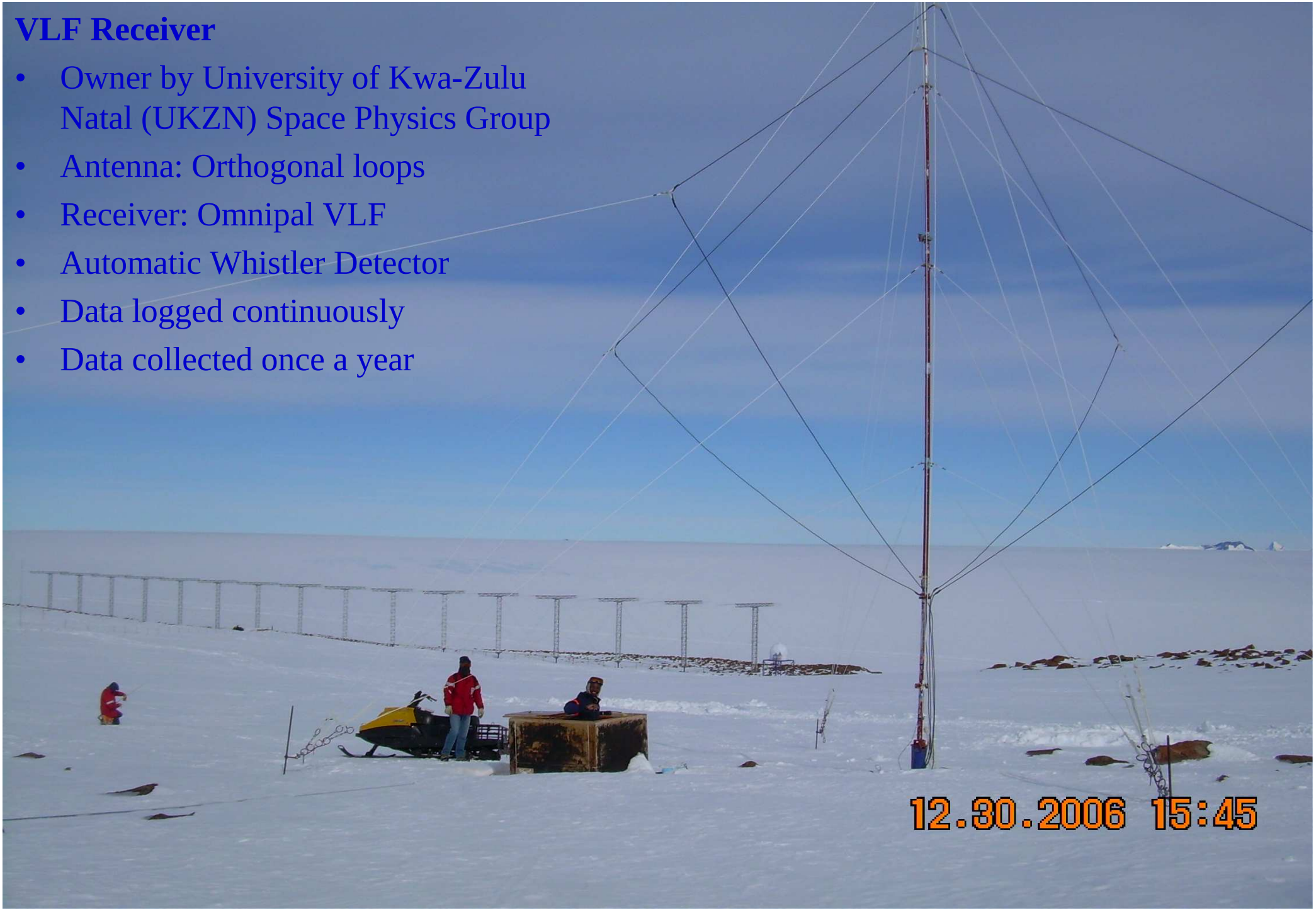
Overlapping fields of view of Antarctic HF Radars



VLF Receiver
SANAE-IV

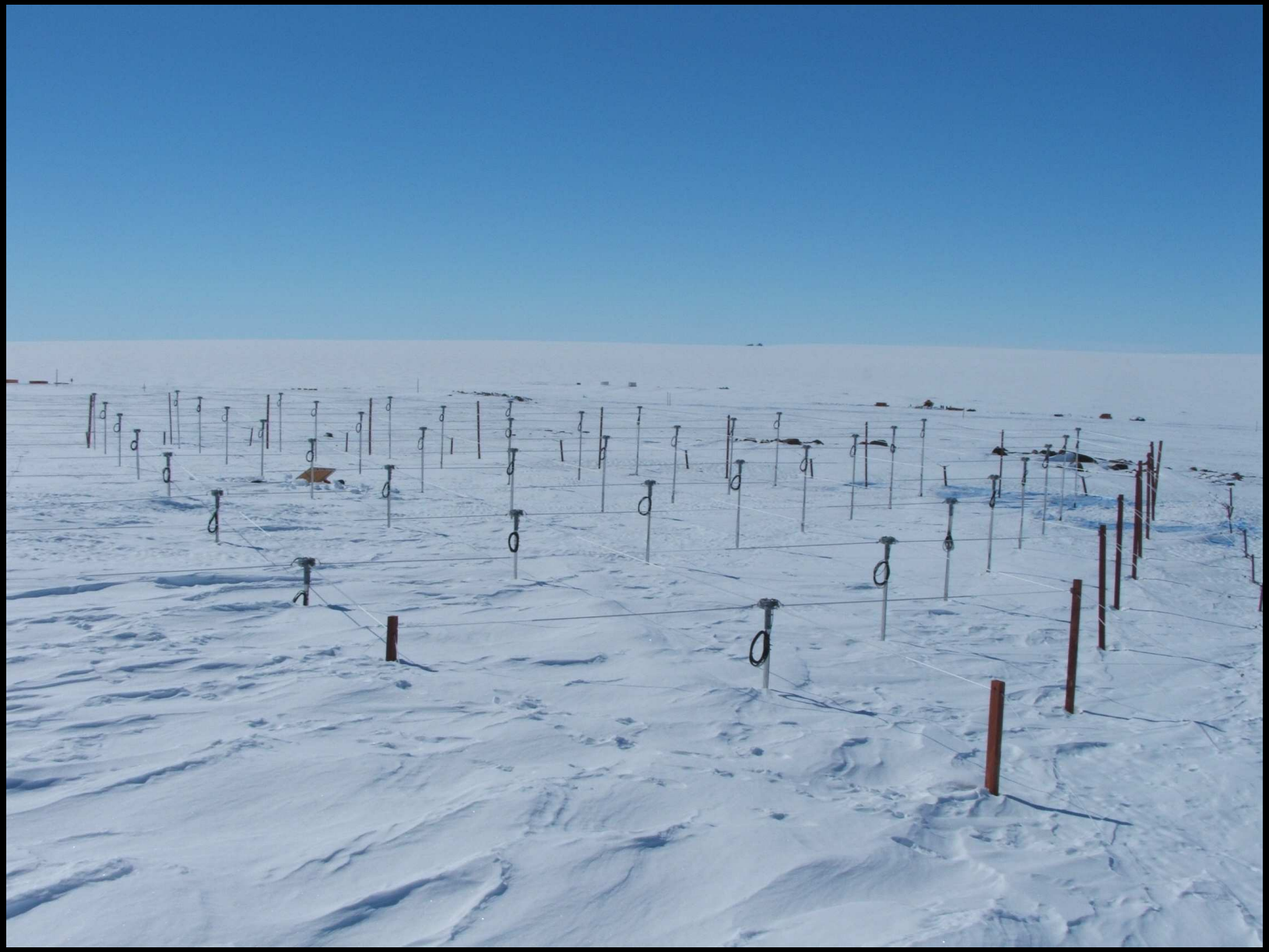
VLF Receiver

- Owner by University of Kwa-Zulu Natal (UKZN) Space Physics Group
- Antenna: Orthogonal loops
- Receiver: Omnipal VLF
- Automatic Whistler Detector
- Data logged continuously
- Data collected once a year

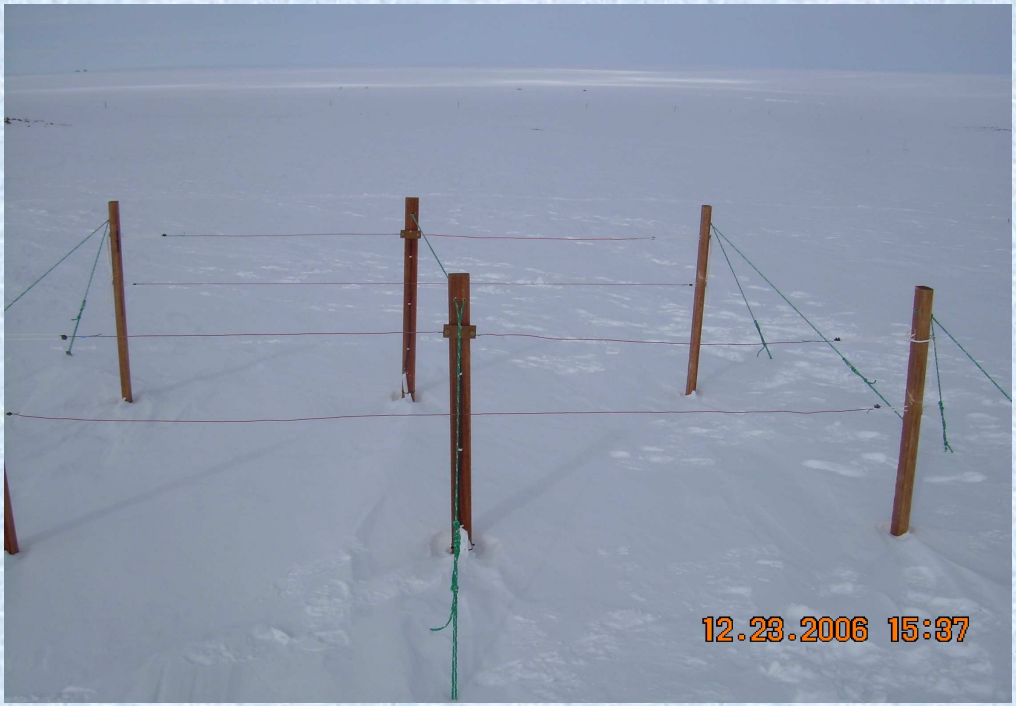


Instruments for Ionospheric Opacity of Cosmic Radio Sources
(Riometers)
at SANAE-IV

SANAE 64 element beam forming imaging riometer at 38.2 MHz



64 element beam forming imaging riometer at 38.2 MHz



Riometers

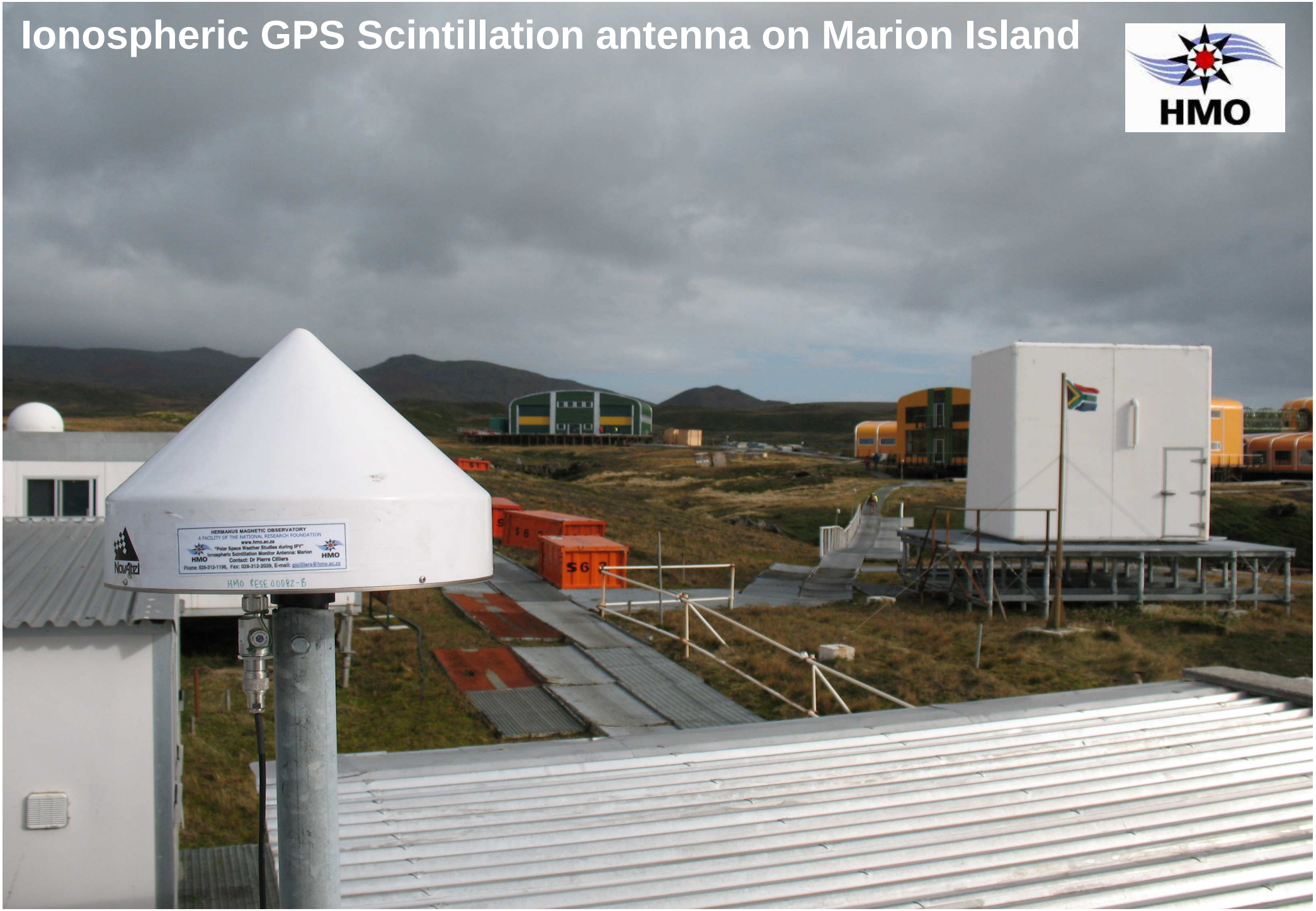
- Owned by North-West University
- 64 element beam forming imaging riometer 38.2 MHz
- Wideband riometers with dipole antennas 51.4 and 30 MHz
- UHF Riometer
- Data collected once a year

- **Aurora Cameras**
- Owned by North-West Univ.
- Low-level white-light, digitized all-sky auroral camera Wide-angle camera B&W
- Narrow angle (25° field of view) colour camera
- Data recorded on Videotape
- Data retrieved once a year by ship

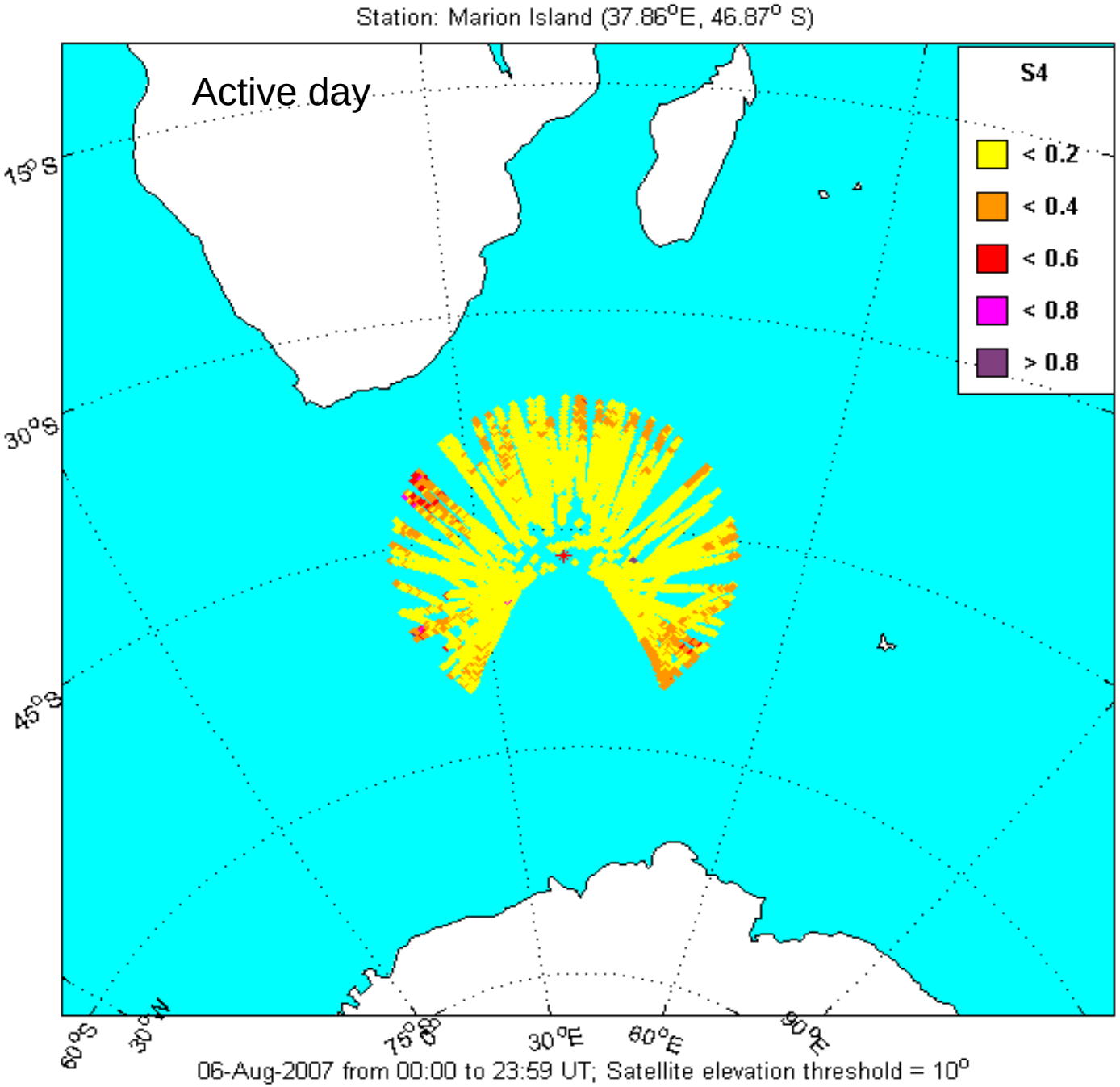
HMO Ionospheric Observation Infrastructure: Marion Island

Marion Island Research Bases

Ionospheric GPS Scintillation antenna on Marion Island

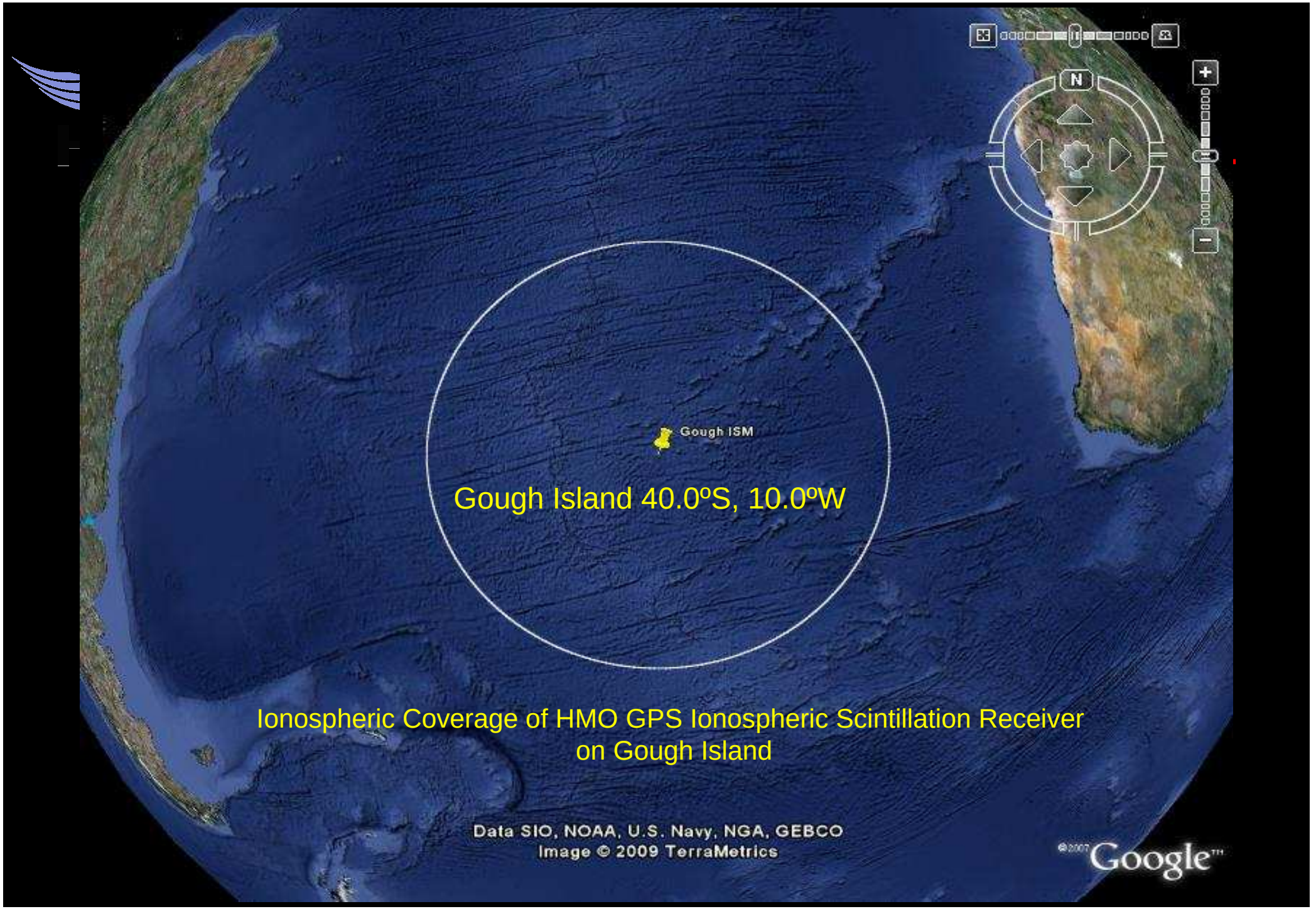


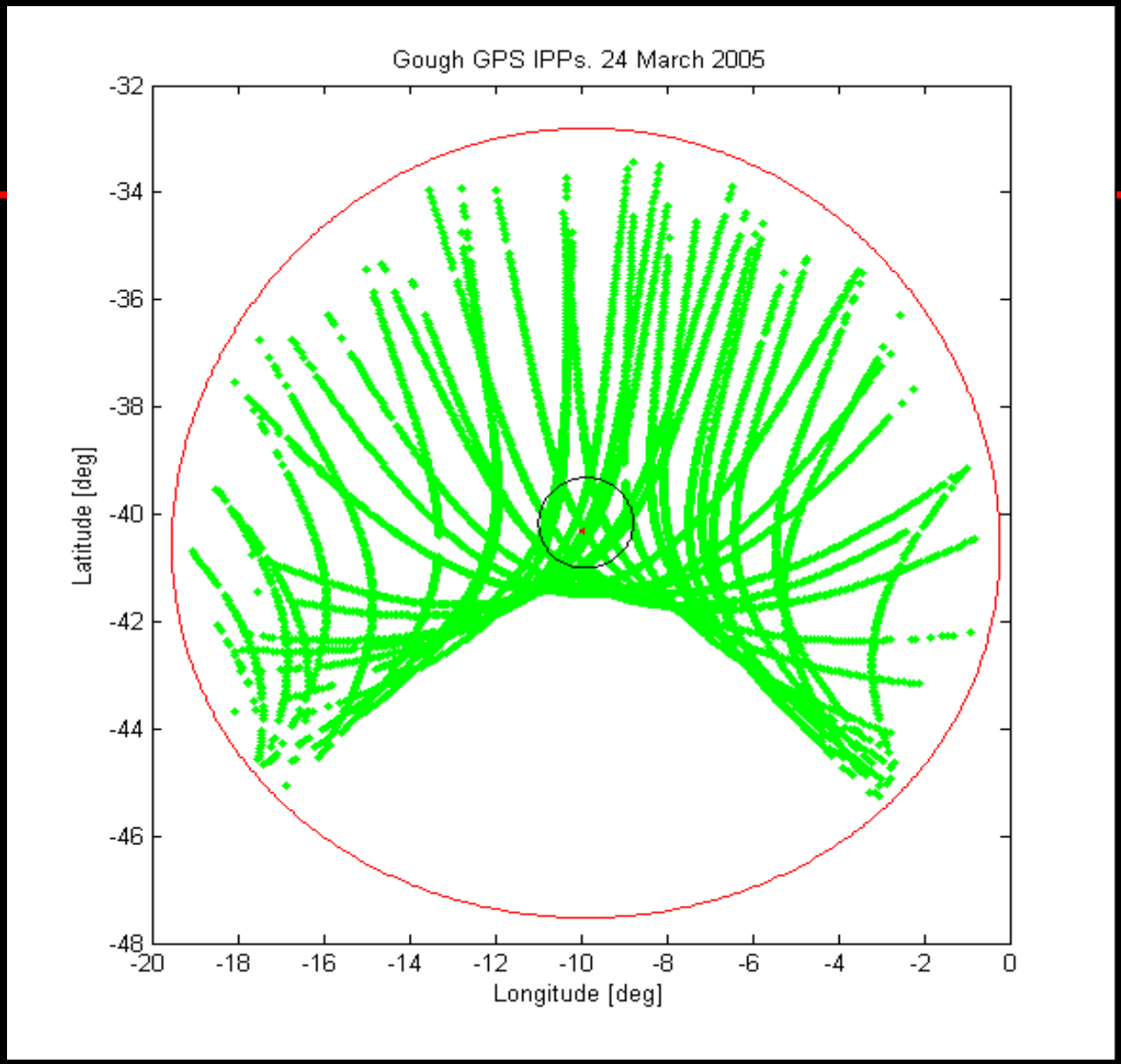
GPS Ionospheric Scintillation receiver on Marion Island


Station: Marion Island (37.86°E, 46.87° S)
Active day
S4
< 0.2
< 0.4
< 0.6
< 0.8
> 0.8
15° S
30° S
45° S
60° S
30° W
75° W
30° E
60° E
90° E
06-Aug-2007 from 00:00 to 23:59 UT; Satellite elevation threshold = 10°

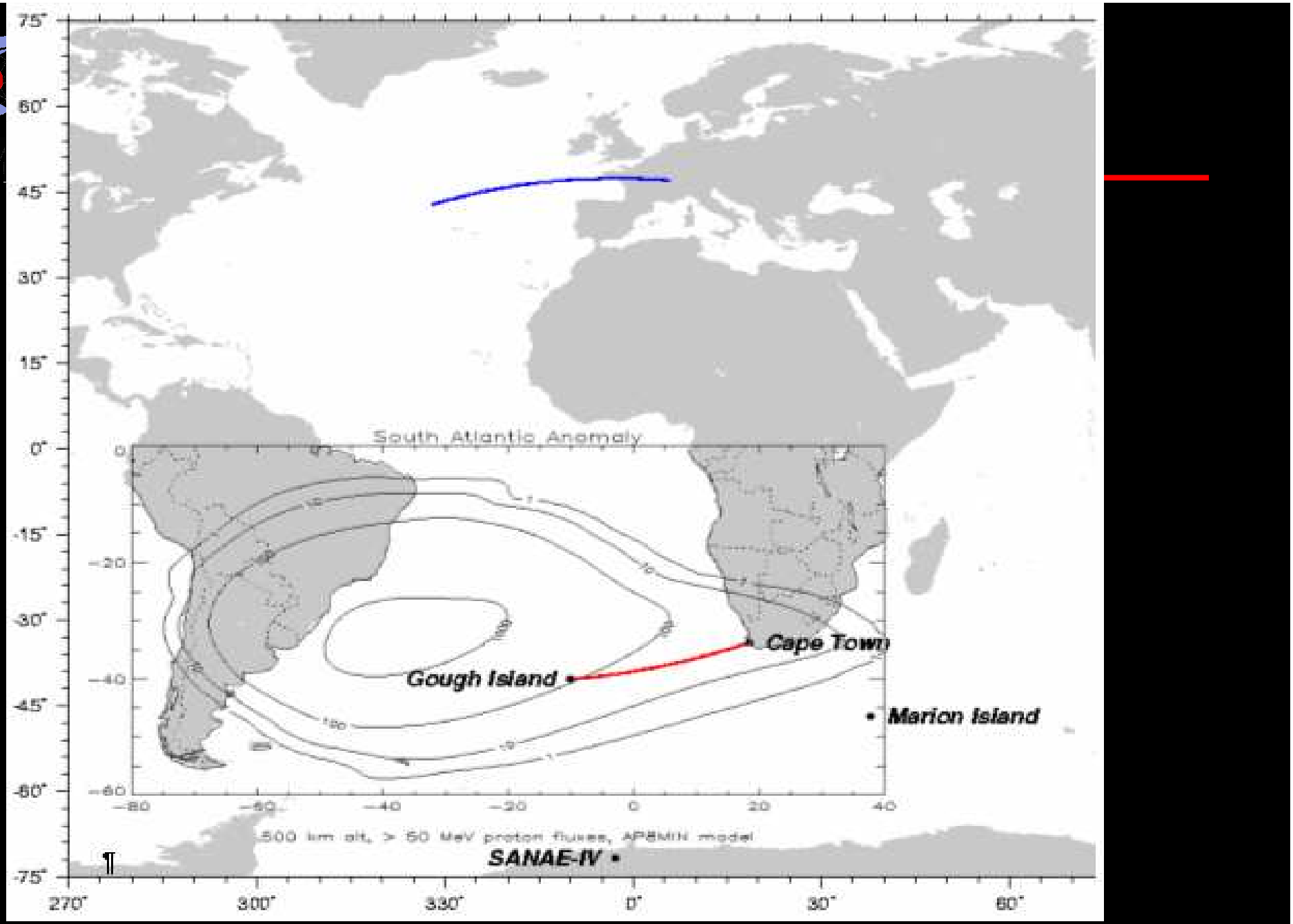
VLF antenna on Marion Island

HMO Ionospheric Observation Infrastructure: Gough Island


Gough ISM
Gough Island 40.0ºS, 10.0ºW
Ionospheric Coverage of HMO GPS Ionospheric Scintillation Receiver
on Gough Island
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image © 2009 TerraMetrics
Google



Ionospheric Coverage of HMO GPS Ionospheric Scintillation Receiver on Gough Island



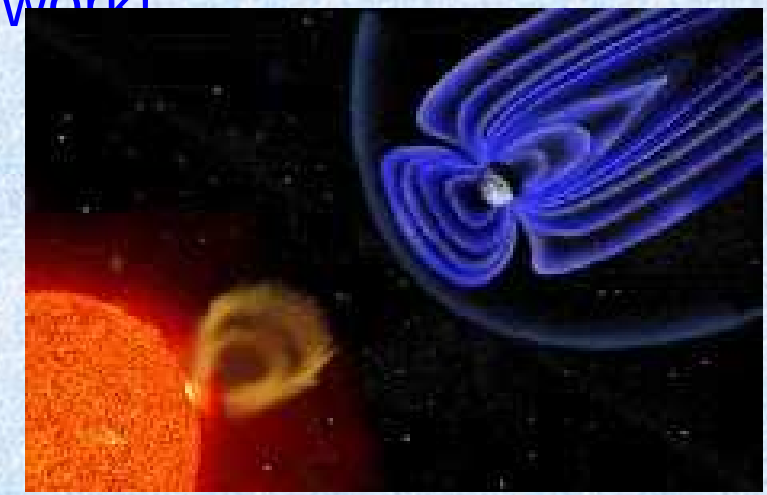
Location of Gough Island relative to the South Atlantic Anomaly

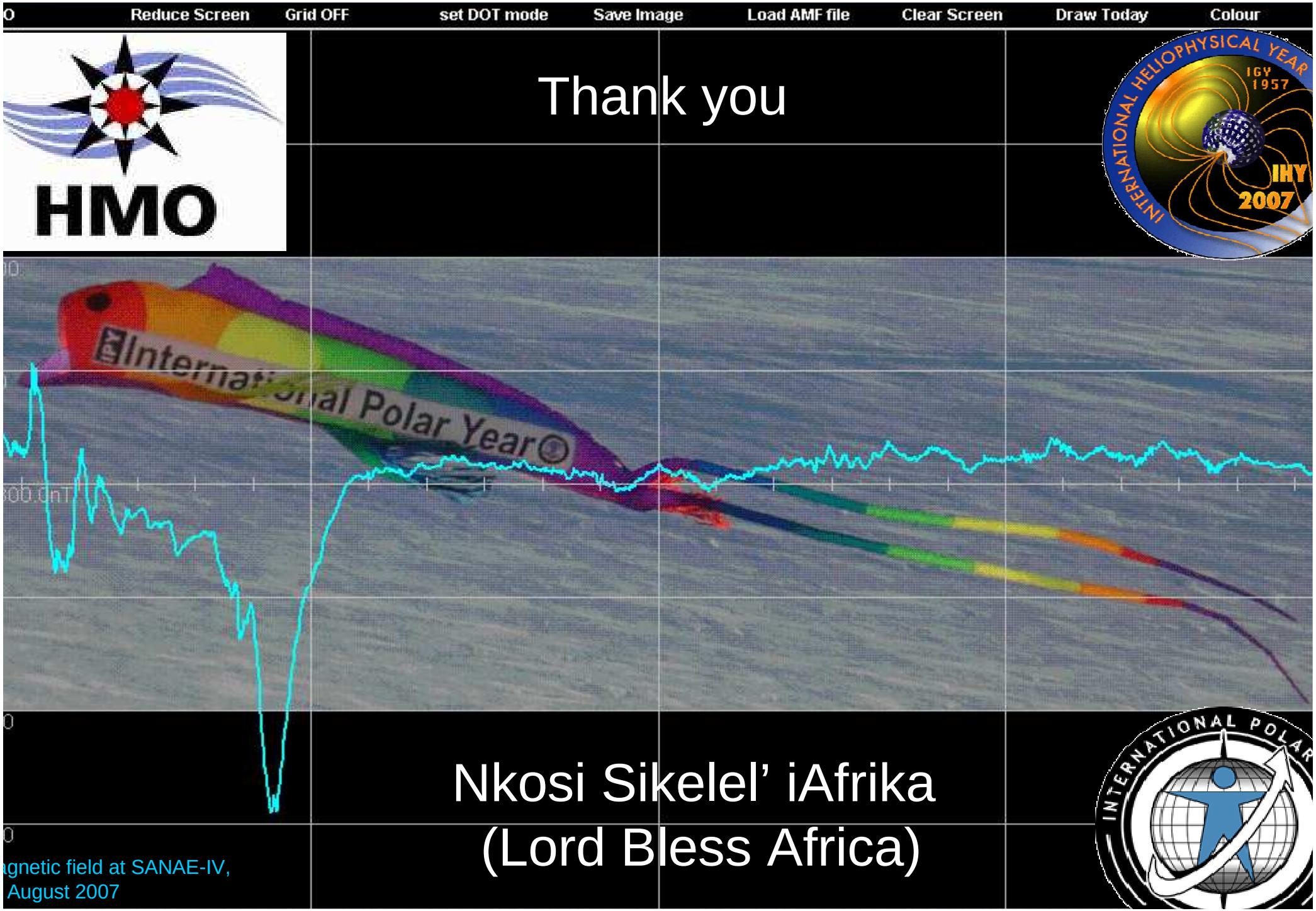

Gough Island GPS
Gough ISM
132 m
Image © 2009 DigitalGlobe
©2007 Google™
N


HMO Ionospheric Scintillation Monitor (ISM)-antenna

Acknowledgements

- The Chief Directorate Surveys & Mapping (CDSM) of South Africa for making available GPS receivers and GPS data.
- HartRAO for making available IGS data from a number of GPS stations.
- Father God, who created the universe, for a body and mind and the opportunity to play in His garden and study His work!




O
Reduce Screen
Grid OFF
set DOT mode
Save Image
Load AMF file
Clear Screen
Draw Today
Colour
HMO
Thank you
INTERNATIONAL HELIOPHYSICAL YEAR
IGY
1957
IHY
2007
International Polar Year
Nkosi Sikelel' iAfrika
(Lord Bless Africa)
INTERNATIONAL POLAR
gnetic field at SANAE-IV,
August 2007