The Abdus Salam International Centre for Theoretical Physics

How to study a geomagnetic storm

(Practical POV)

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60 ICTP 1964–2024

OUTLINE

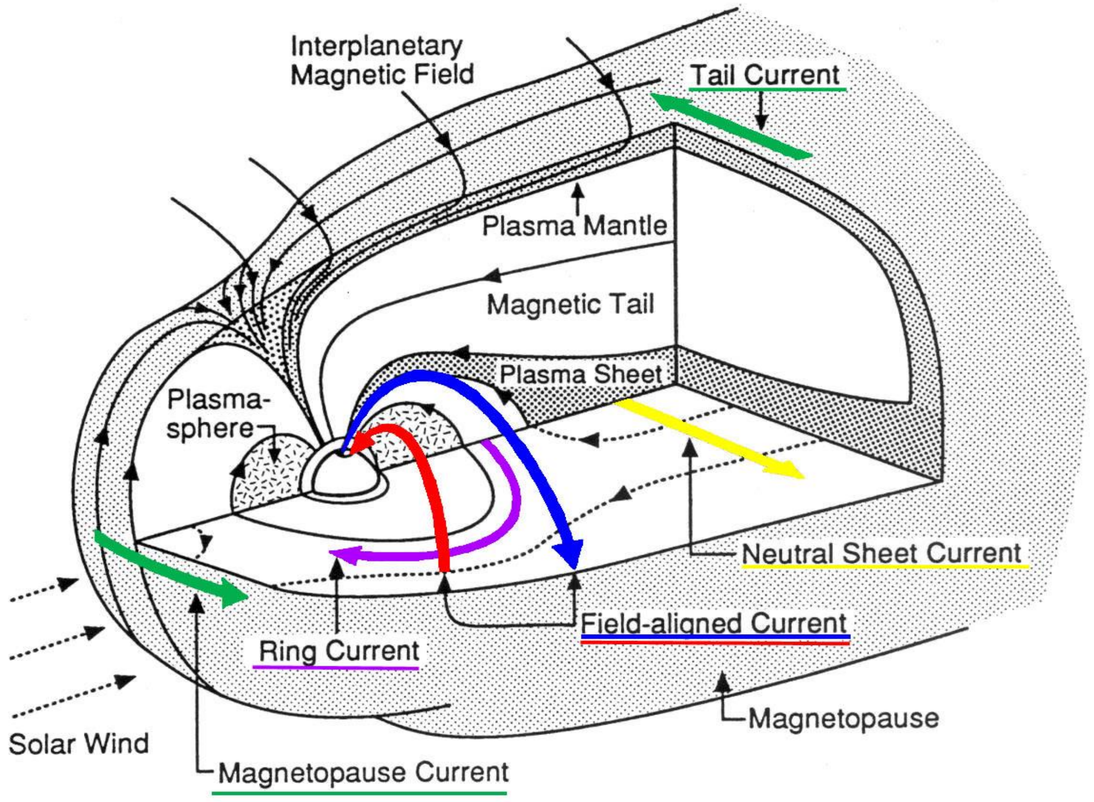
- GEOMAGNETIC STORM DEFINITION AND PHASES
- USE OF MAGNETIC INDICES FOR GEOPHYSICS STUDIES
- GUIDELINES TO STUDY A STORM (POV)
- RESOURCES

SOME MAGNETIC INDICES FOR GEOPHYSICS STUDIES

MAGNETIC INDICES

- THE CONCEPT OF MAGNETIC INDICES
  - K index, S_R
- USE OF MAGNETIC INDICES FOR GEOPHYSICS STUDIES
  - Kp(ap)/ Km (am)
  - Storm Dst index
  - Auroral indices AU and AL
  - Polar cap indices PCN and PCS

SOME MAGNETIC INDICES FOR GEOPHYSICS STUDIES



WHY USE MAGNETIC INDICES?

TO APPROACH A COMPLEX REALITY

MAGNETIC INDICES ARE PROXIES

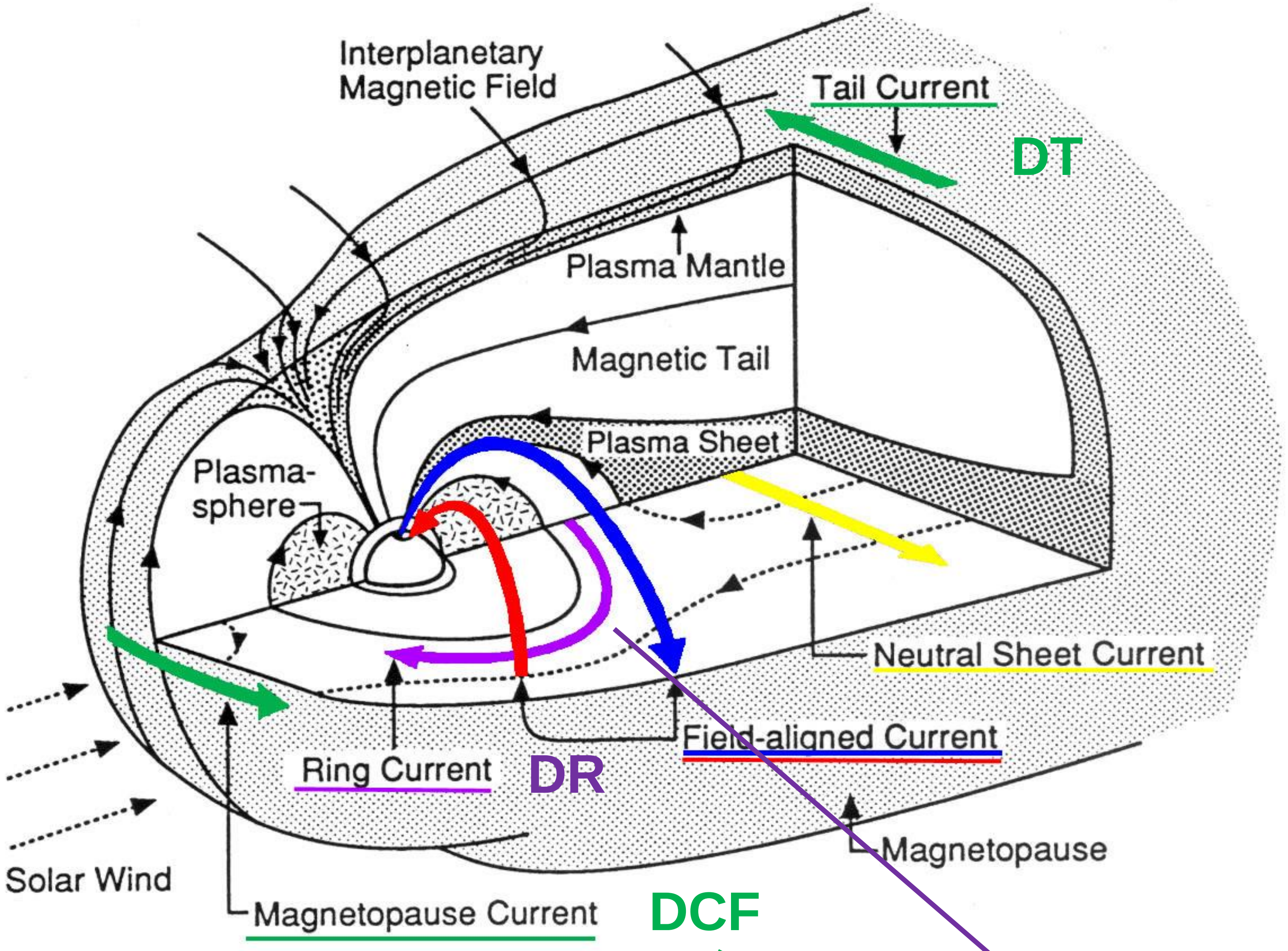
MAGNETIC INDICES ARE COMPLEMENTARY

THE CONCEPT OF MAGNETIC INDICES

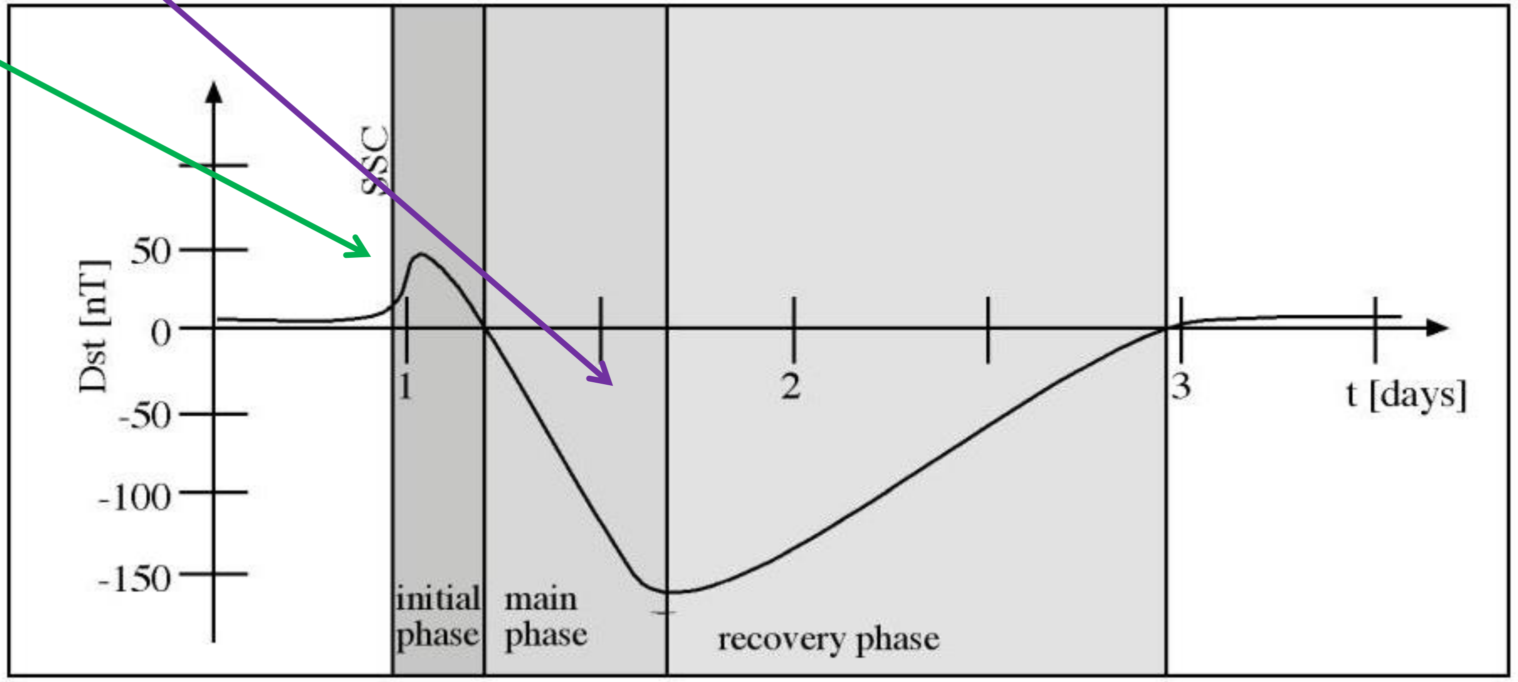
Permanent Dynamo	Motions—V	Magnetic Field B	Order of Magnitude of V and B
Sun	2 motions: rotation and convection	The two components of the sun magnetic field Dipolar Toroïdal <= > sunspot	Rotational speed of the Sun at the equator: ~7008 km/h Dipolar component: ~5 10^{-3} T Toroidal component: ~0.3 to 0.5 T
Solar wind Magnetosphere	Solar wind	Bi (IMF) Interplanetary magnetic field	Solar wind speed ~ [300 to 2000 km/s] Bi (IMF) ~ qq 10 nT
Atmospheric wind Ionosphere	Atmosphere	Terrestrial magnetic field: Bt	Atmospheric wind speed ~100 m/s Bt ~ qq 10,000 nT ~30,000 nT at the pole ~60,000 nT at the equator
Earth's Dynamo inside the Earth	Metallic core	Terrestrial magnetic field: Bt	Indirect measurements deduced from the Earth's planetary magnetic field and the secular variation Velocity ~ qq km/year Bt ~ qq 10,000 nT

- Amory-Mazaudier, 2022, Magnetic Signatures of Large Scale Electric Currents in the Earth's environment at middle and low latitudes

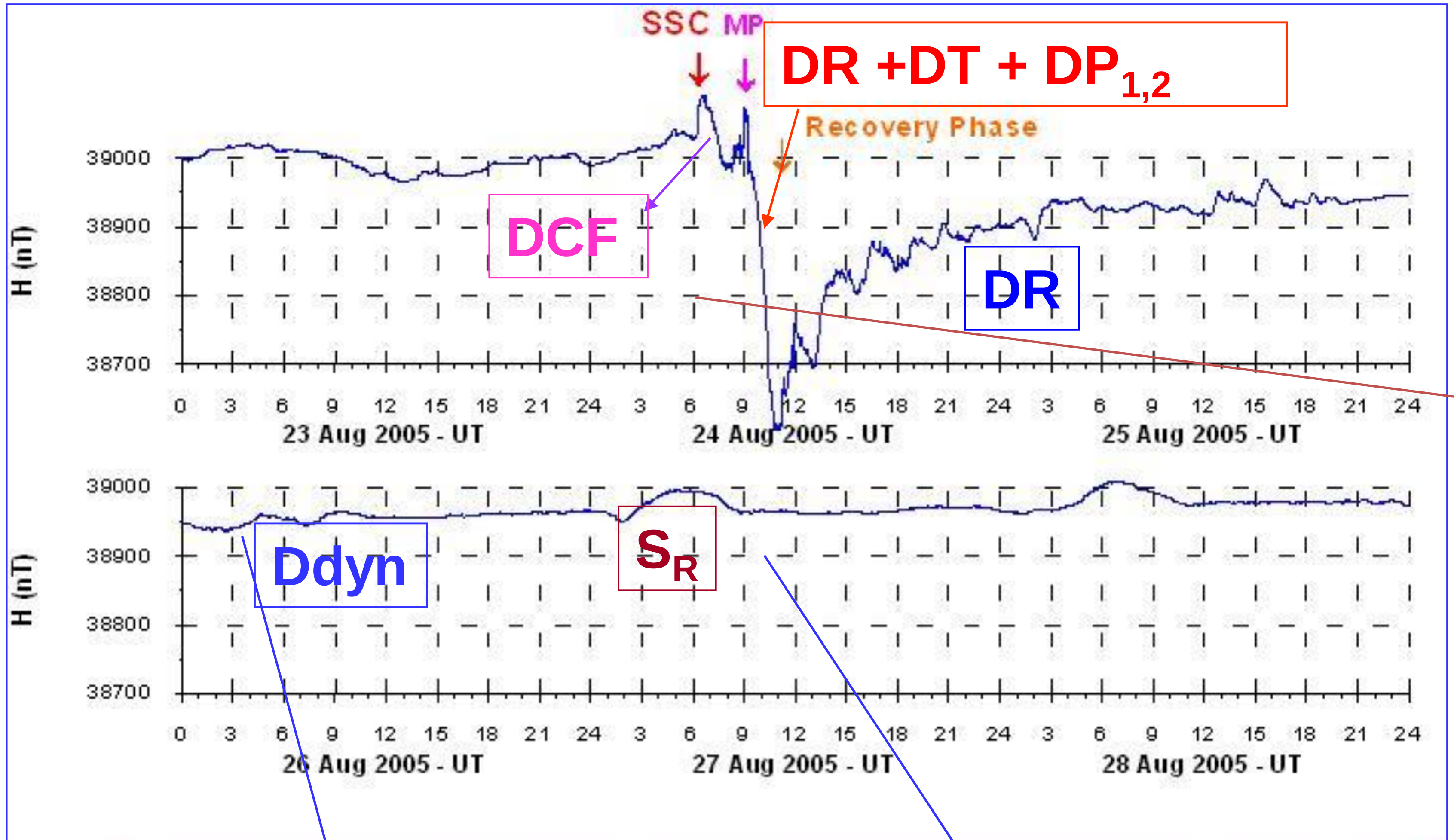
MAGNETOSPHERE



Dst , SYMH, ASYMH
magnetospheric
electric currents.



DCF : Chapman-Ferraro current
DR : Ring current
DT : Tail current



Time variation of the H-component observed at Phu Thuy (Hanoi – Vietnam) from 23th to 28th August 2005

SOLAR WIND MAGNETOSPHERE DOMINATING

COUPLING SOLAR WIND MAGNETOSPHERE IONOSPHERE

RADIATIONS IONOSPHERE DOMINATING

K INDEX / S_R

A measure of the range of irregular and rapid storm-time magnetic activity.

- Mayaud, 1980, Derivation Meaning and Use of geomagnetic indices

- Menvielle et al, 2008, A guide to geomagnetic indices derived from Earth surface data

K INDEX / S_R

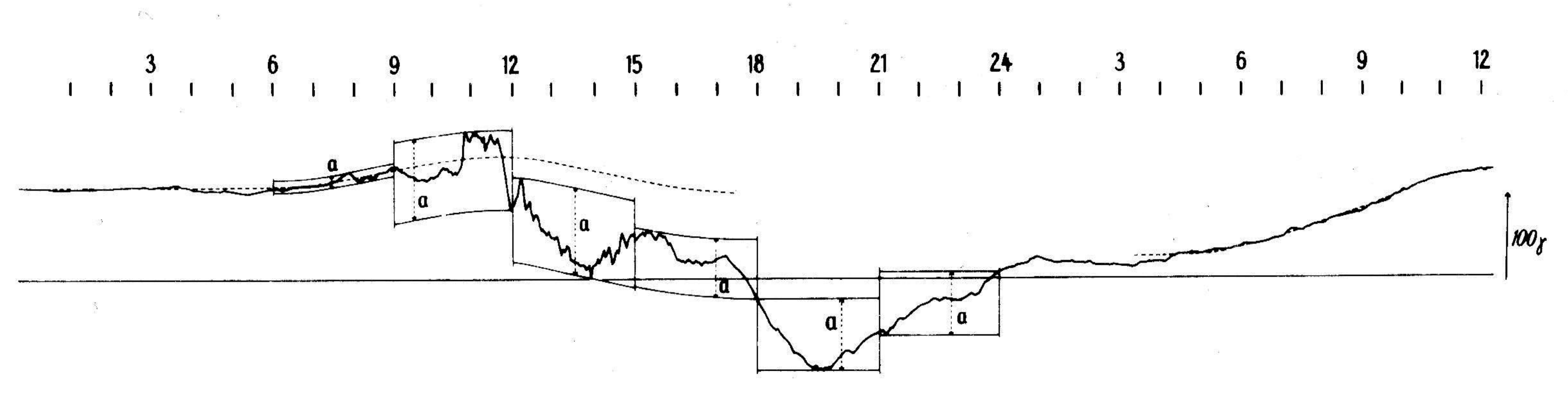


Figure from Mayaud, 1980

K index is an integer in the range 0 to 9 corresponding to a class that contains the largest range of geomagnetic disturbances in the two horizontal components during a 3-hour UT interval. The limits of these classes at a particular observatory are defined with the intent of producing a geomagnetic disturbance characterisation that does not depend significantly on the location of a sub-auroral, mid- or low-latitude observatory. K indices are assigned to successive 3-hour UT intervals (0-3 hr, 3-6 hr, ..., 21-24 hr UT) giving eight K indices per UT day.

K indices can be hand-scaled from magnetograms by an experienced observer, or computer derived using one of the four algorithms that are acknowledged by IAGA. (*Menvielle et al., 2008*)

THE CONCEPT OF MAGNETIC INDICES

Kp (ap)/Km (am)/aa

- USE OF MAGNETIC INDICES

  To select Magnetic Quiet Days:

  The physical processes related to solar radiations are dominant, except for quiet days after big storms ➡ ionospheric disturbance dynamo

THE CONCEPT OF MAGNETIC INDICES

Kp (ap)/Km (am)/aa

- K index weak => magnetic quiet day

  S_R dominates / radiation

- K index large => magnetic disturbed day

  Disturbance dominates / solar wind

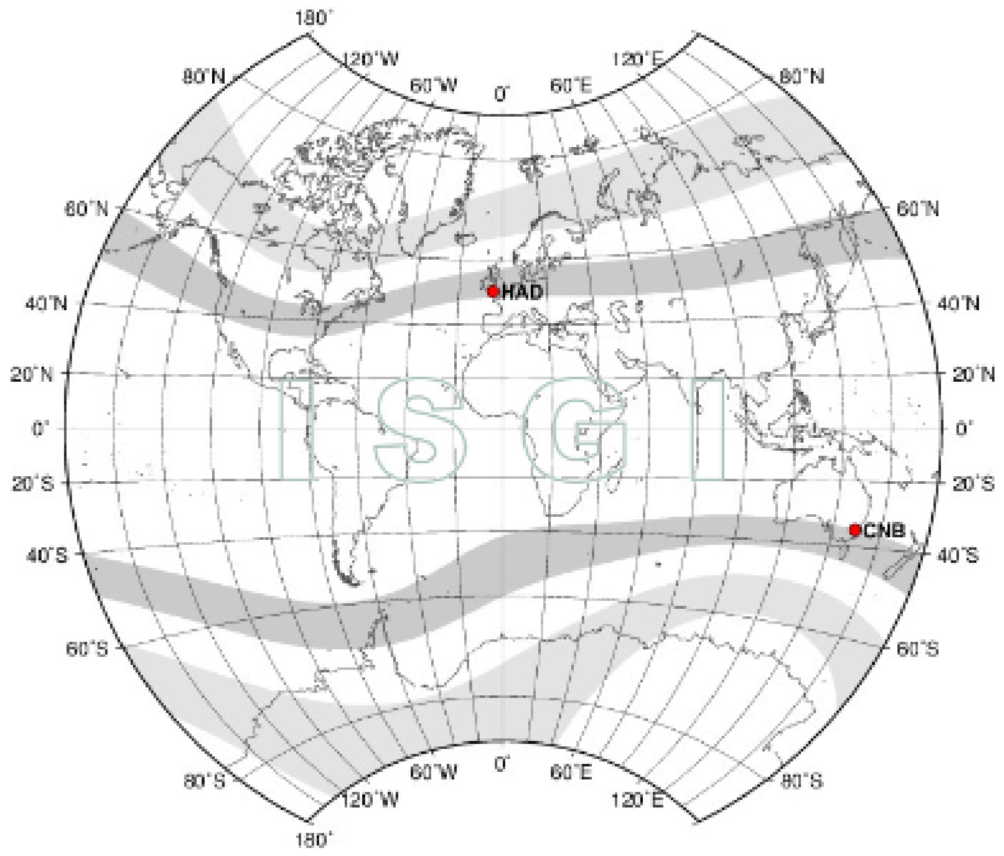
- Magnetic indices based on index K

Kp	Ap
Km	Am
Aa	

aa INDEX

Index	***aa*** **time resolution**: 3-hour (UT) interval **unit**: nT
Available	from 1868 onwards
Type of index	*K*-derived planetary
Purpose	To measure the amplitude of global geomagnetic activity during 3-hour intervals normalized to geomagnetic latitude ±50°. *aa* was introduced to monitor geomagnetic activity over the longest possible time period.
Network	Made of 2 antipodal magnetic observatories. (see **list of actual and previous *aa* magnetic observatories**)

Distribution of *aa* observatories

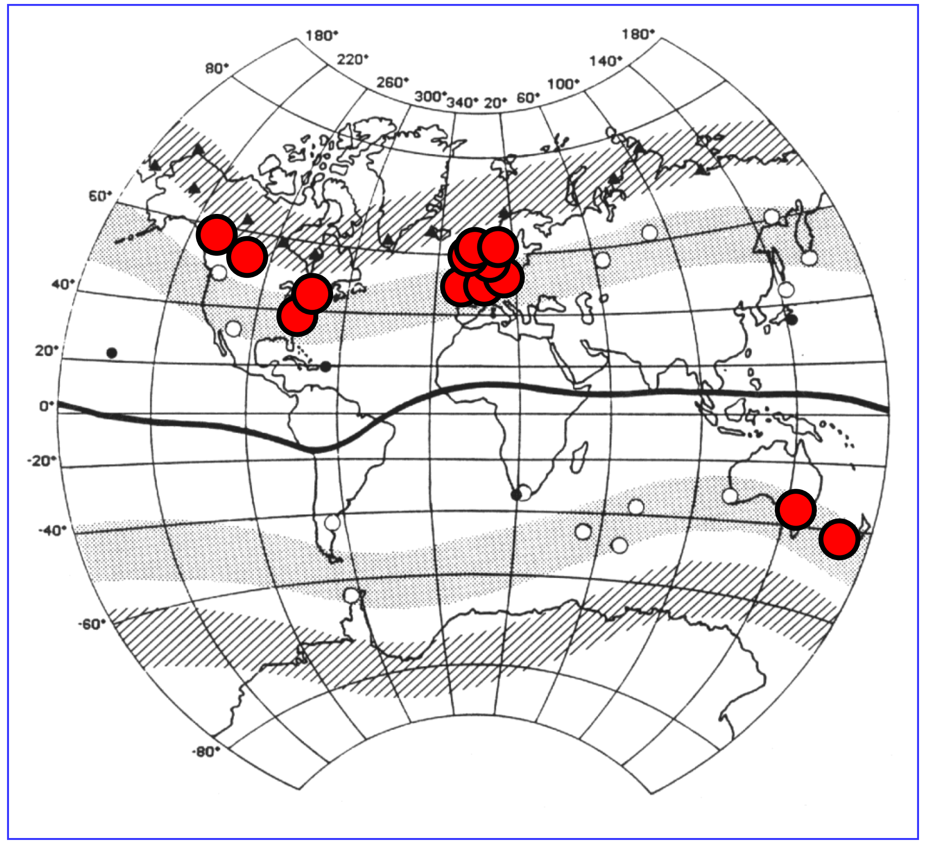


Citation	**Mayaud, P.-N., Menvielle, M., & Chambodut, A.** (2023). *aa geomagnetic index*. EOST. (Dataset). **doi:10.25577/9z05-v751**

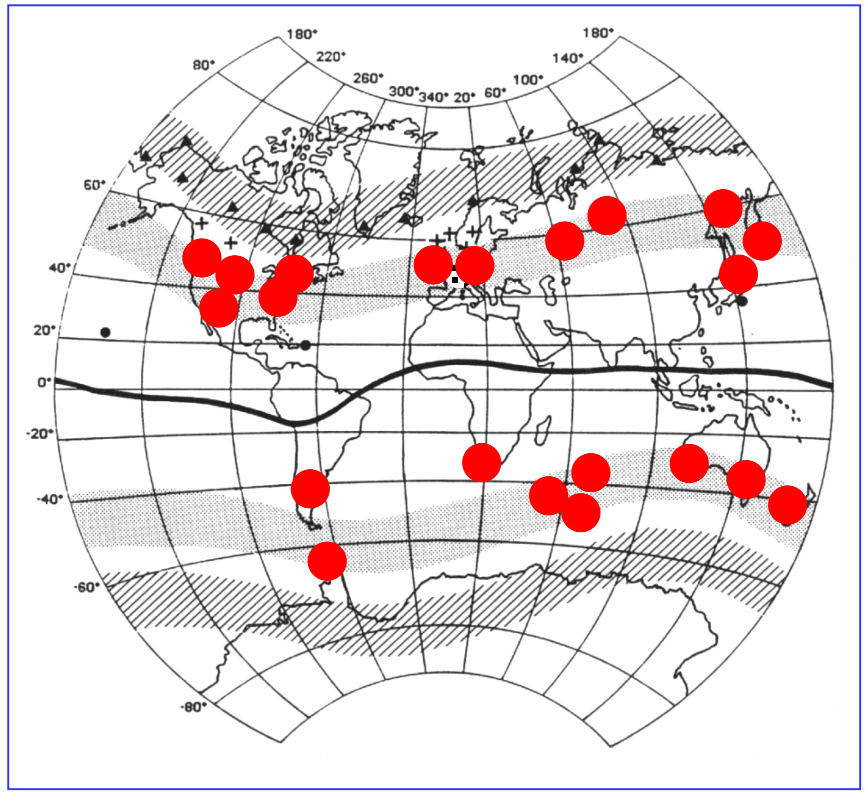
Stations used for the Kp (ap) and Km(am)

Quiet magnetic activity

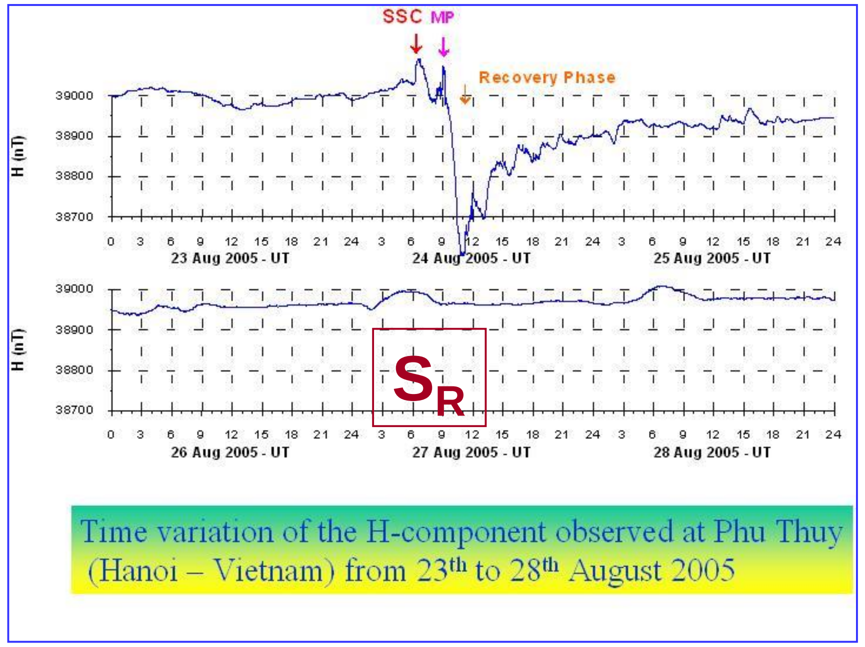
am/ap< 20nT=> quiet day ; am/ap < 13 nT => very quiet day with all the Km/Kp < 2+



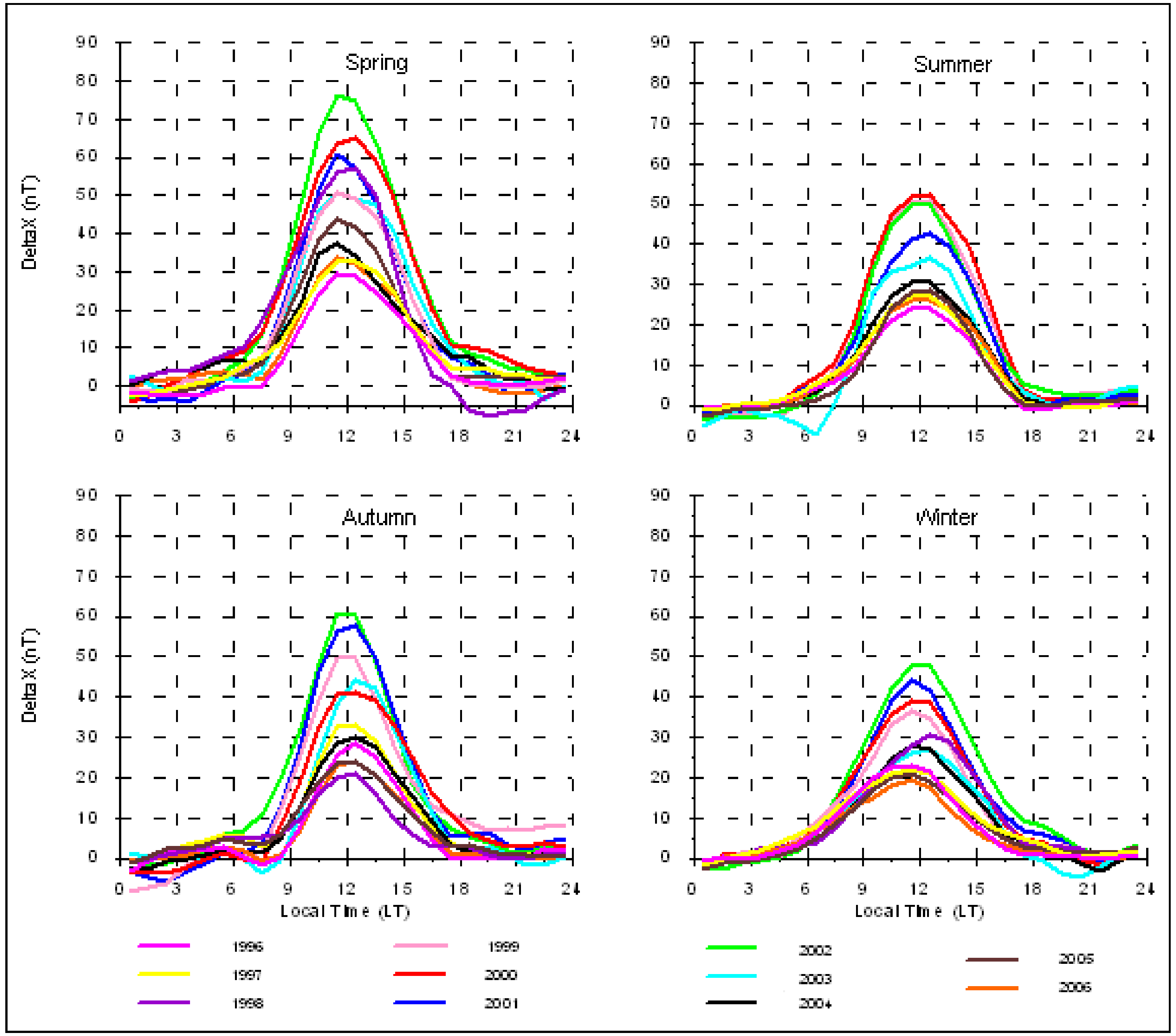
Kp: 12 observatories
9 in the northern hemisphere
2 in the southern hemisphere
(ap, Ap)



am: 23 observatories
12 in the northern hemisphere
9 in the southern hemisphere
K_N and K_S
(Km, Am)



Daily am/ap < 20 nT

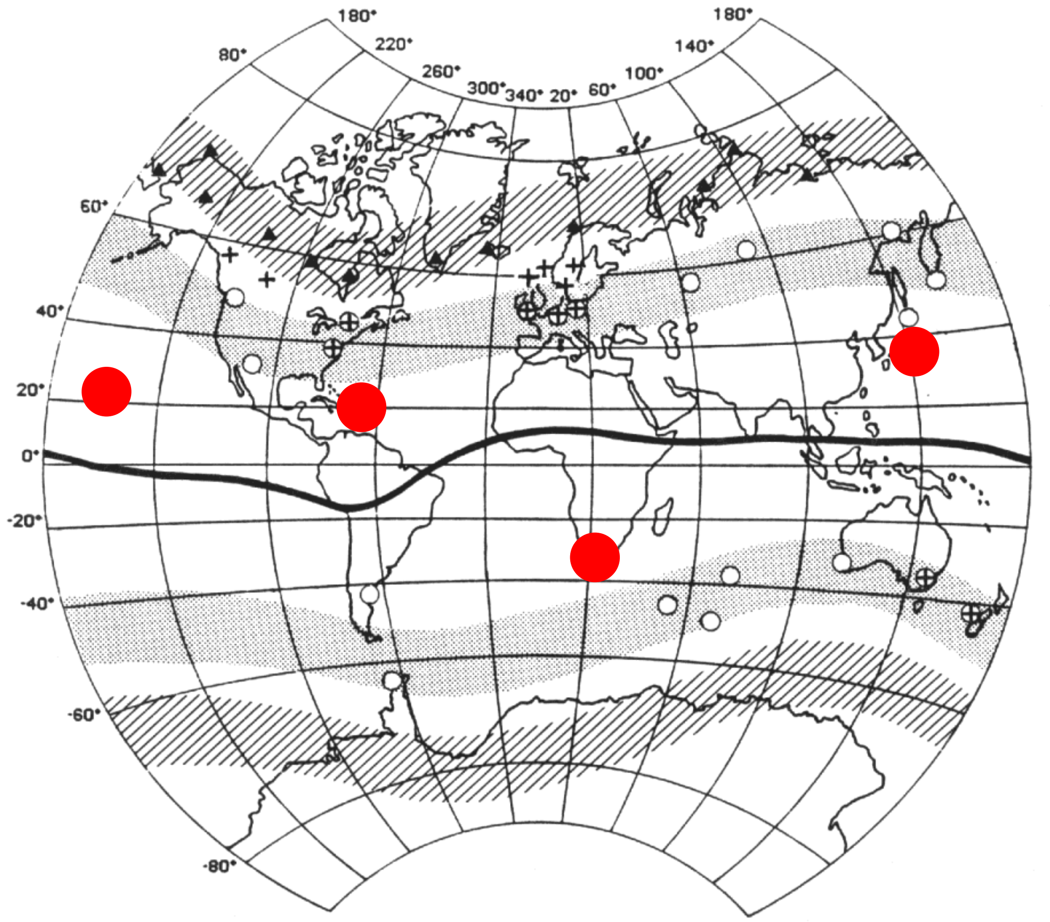


Study on the regular ionospheric dynamo at the origin of the S_R

The selection of days is essential for all Studies in GEOPHYSICS

Pham Thi Thu et al., 2009

H component observed at Phu Thuy/Vietnam
Solar cycle variations



Dst index ⟷ symmetric part of the ring current

Geomagnetic storm	SYMH-index (nT)
Super	-100 < SYMH ≤ -250
Intense	-50 < SYMH ≤ -100
Moderate	-30 < SYMH ≤ -50
Small (typical substorm)	-30 ≤ SYMH

Gonzalez et al., 1994

Dst is computed using 1-minute values from four low latitude observatories.

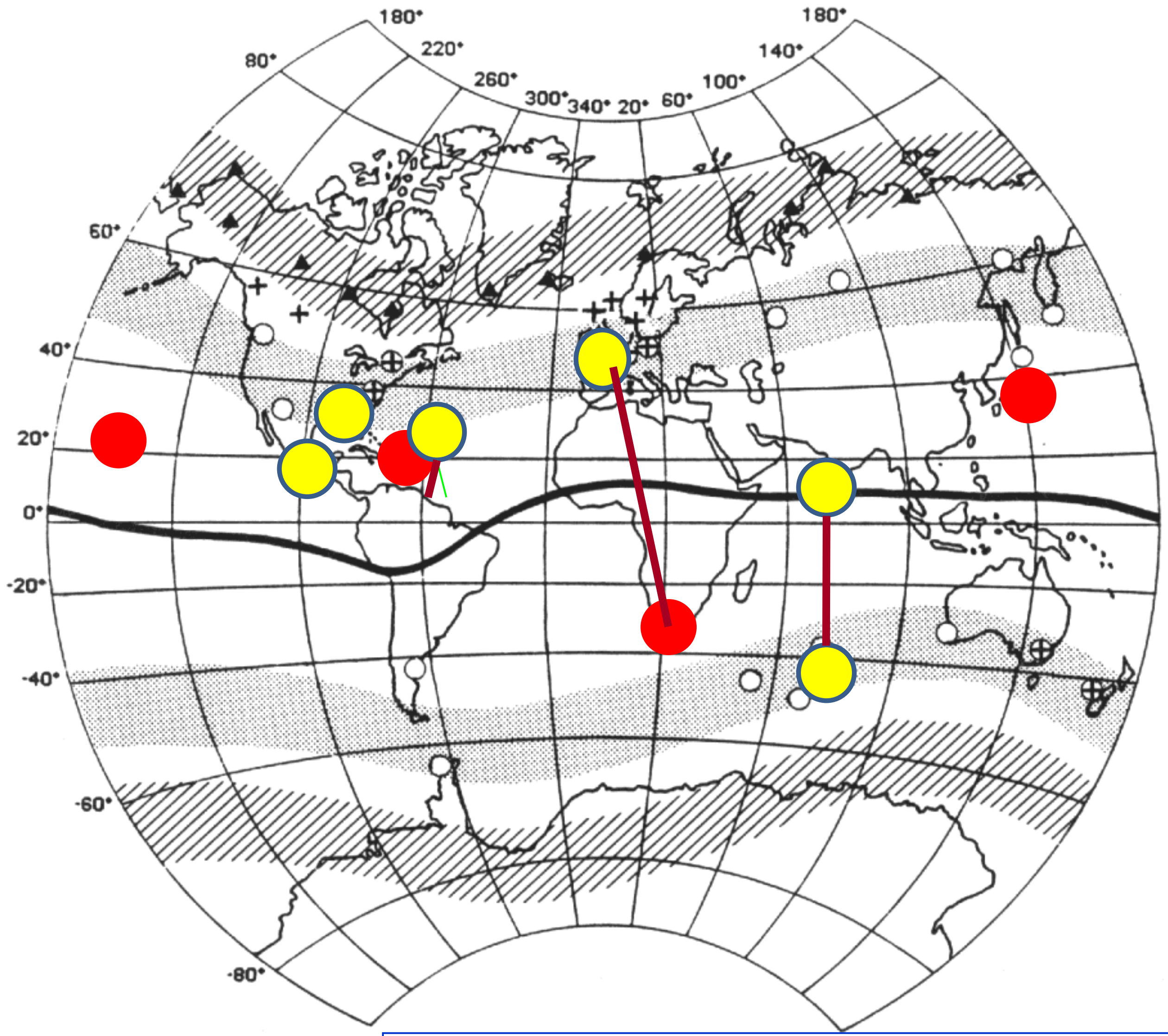
To monitor the axis-symmetric magnetic signature of magnetosphere currents, including mainly the ring current, the tail currents and also the magnetopause Chapman-Ferraro current.

Contributions to H from the background field (non-transient field of core and crustal origin) and the solar regular daily variation S_R are first subtracted from the observed value of H. The local Dst value is deduced from the so-obtained residual D through normalization to the dipole equator.
For each 1-hour UT interval, the Dst index is the average of the local Dst hourly mean values at the four "Dst" observatories." (Menvielle et al., 2008).

SYM and ASY indices
SYM (1') ⇔ Dst (1h)

SYMH + ASYH

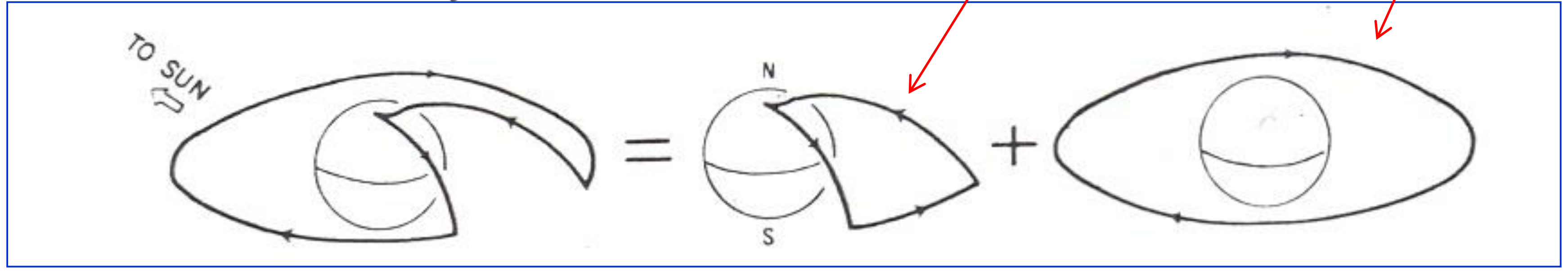
Dst



Describe the geomagnetic disturbances in terms of longitudinally asymmetric (*ASY*) and symmetric (*SYM*) disturbances for both *H* and *D* components respectively parallel and perpendicular to the dipole axis.

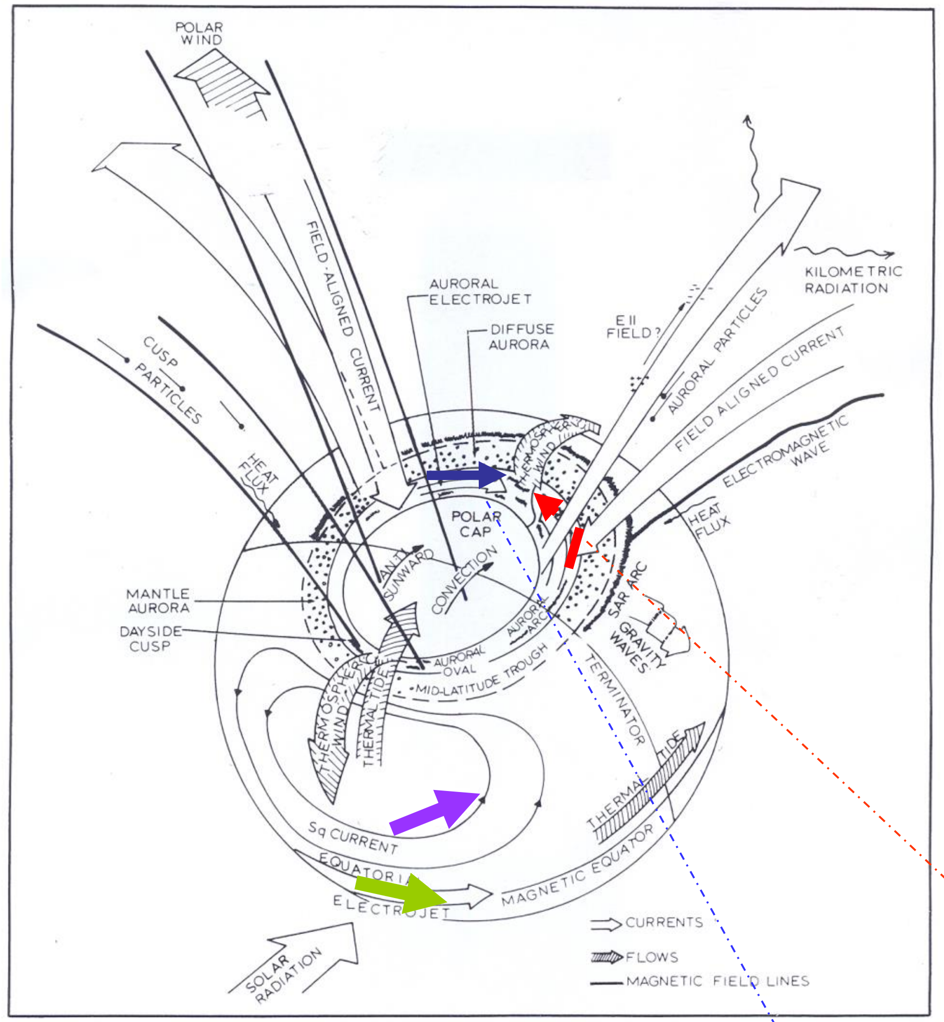
ASYH

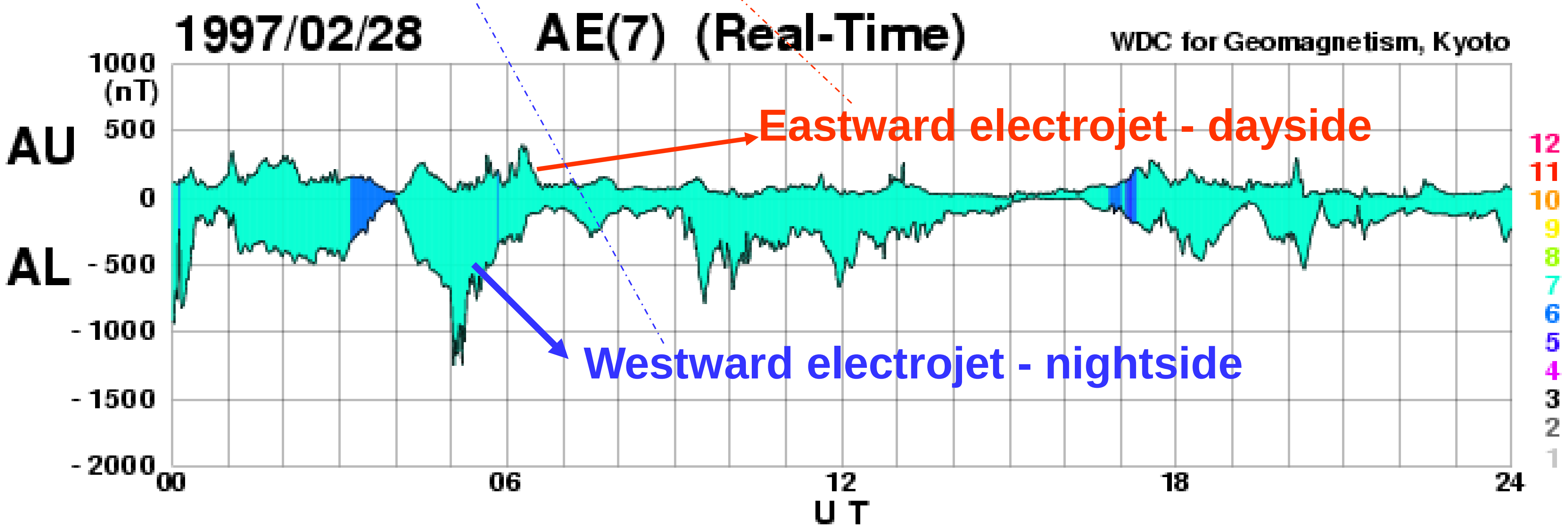
SYMH ~ Dst



Auroral indices

Auroral electrojets

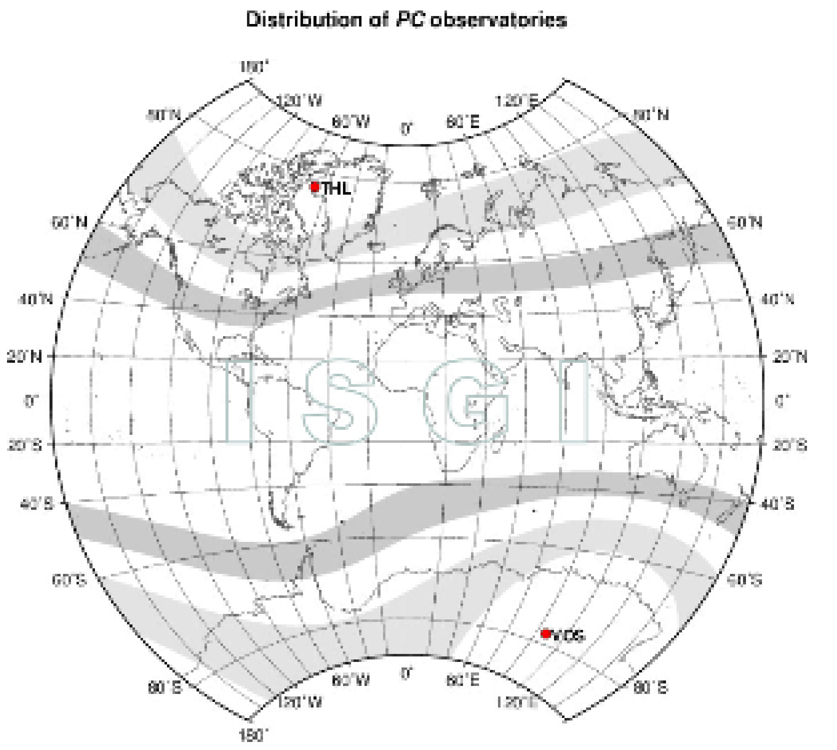




From ISGI website

POLAR CAP (*PC*) MAGNETIC ACTIVITY INDICES

Indices	*PCN, PCS* **time resolution**: 1 minute (UT) interval **unit**: mV/m
Available	*PCN*: from 1975 onwards *PCS*: from 1995 onwards
Type of index	Polar Cap index horizontal component disturbances
Purpose	To monitor the geomagnetic activity over the polar caps caused by changes in the interplanetary magnetic field (IMF) and solar wind, driven by the geoeffective interplanetary electric field irrespective of time, season and solar cycle.
Network	Made of 2 polar cap stations. (see **list of actual and previous *PC* magnetic observatories**)
Derivation	The *PC* index is deduced (*) from the deviations in the horizontal H and D magnetic field components from the quiet level at two polar cap stations (Thule and Vostok for respectively the *PCN* and *PCS*). (*) More specific and detailed information may be found on the **PC-index website** devoted to *PC* index.

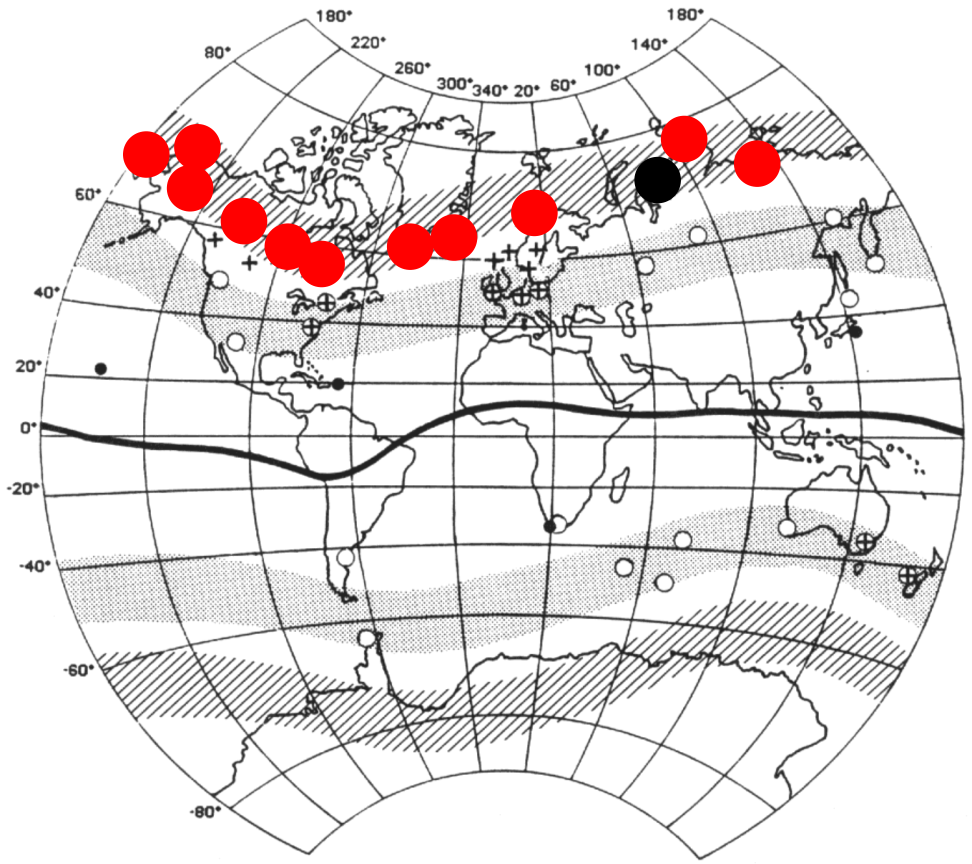


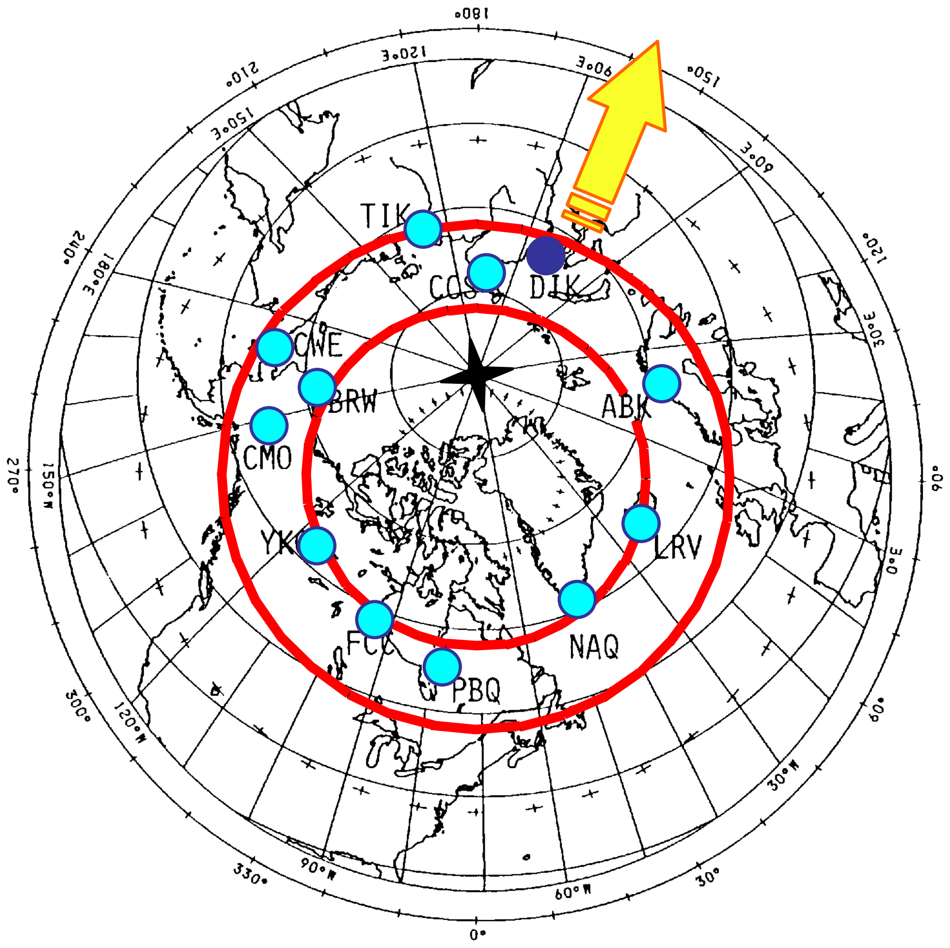
The Polar cap (PC) index is a proxy of the merging electric field.

$EM = V_{SW} B_T \sin2(\theta/2)$ (2)

The solar wind velocity, V_{SW}, and the transverse component, B_T , ($B_T = (B_Y^2 + B_Z^2)^{1/2}$) of the interplanetary magnetic field (IMF) in the solar wind includes a strong dependence on the field direction represented by the polar angle θ of the transverse component of the IMF with respect to the direction of the Z-axis in a “Geocentric Solar Magnetospheric” (GSM) coordinate system (i.e., $\tan(\theta) = |B_Y|/B_Z$, $0 \le \theta \le \pi$). (Stauning, 2012)

AU, AL
auroral electrojets





The H magnetograms from the "AE" stations are superimposed: the upper envelope defines the AU index, and the lower envelope defines the AL index;
AE = (AU-AL) and AO = (AU-AL) / 2.

From 2005 onwards, the AE indices are calculated from data from up to 12 sites in the northern auroral zone and is expressed in nT units (Menvielle et al., 2008)

Summary

Magnetic indices are

- **Transdisciplinary tools**
- **Computed continuously**
- **Available on the web**
- **Essential to:**

    - Define the geophysical context

    - Approach physical parameters

    - Classify days, etc.

How to study a geomagnetic storm

General Guidelines

1.- Identify the event in the given period.

2.- Characterize the Solar-Terrestrial conditions.

- Use available solar and magnetic indices to characterize the impact of the solar event.

3.- Select the dataset of the region of study (latitudes, longitudes, stations).

4 .- Characterize the regular variation (based on selection of Quiet Days)

5.- Analyze the effect of the disturbance on TEC, Ne, earth magnetic field, etc.

Online Resources

- Indices and geomagnetic data -

https://solarscience.msfc.nasa.gov/SunspotCycle.shtml
https://www.swpc.noaa.gov/products/solar-cycle-progression
Sunspot cycle

www.spaceweather.com
https://www.swpc.noaa.gov/
https://swe.ssa.esa.int/
SW general situation (CME-Solar Flare -Coronal Hole)

https://kp.gfz-potsdam.de/en/hp30-hp60
HPO

https://www.swpc.noaa.gov/products/predicted-sunspot-number-and-radio-flux
F10.7cm, sunspot number

http://isgi.unistra.fr/geomagnetic_indices.php
Aa, A_p/K_p, A_m/K_m

WORLD DATA CENTER KYOTO
http://wdc.kugi.kyoto-u.ac.jp/
All indices and some magnetometers

OMNIWEB
https://omniweb.gsfc.nasa.gov
V_s B_{imf}, E_{yimf}, SYM-H, Dst, AU, AL AE

MAGNETOMETERS INTERMAGNET
http://www.intermagnet.org/
Magnetometers all over the world

Online Resources
- Catalogs and ionospheric data -

https://giro.uml.edu/
GIRO ionogram database

https://arplsrv.ictp.it
ICTP Calibrated TEC service

https://cdaw.gsfc.nasa.gov/CME_list/
List of CME

http://www.geodin.ro/varsiti/
List HSSW

https://xrt.cfa.harvard.edu/flare_catalog/
List of SF

https://obsebre.es/en/variations/rapid
List of SSC, SFe

http://guvitimed.jhuapl.edu/data_products
GUVI O/N2

https://gold.cs.ucf.edu/data/search/
GOLD O/N2

GNSS Websites with available free data

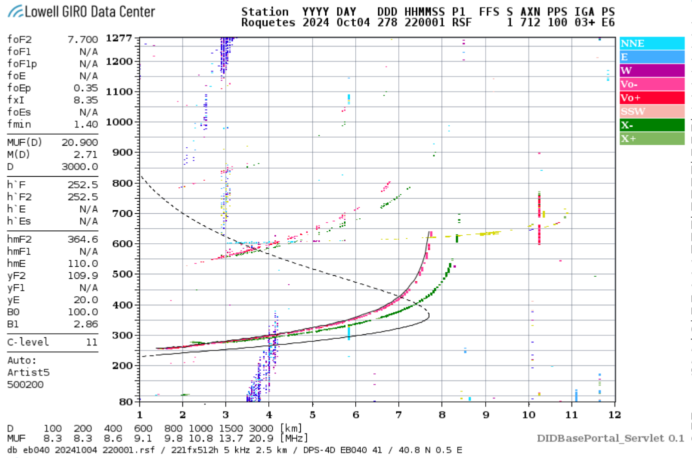
About RINEX format: ftp://igs.org/pub/data/format/
Hatanaka Format Information at UNAVCO
https://www.unavco.org/data/gps-gnss/hatanaka/hatanaka.html

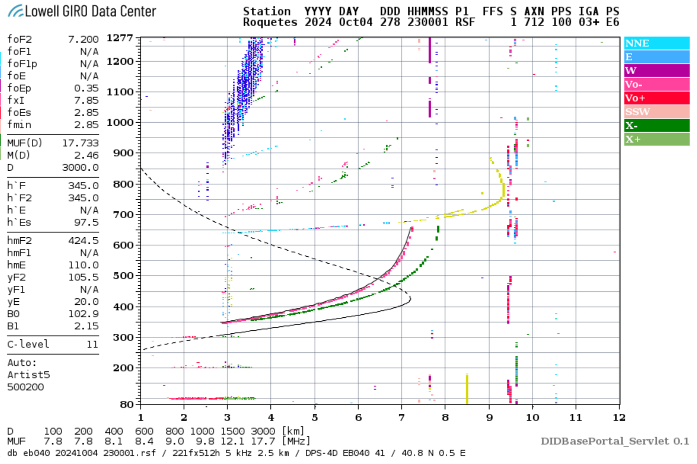
IGS network http://www.igs.org/about/data-centers
CDDIS (USA) - 1992-now: https://cddis.nasa.gov/Data_and_Derived_Products/GNSS/
SOPAC (USA) - 1988-now: https://garner.ucsd.edu/pub/rinex/
CORS https://www.ngs.noaa.gov/CORS/data.shtml
GARNER http://garner.ucsd.edu/pub/
ftp://garner.ucsd.edu/rinex/
IGN (France) - 1990-now: https://rgp.ign.fr/
BKG (Germany) - 1991-now: https://igs.bkg.bund.de/
UNAVCO (USA) - 1992-now: https://www.unavco.org/data/gps-gnss/data-access-methods/dai1/perm_sta.php
EUREF https://www.epncb.oma.be/
AFREF (South Africa) - 2004-now: https://ftp.afrefdata.org/
only stations in Africa
SONEL https://sonel.org/
MGEX Campaign ftp://igs.ign.fr/pub/igs/data/campaign/mgex/daily/rinex3/
AuScope (Australia) - 1993-now: ftp://ftp.ga.gov.au/geodesy-outgoing/gnss/data/daily/
stations in Australia and Pacific
TIGA - 1990-now: ftp://ftp.sonel.org/gps/data/
stations near sea
NOAA - 1994-now: ftp://geodesy.noaa.gov/cors/rinex/
stations mainly in the USA
IONEX (MAPS) https://cddis.gsfc.nasa.gov/gps/products/ionex/
ftp://ftp.unibe.ch/aiub/CODE/

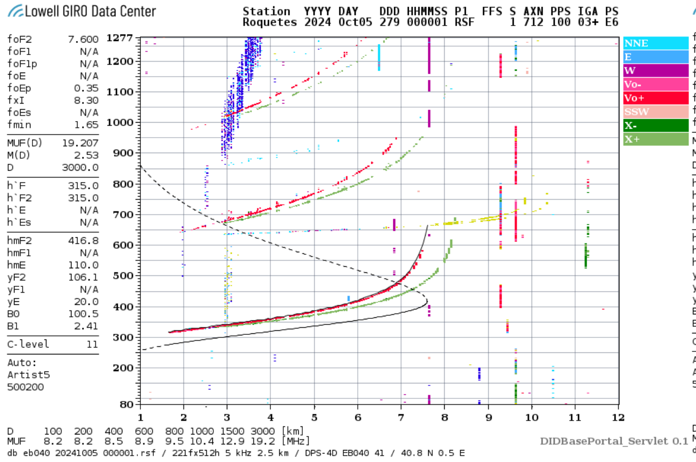
http://mycoordinates.org/
Space Weather, From the Sun to the Earth : the key role of GNSS
Part 1: February
Part 2: March

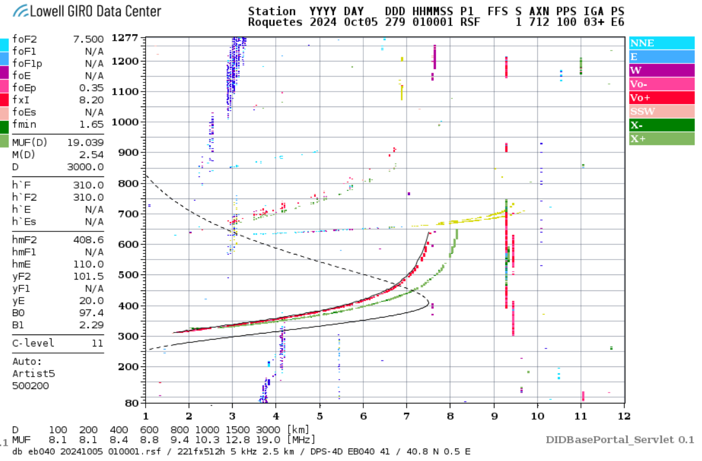
Roquetes

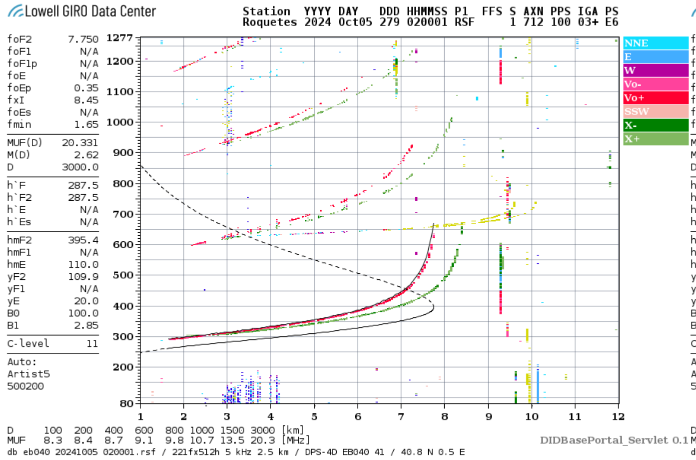
Quiet Day

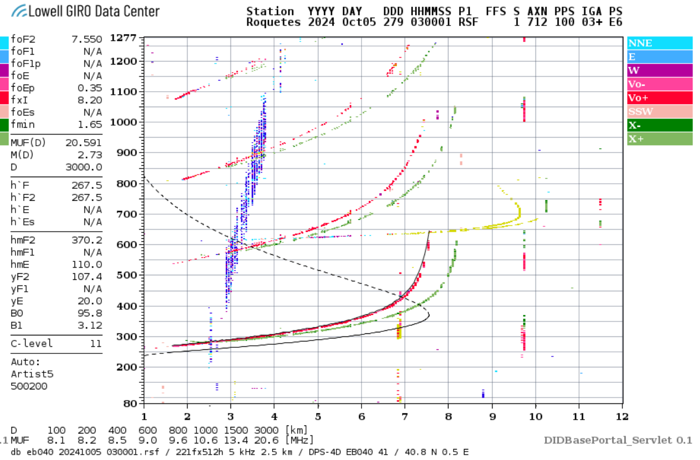




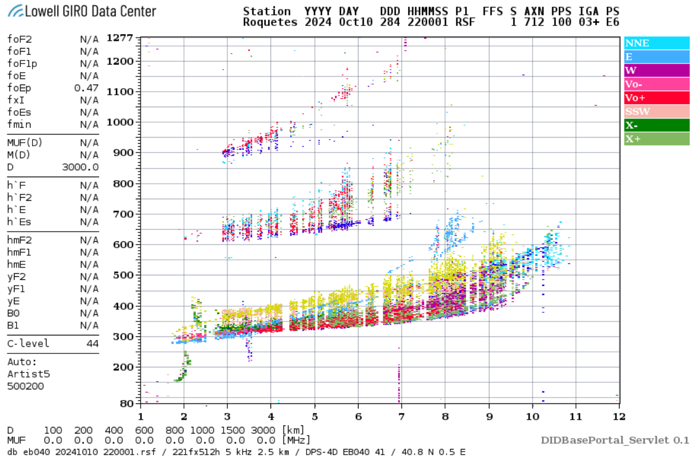


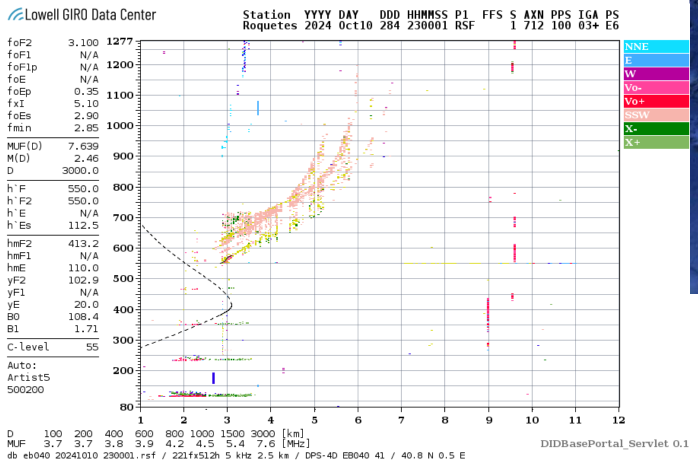


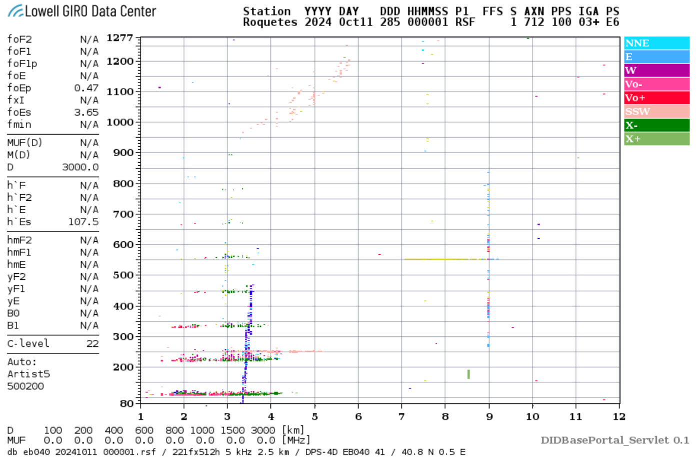


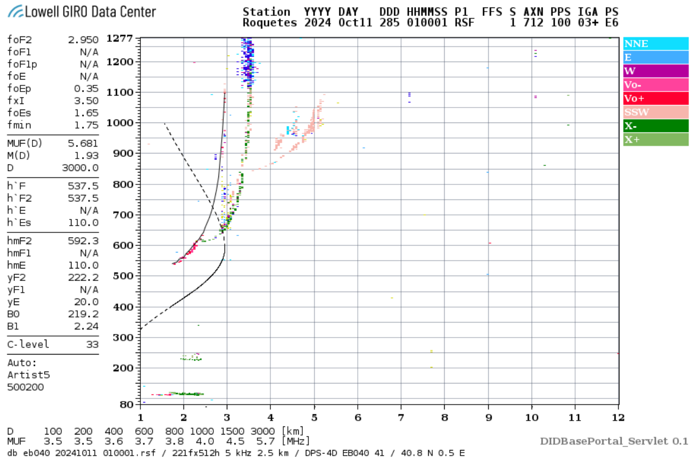


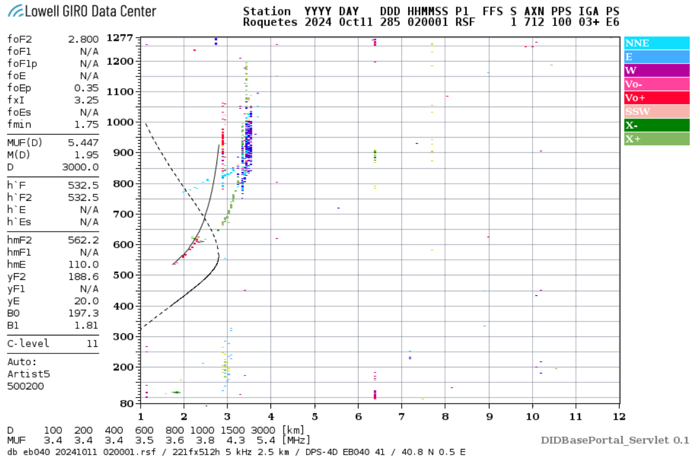
Storm Day

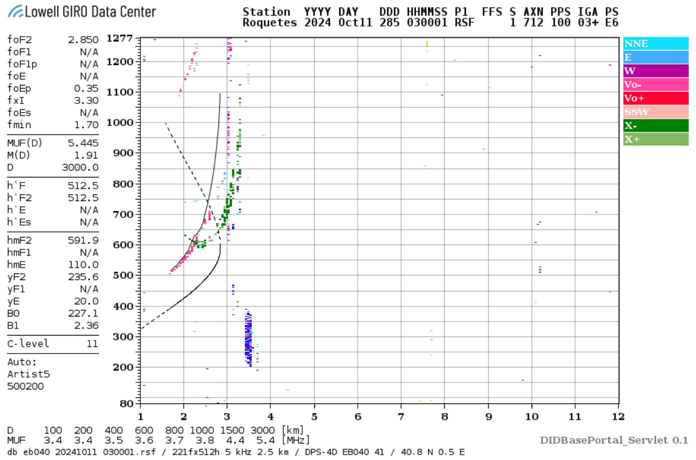






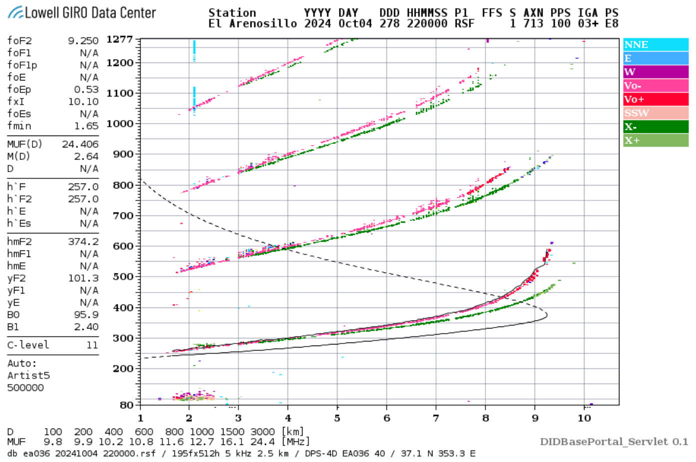


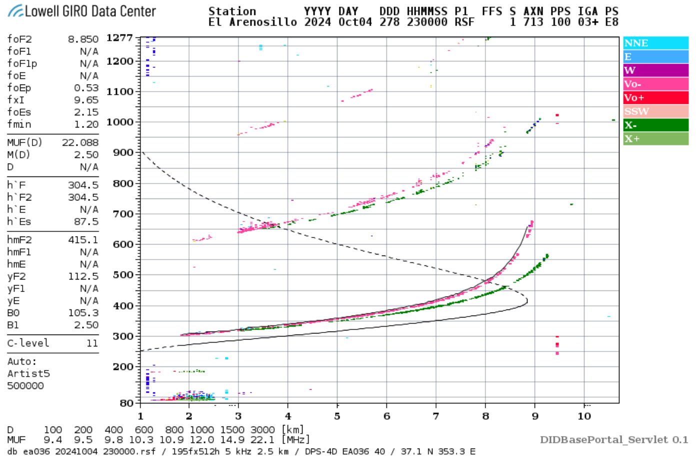


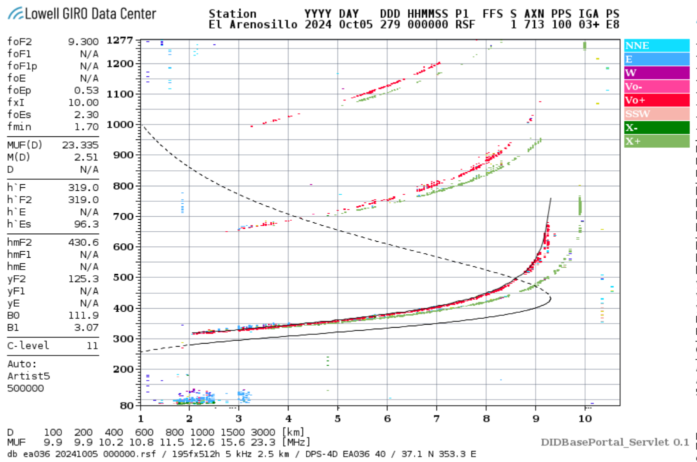


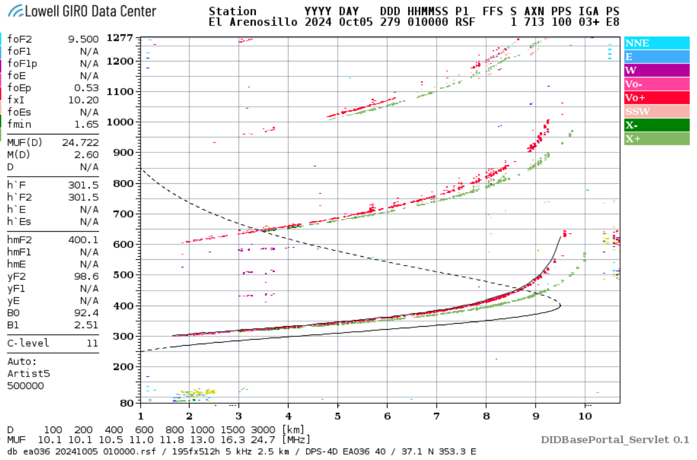
El Arenosillo

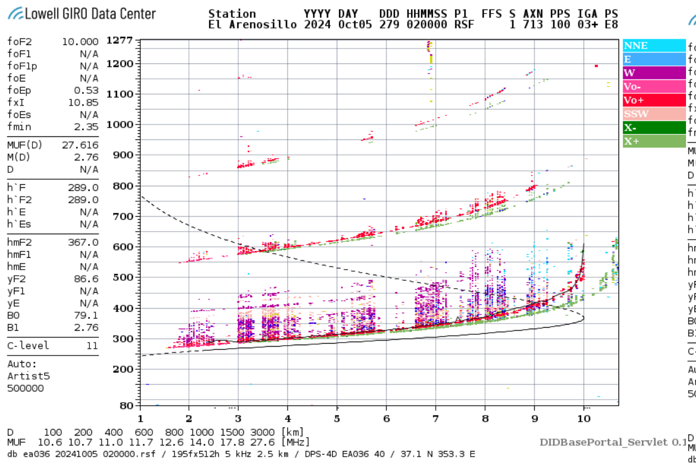
Quiet Day

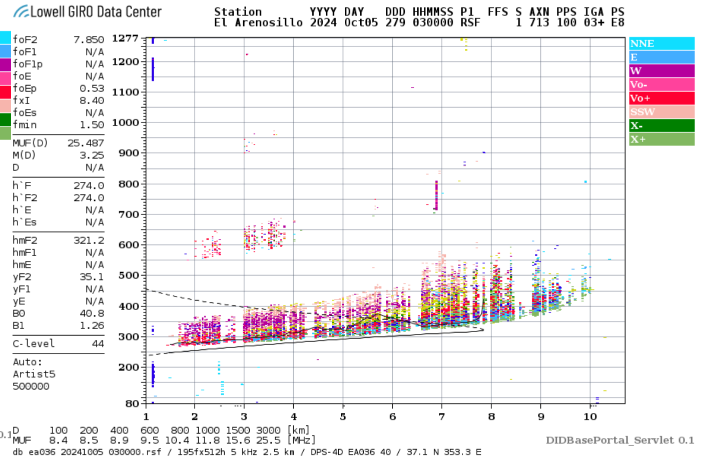




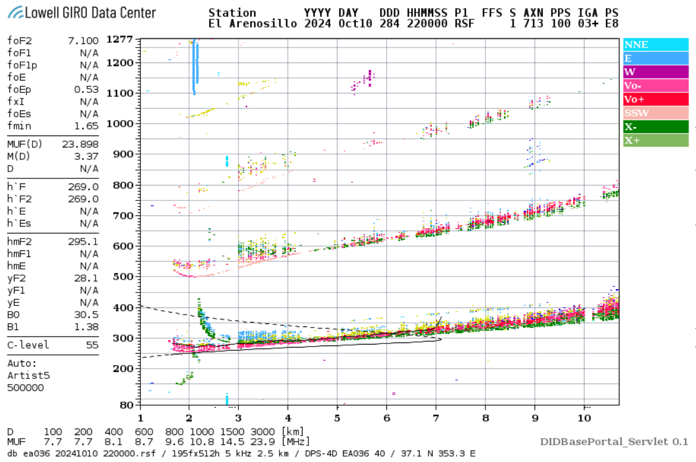


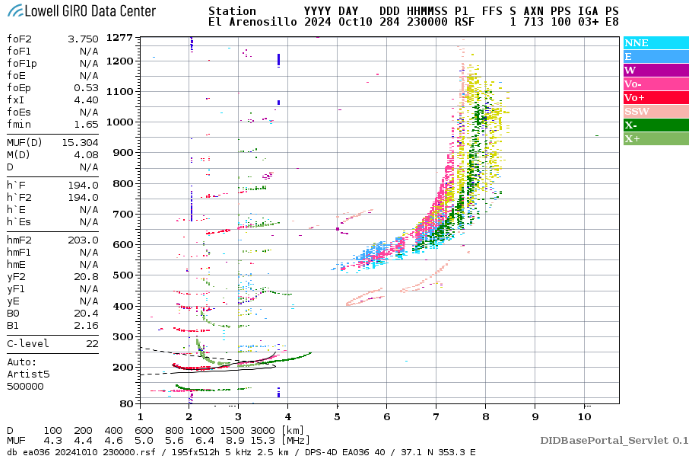


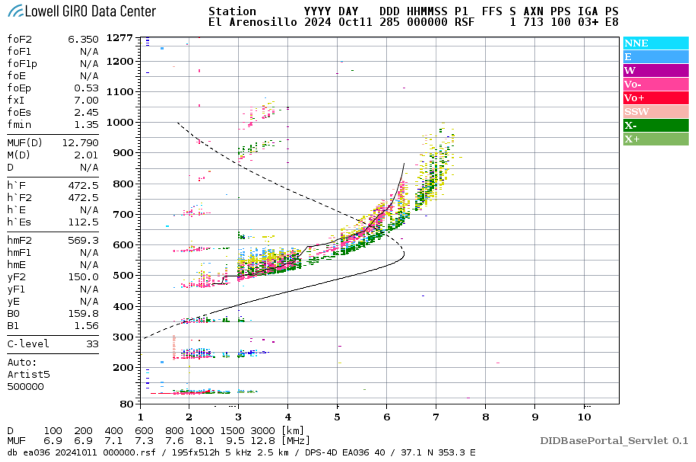


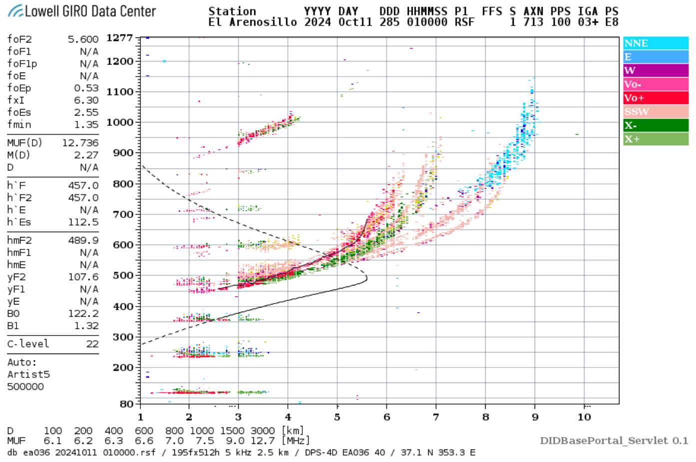


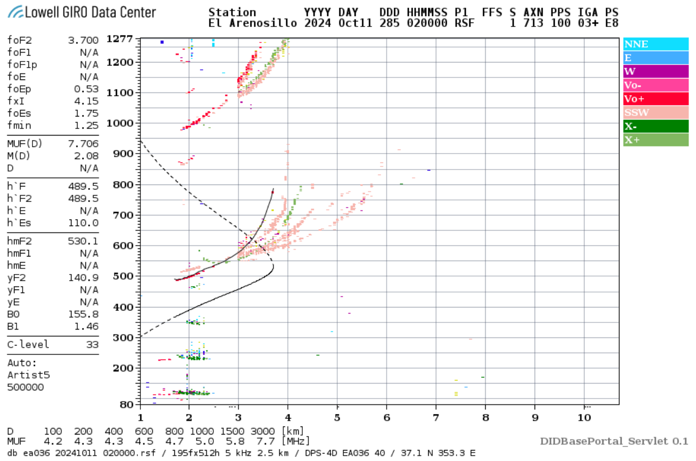
Storm Day

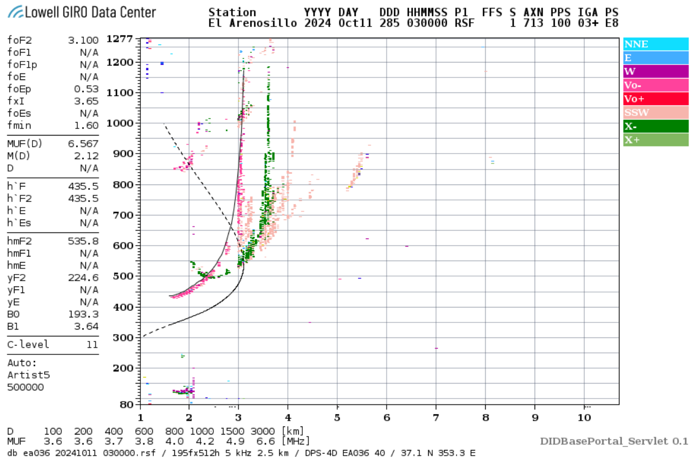


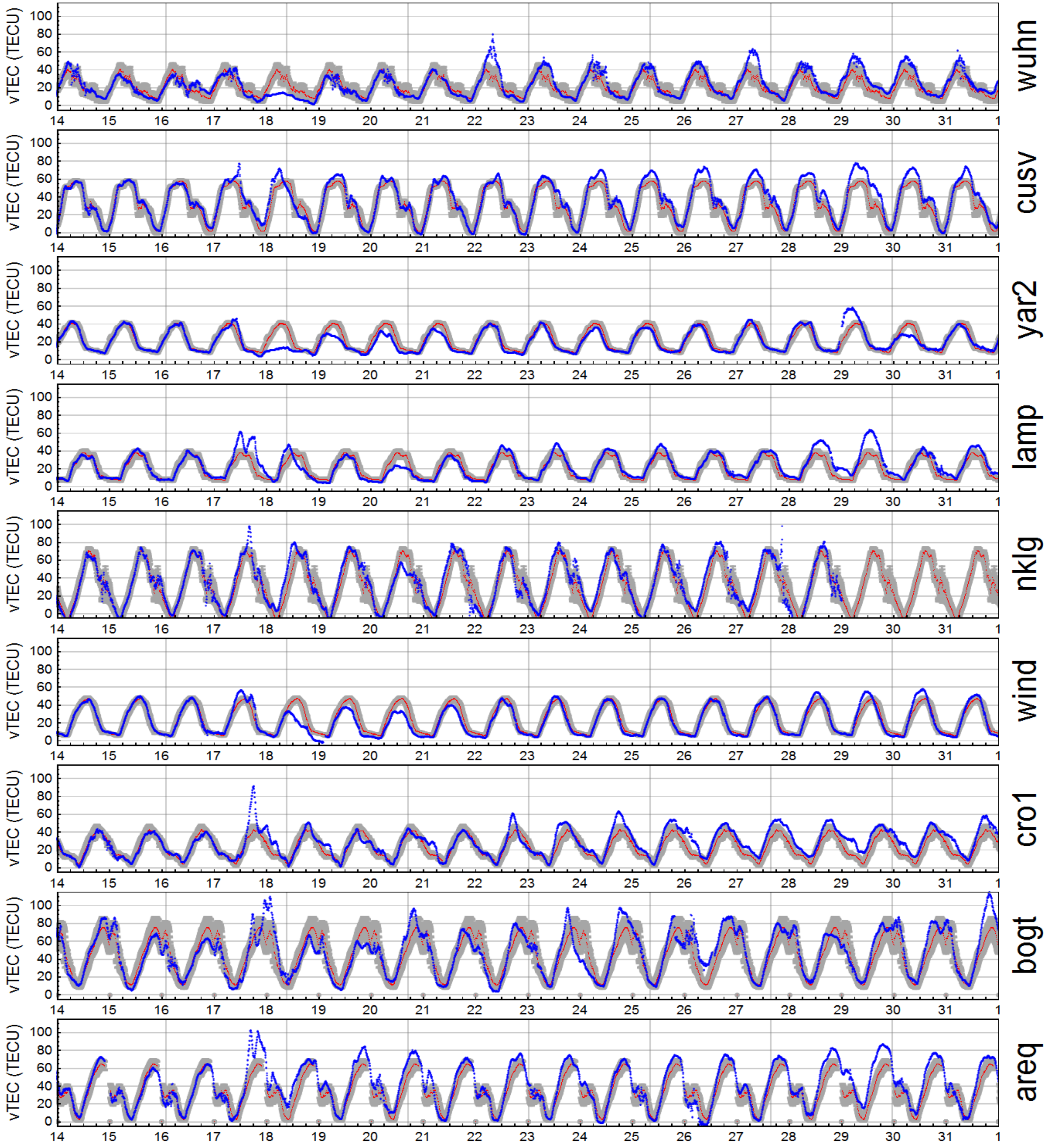




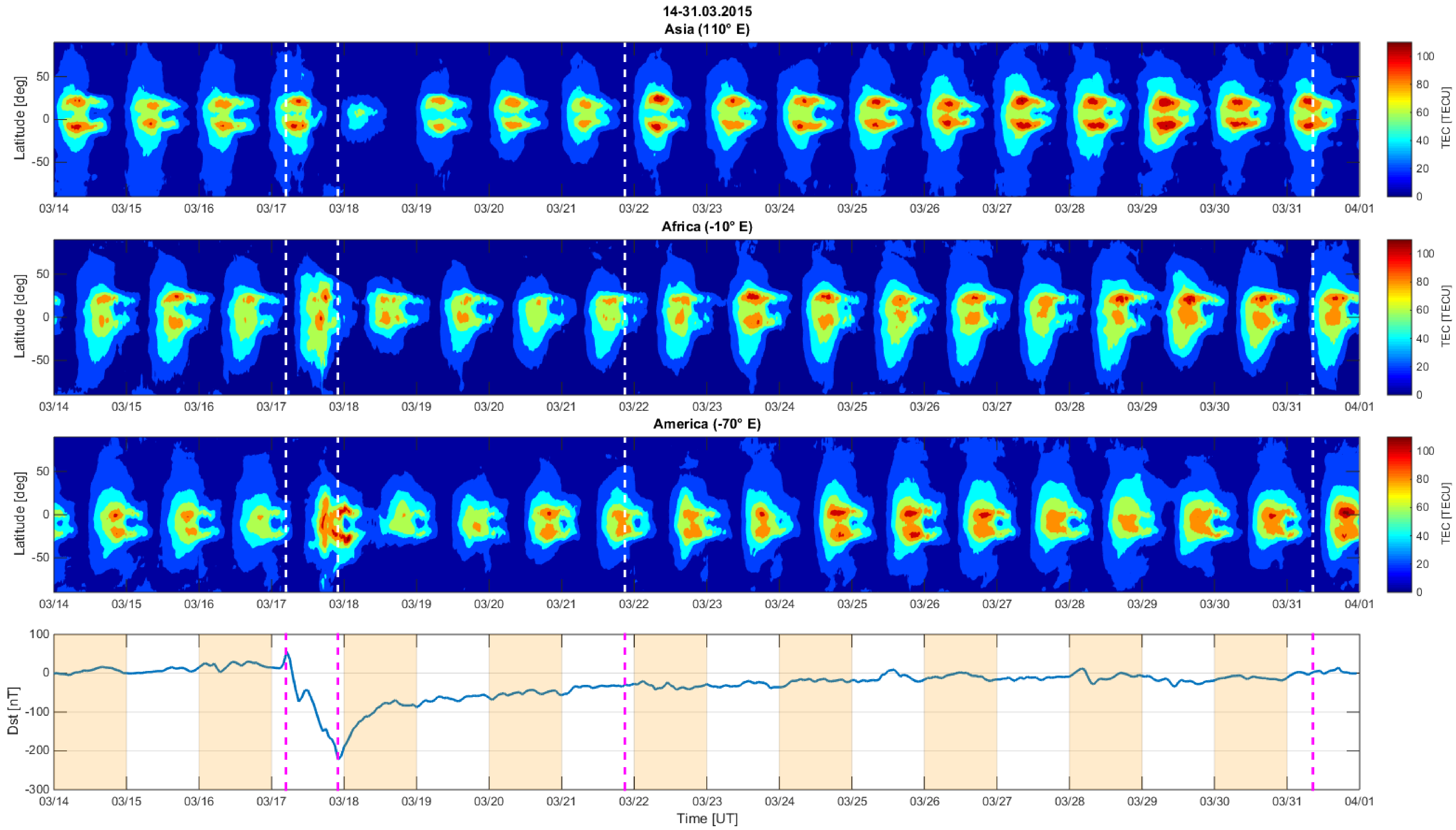








Nava B. Nava, J. Rodríguez-Zuluaga, K. Alazo-Cuartas, A. Kashcheyev, Y. Migoya-Orué, S.M. Radicella, C. Amory-Mazaudier, R. Fleury, Middle- and low-latitude ionosphere response to 2015 St. Patrick's Day geomagnetic storm, 2016



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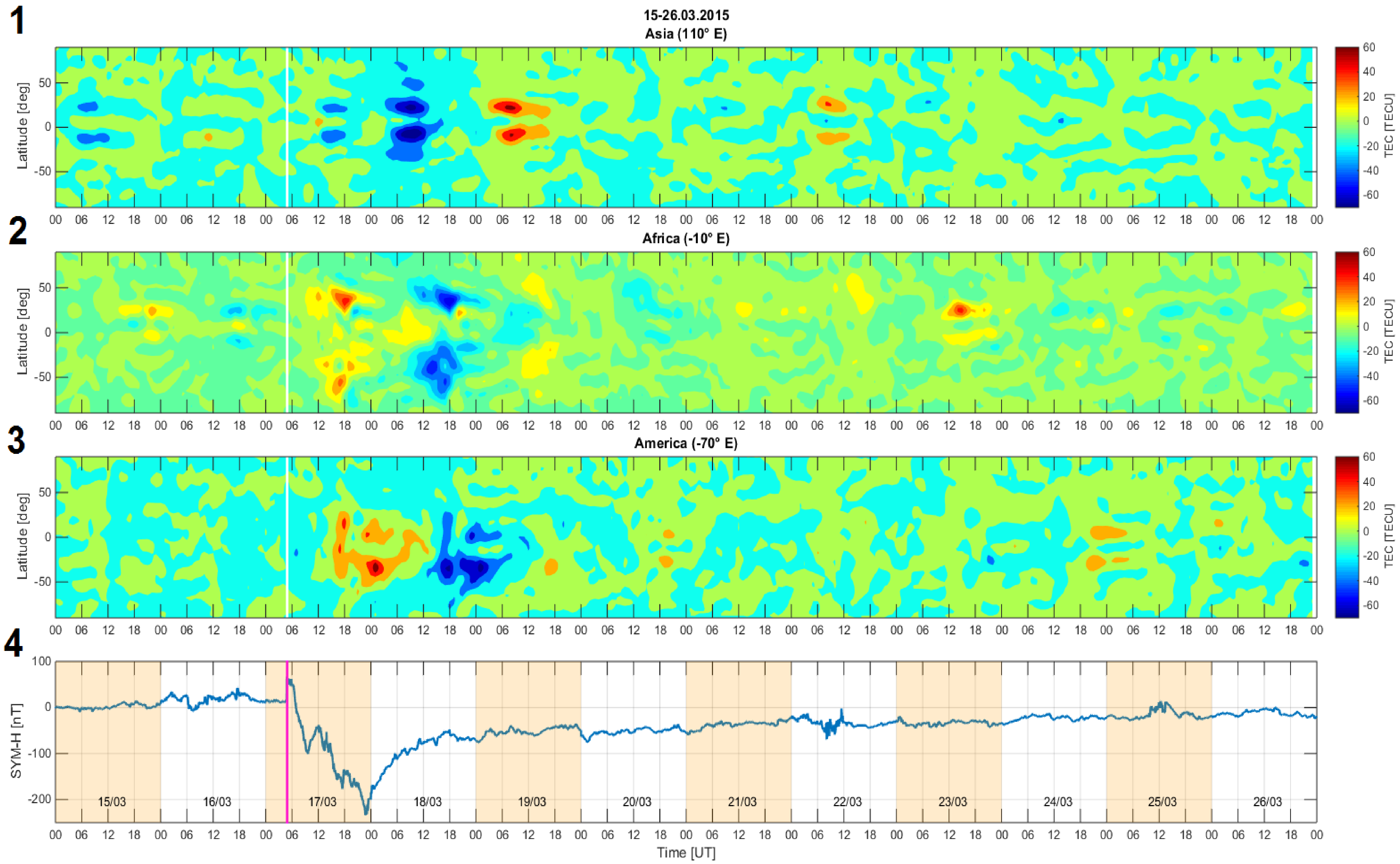

A. Kashcheyev, Y. Migoya-Orué, C. Amory-Mazaudier, R. Fleury, B. Nava, K. Alazo-Cuartas and S.M. Radicella, Multi-variable comprehensive analysis of two great geomagnetic storms of 2015, 2018.

Thank you

yenca@ictp.it

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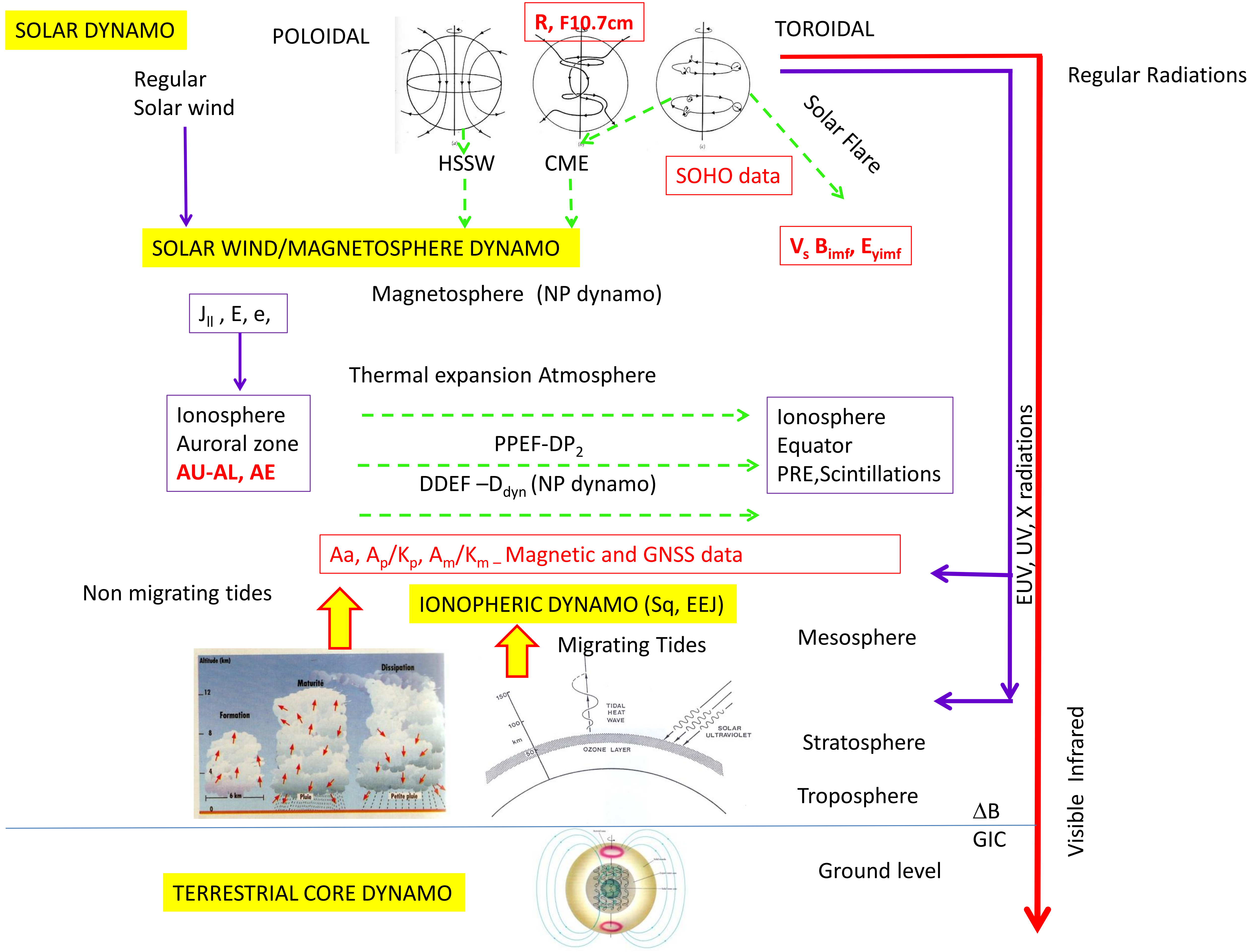
Backup Slides



SOLAR DYNAMO
POLOIDAL
R, F10.7cm
TOROIDAL
Regular Radiations
Regular
Solar wind
HSSW
CME
SOHO data
Solar Flare
SOLAR WIND/MAGNETOSPHERE DYNAMO
V_s B_{imf}, E_{yimf}
Magnetosphere (NP dynamo)
$J_{||}$, E, e,
Thermal expansion Atmosphere
Ionosphere
Auroral zone
AU-AL, AE
PPEF-DP_2
DDEF –D_{dyn} (NP dynamo)
Ionosphere
Equator
PRE,Scintillations
EUV, UV, X radiations
Aa, A_p/K_p, A_m/K_m – Magnetic and GNSS data
Non migrating tides
IONOPHERIC DYNAMO (Sq, EEJ)
Migrating Tides
Mesosphere
Altitude (km)
Maturité
Dissipation
Formation
Pluie
Petite pluie
6 km
TIDAL
HEAT
WAVE
SOLAR
ULTRAVIOLET
OZONE LAYER
km
Stratosphere
Troposphere
ΔB
GIC
Visible Infrared
Ground level
TERRESTRIAL CORE DYNAMO

PPEF and DDEF

- PPEF : Prompt Penetration of the magnetospheric electric field
- Current system DP2

- DDEF: Disturbance Dynamo Electric field
- Current system Ddyn

H component at middle and low latitudes

$$\Delta H = \mathbf{Sq/S_R + SYM\text{-}H + \ Diono}$$

$Sq = \langle S_R \rangle$ on quiet days

Dayside only

$$D_{iono} = \Delta H - Sq/S_R - SYM\text{-}H \cos(\lambda)$$

λ: dip latitude

$\cos(\lambda)=1$ at the Equator

$\cos(\lambda)= 0$ at the pole

at Low latitudes : $D_{iono} = DP_2 + D_{dyn}$