Ionospheric sounding at the RMI Geophysical Centre in Dourbes: digital ionosonde performance and ionospheric monitoring service applications

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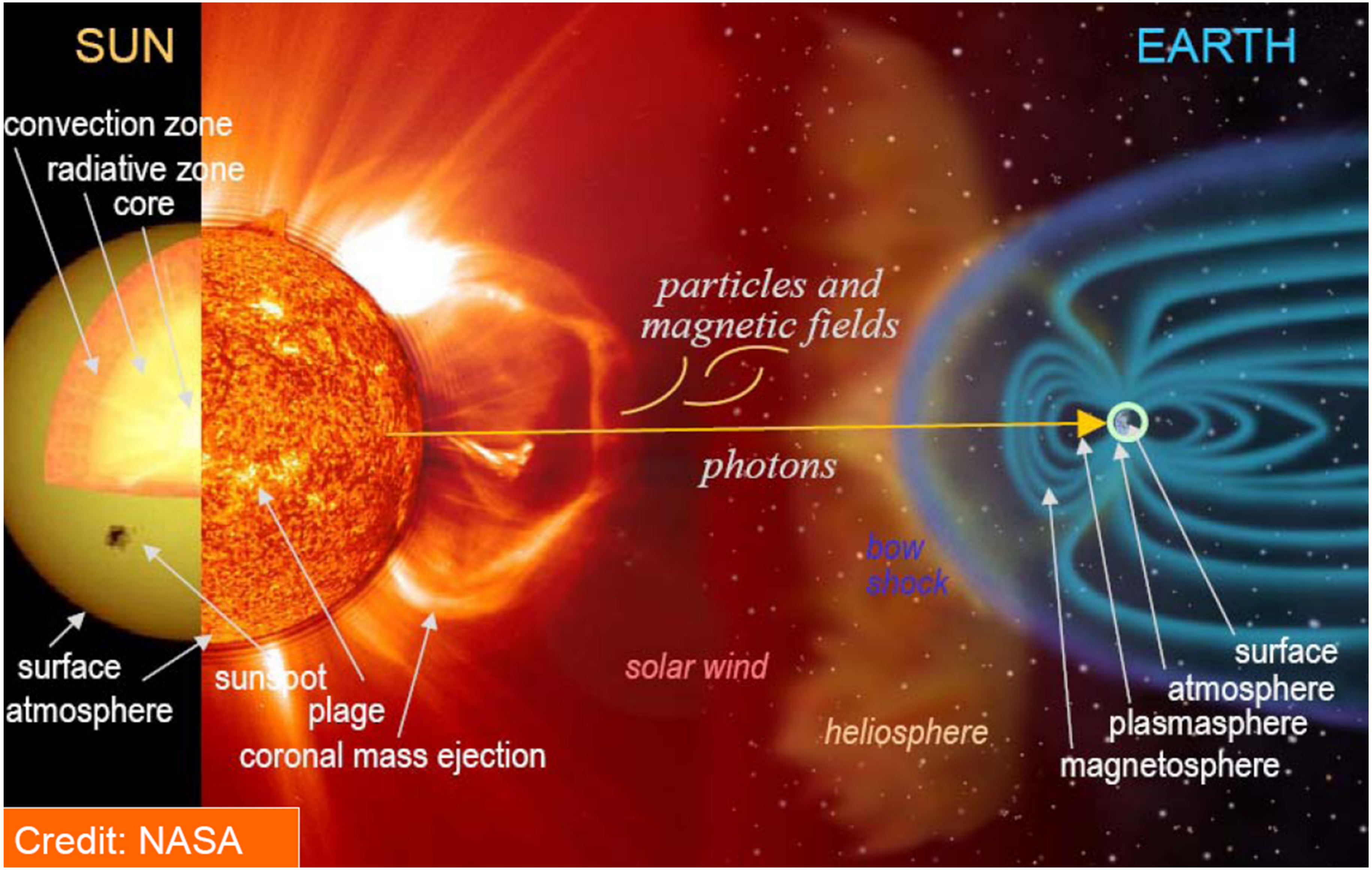
Outline

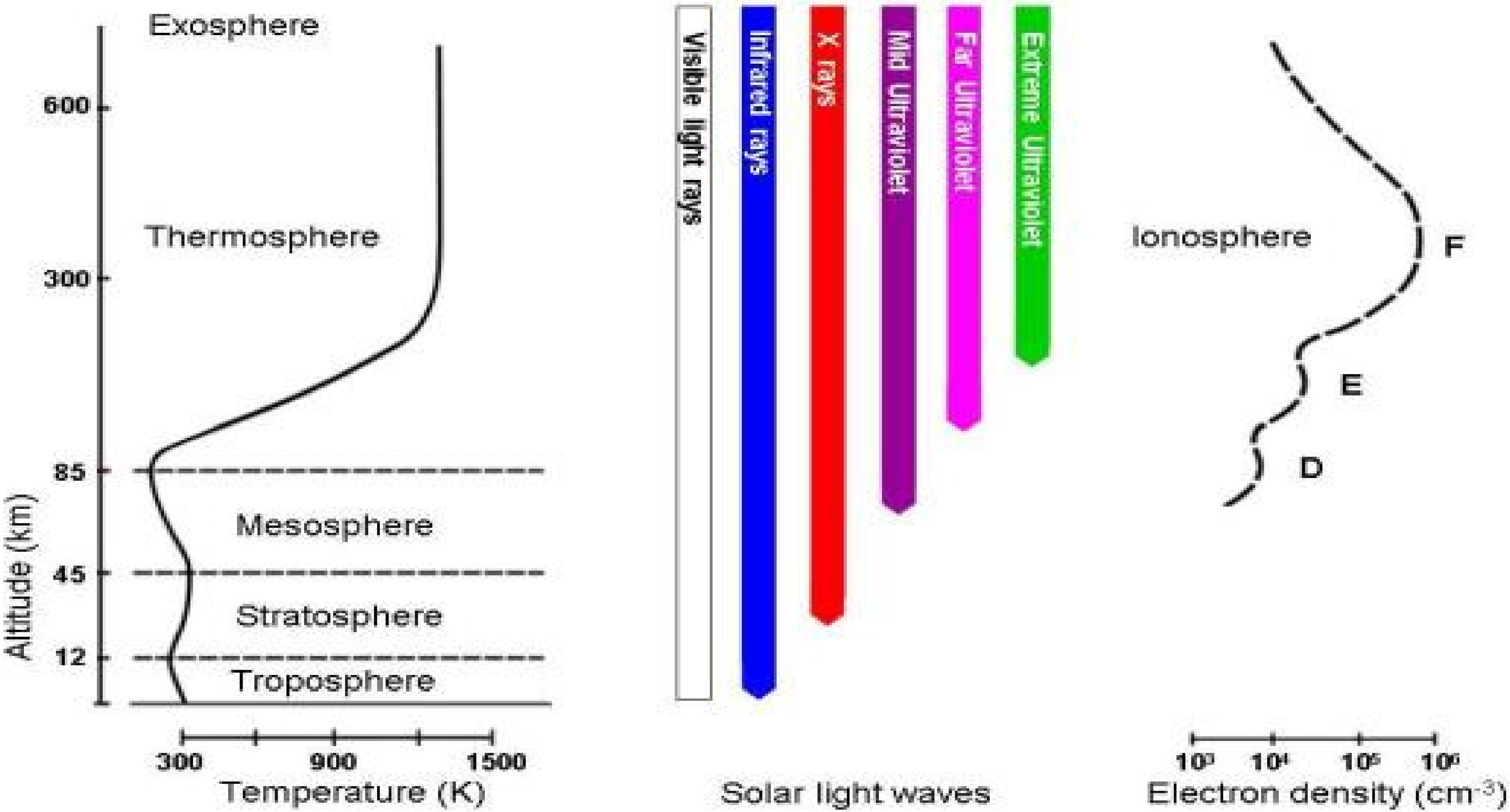
- Introduction
- Vertical Incidence Sounding (ionosonde) measurements
- Ionosonde measurements at Dourbes
- Digisonde performance evaluation
- Applications (LIEDR)
- Summary and Outlook

Ionosphere



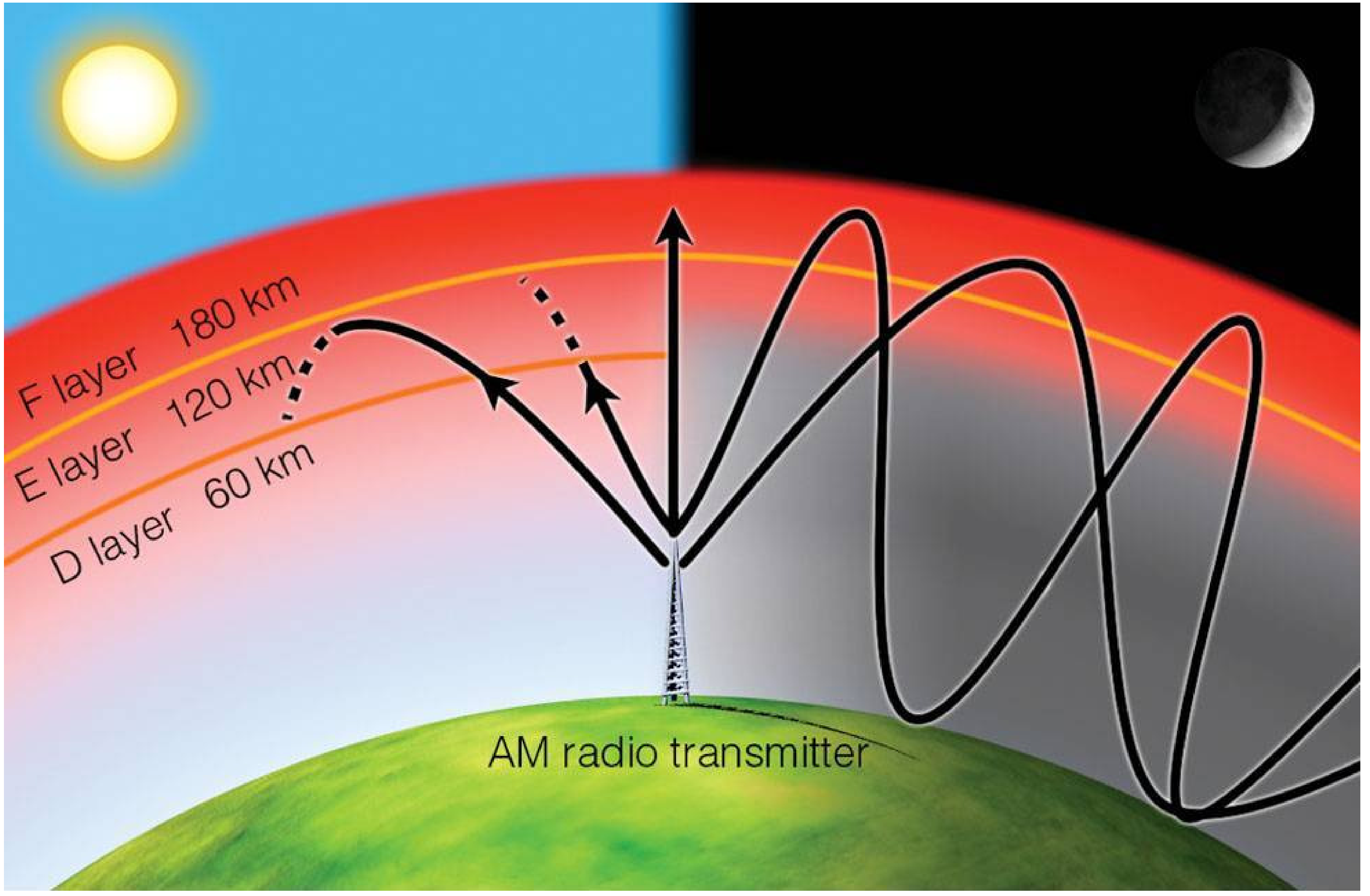
The Sun-Earth connection

Ionosphere



The **ionosphere** is the inner part of the upper atmosphere, extending from about 50 km to 1000-2000 km altitude, which is being **ionised by the solar radiation**. The major part of the ionisation is produced by solar X-ray and ultraviolet radiation and by corpuscular radiation from the Sun.

Ionosphere



In the ionosphere, **free electrons occur in sufficient density to have an appreciable influence on the propagation of radio frequency electromagnetic waves**. The ionospheric plasma consists of mostly H^+ and He^+ ions above 1000 km, O^+ ions from 300 to 500 km, and molecular ions (N_2^+, O_2^+, NO^+) below 200 km. Total ion densities (= electron density) range from 10^8 to 10^{13} m^{-3}.

The **vertical incidence sounding** remains one of the most accurate and important ionosphere-monitoring techniques. In this technique, low- and high-frequency radio waves are transmitted upward and reflected in the ionosphere at the height where the refractive index becomes zero for vertical incidence, or $\sin(\varphi_0)$, where φ_0 is the incidence angle.

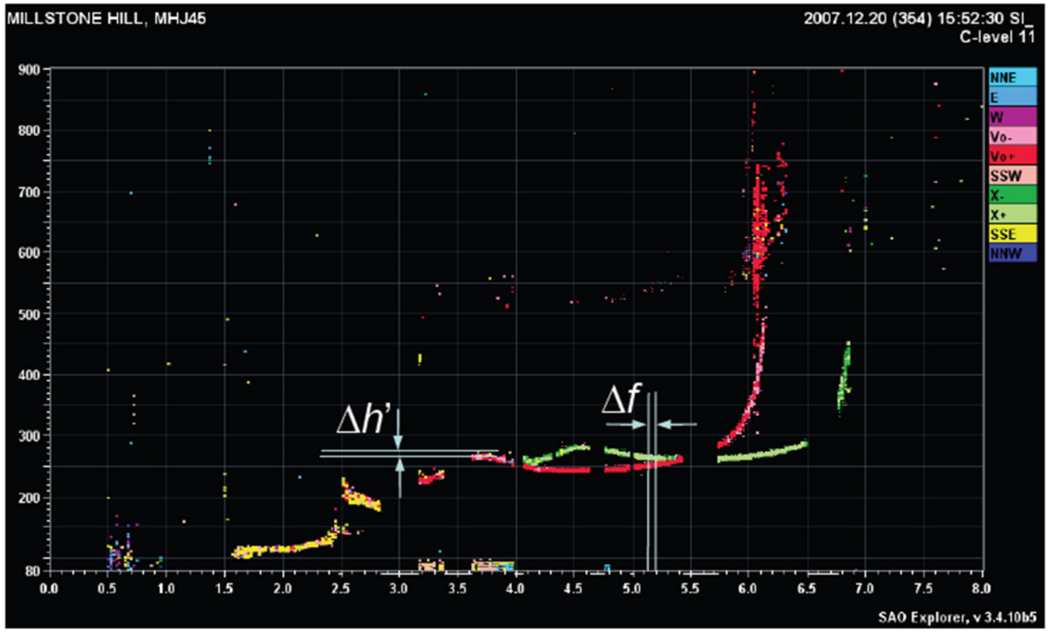
The standard piece of equipment employed for the purpose is called **ionospheric sounder** (**ionosonde**), in which a transmitter and a receiver are swept synchronously in frequency, and the propagation time of the reflected signal is recorded for each of the transmitted frequencies.

Ionosonde operation concept

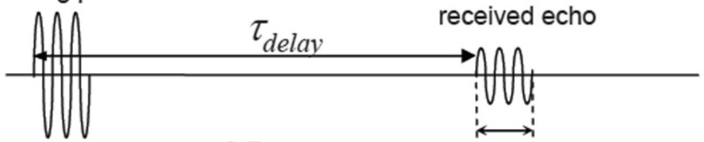
UNIVERSITY OF MASSACHUSETTS LOWELL UMLCAR CENTER FOR ATMOSPHERIC RESEARCH

Ionosonde technique:

To measure the height of signal reflection from the ionosphere at each operating frequency.



Measuring echo delay:



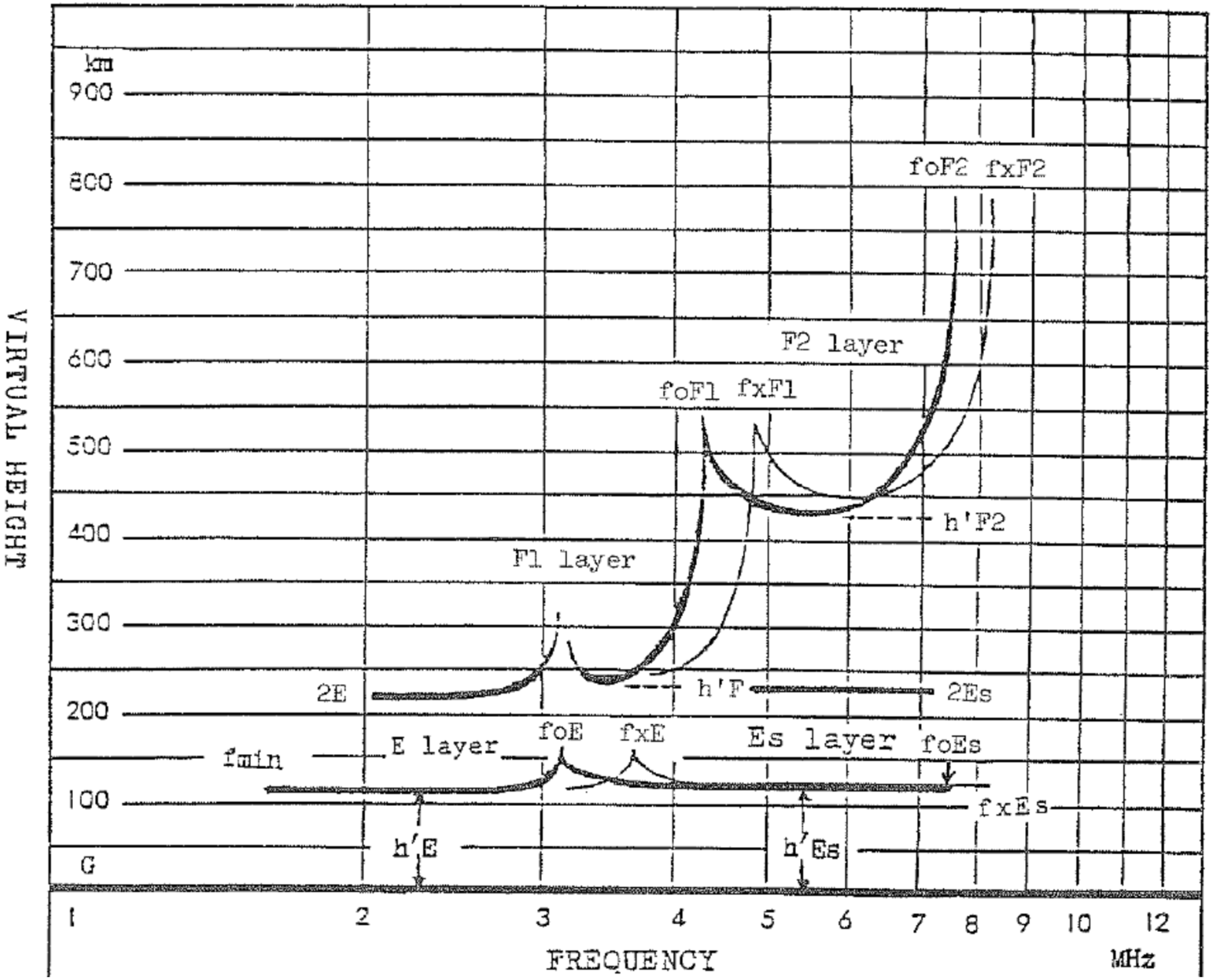
$$h' = \frac{c\tau_{delay}}{2}$$

$\tau_{delay} \Rightarrow h'$ "Classic ionosonde time-delay method"

$\Delta h' \sim \Delta\tau_{pulse}$ Height resolution

h' is a virtual height of signal reflection

Ionosonde Measurements

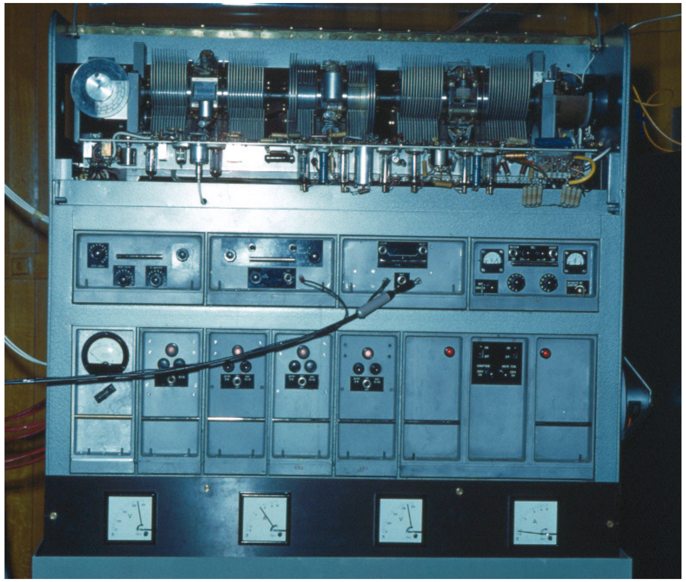


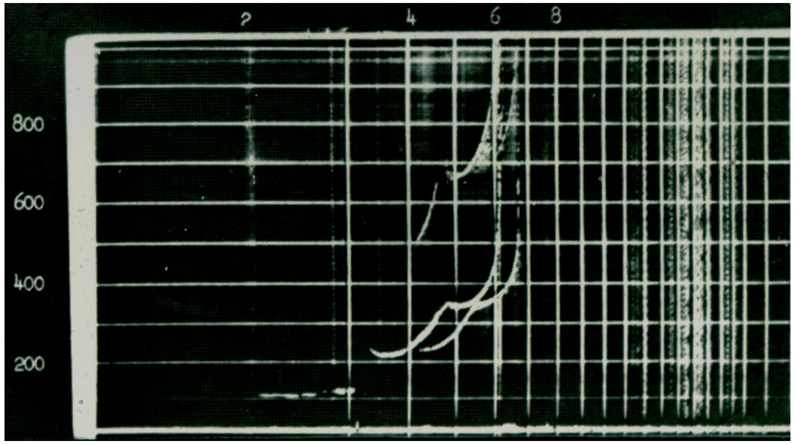
A typical ionogram with the key ionospheric characteristics (*Wakai* et al., 1987)

The **ionogram** is an instantaneous record of the ionospheric conditions (above the sounder) indicated by the relationship between the frequency of the radio pulse emitted upwards and the virtual heights of echoes reflected from the ionosphere.

Ionosonde Measurements

1957 - 1970
Ionosonde Panoramique

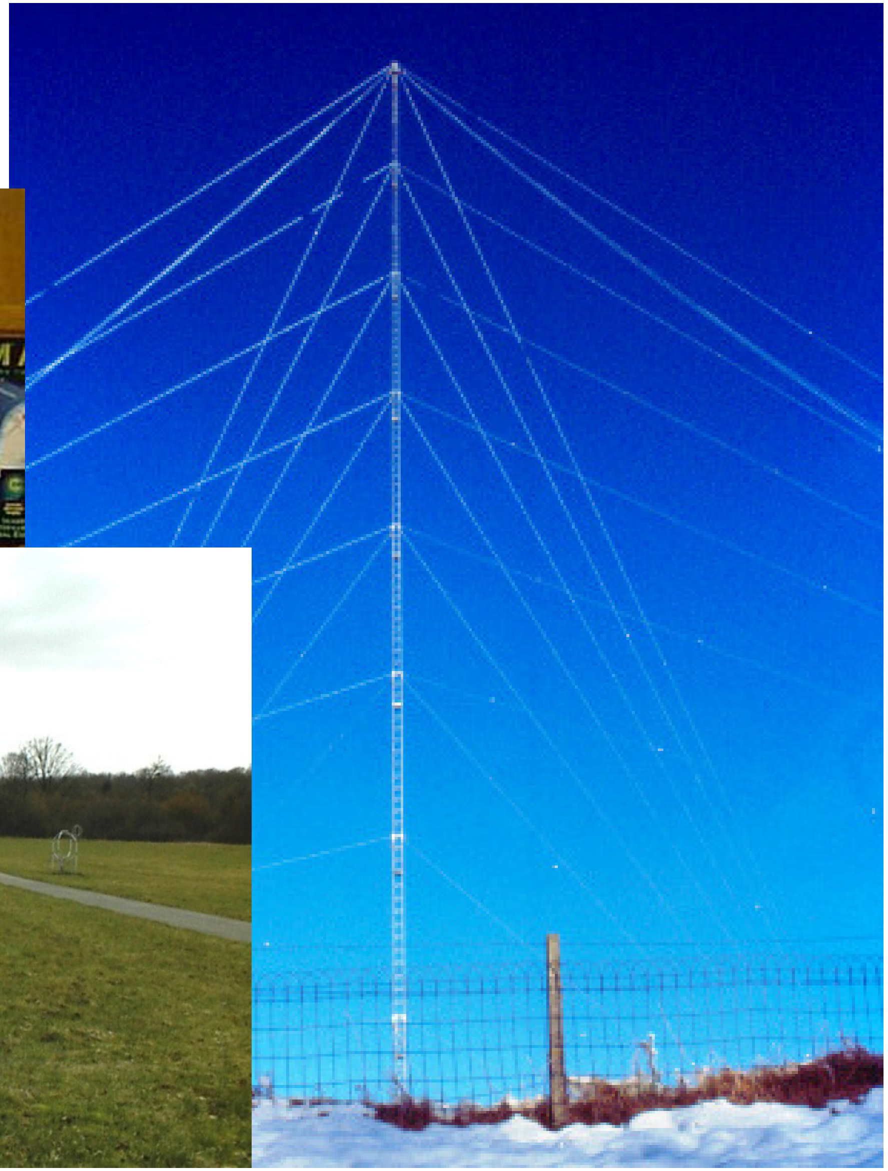




1970 - 1984
Digisonde -128

Ionosonde Measurements

1984 - 2011
Digisonde-256



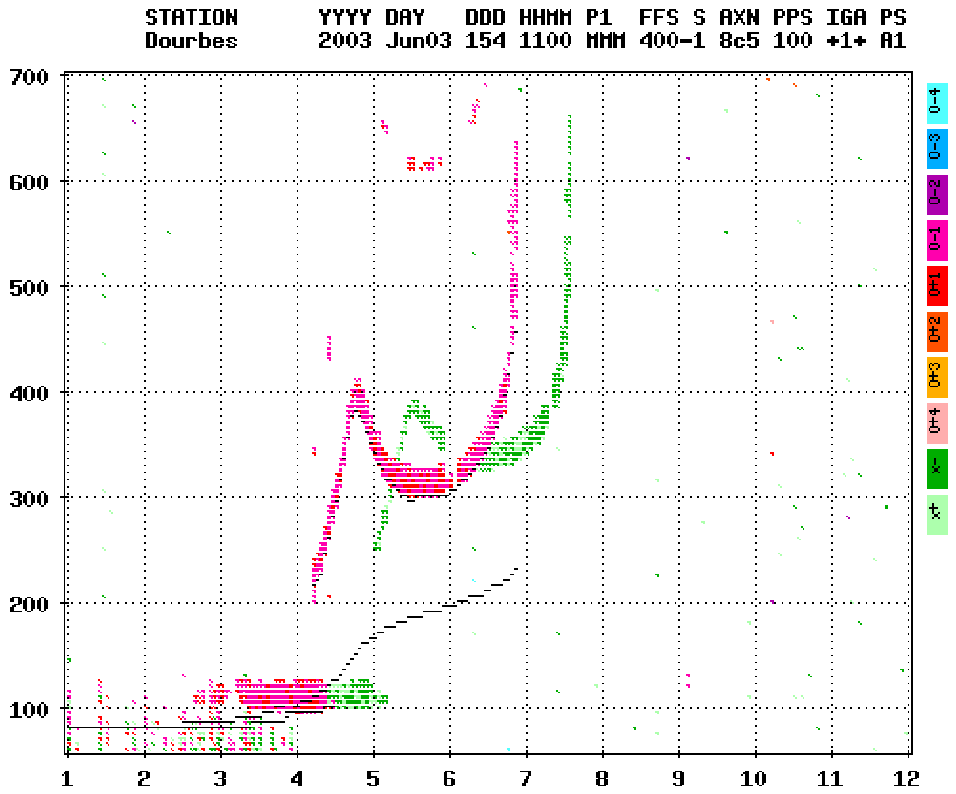
Ionosonde Measurements

1984 - 2011
Digisonde-256

Lowell Digisonde

foF2	MHz	F2 layer critical frequency
foF1	MHz	F1 layer critical frequency
foF1p	MHz	Predicted value of foF1
foE	MHz	E layer critical frequency
foEp	MHz	Predicted value of foE
fxI	MHz	Maximum frequency of F-trace
foEs	MHz	Es layer critical frequency
fmin	MHz	Minimum frequency
MUF(D)	MHz	Maximum usable frequency
M(D)	-	M(D) = MUF(D)/foF2
D	km	Distance for MUF calculation
h'F	km	Minimum virtual height of F trace
h'F2	km	Minimum virtual height of F2 trace
h'E	km	Minimum virtual height of E trace
h'Es	km	Minimum virtual height of Es trace
zmF2	km	Peak height of F2-layer
zmF1	km	Peak height of F1-layer
zmE	km	Peak height of E-layer
yF2	km	Half thickness of the F2 layer,
yF1	km	Half thickness of the F1 layer
yE	km	Half thickness of E layer
B0	km	IRI thickness parameter
B1	-	IRI profile shape parameter
C-level	-	Confidence level: 1 (highest)

foF2	6.88
foF1	4.77
foF1p	4.83
foE	3.81
foEp	3.46
fxI	7.60
foEs	4.45
fmin	1.00
MUF	21.99
M	3.199
D	3000
h'F	215
h'F2	295
h'E	80
h'Es	95
zmF2	232
zmF1	152
zmE	85
yF2	71
yF1	76
yE	5
B0	110.9
B1	1.35
C-level	21



D	100	200	400	600	800	1000	1500	3000	[km]
MUF	7.6	7.7	8.0	8.6	9.3	10.4	13.7	22.0	[MHz]

DB049_2003154110005.MMM / 220fx128h 50 kHz 5.0 km 2x3 / DGS-256 (049-049) 50.1 N 4.6 E

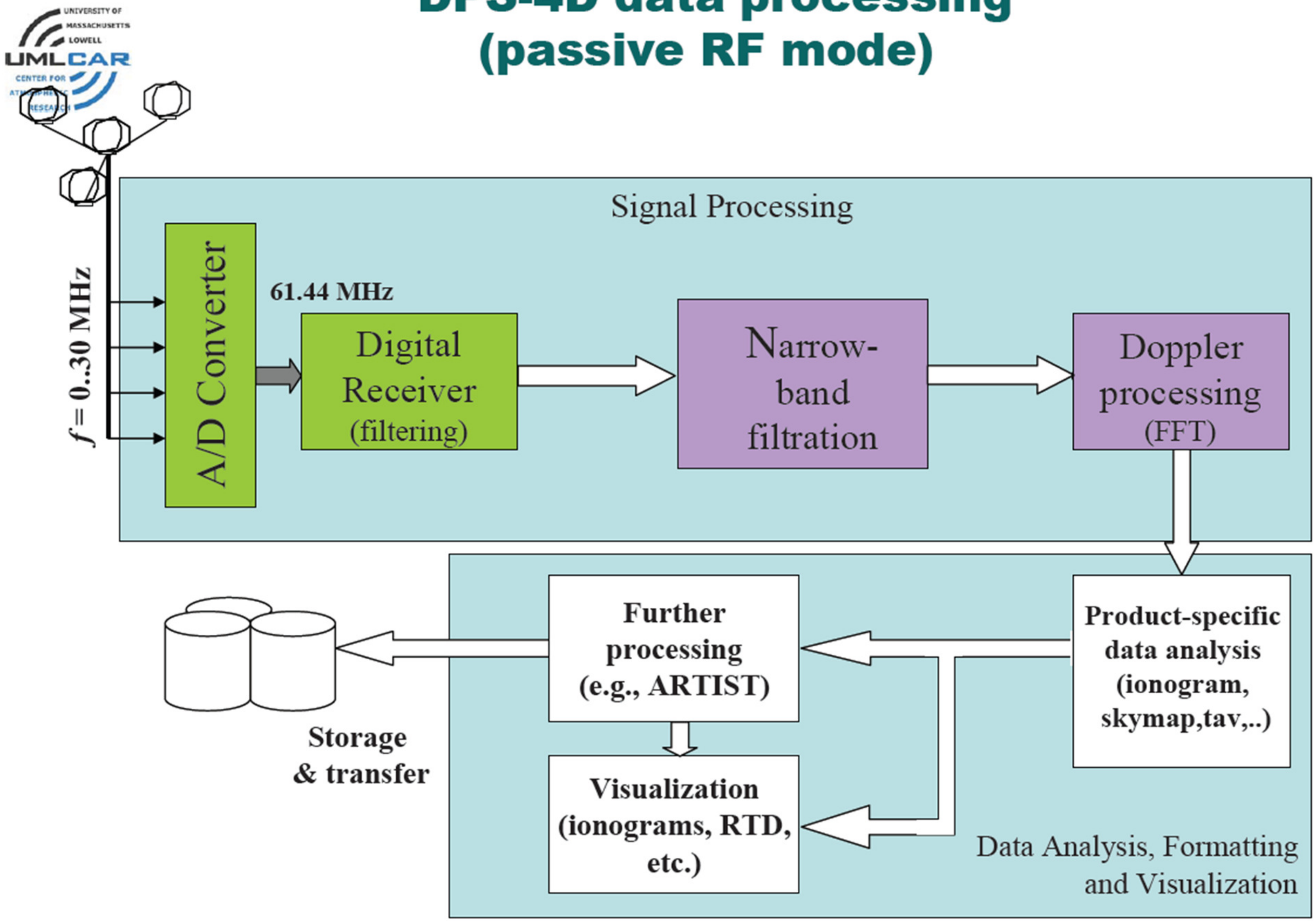
Ionosonde Measurements

April 2011 -

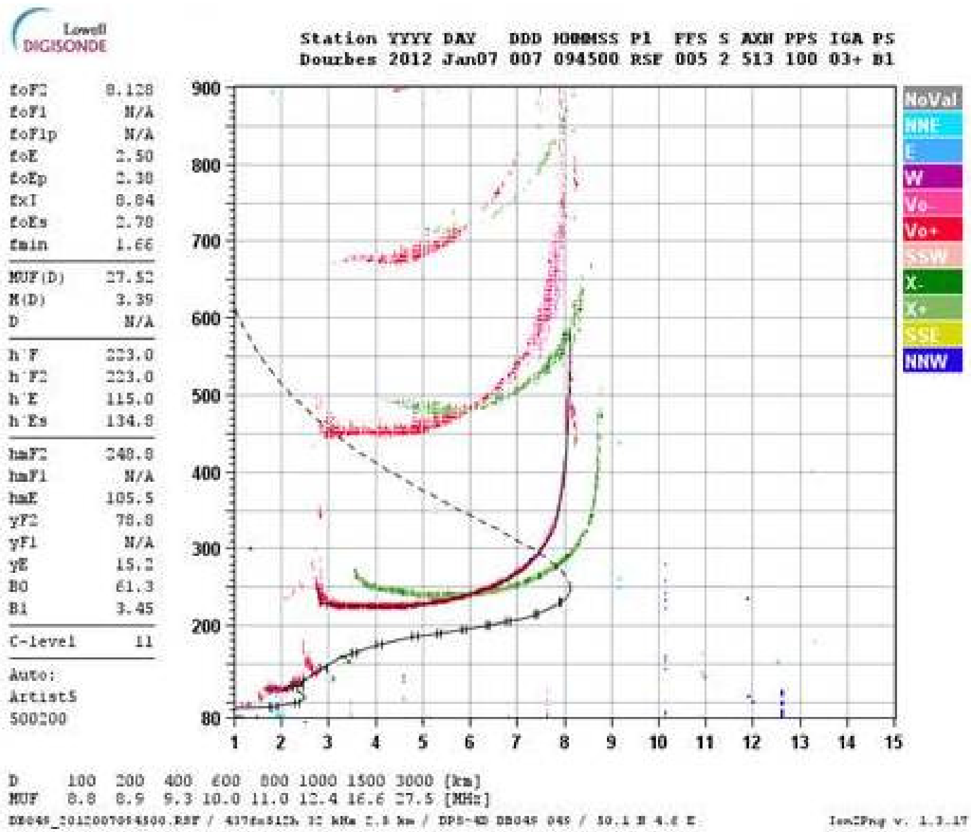
- Type: **Lowell Digisonde-4D**
  Location: Dourbes (50.1ºN, 4.6ºE)
  URSI code: DB049

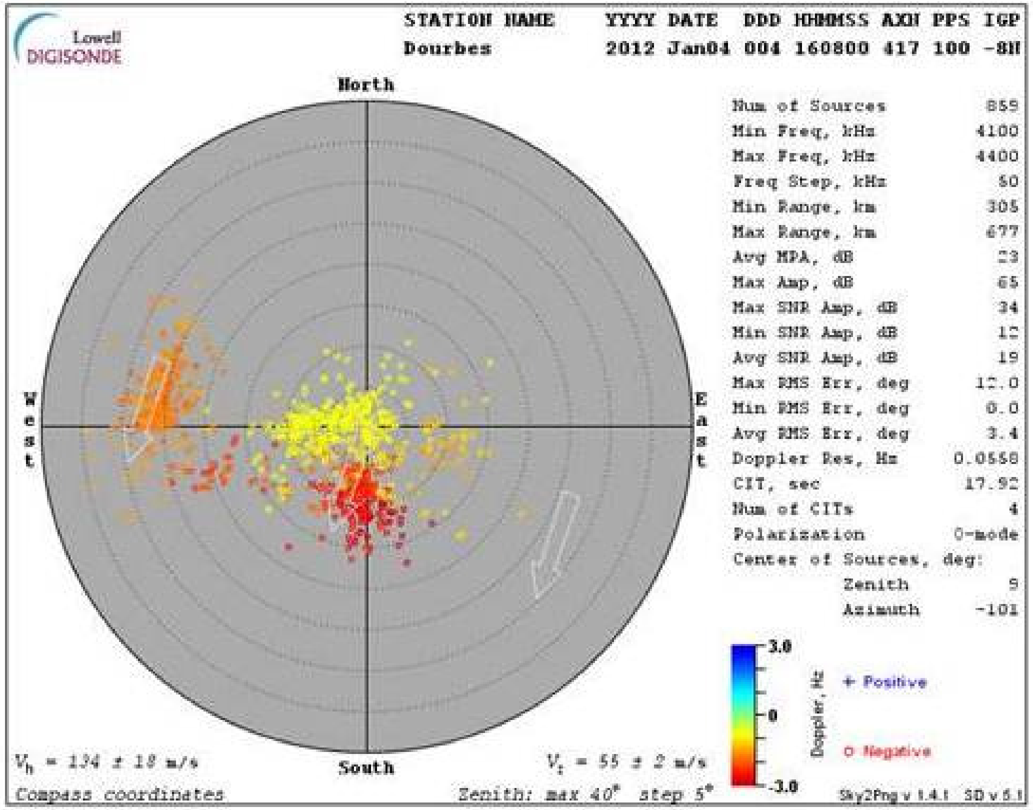
- Cadence: 5 min

DPS-4D data processing (passive RF mode)

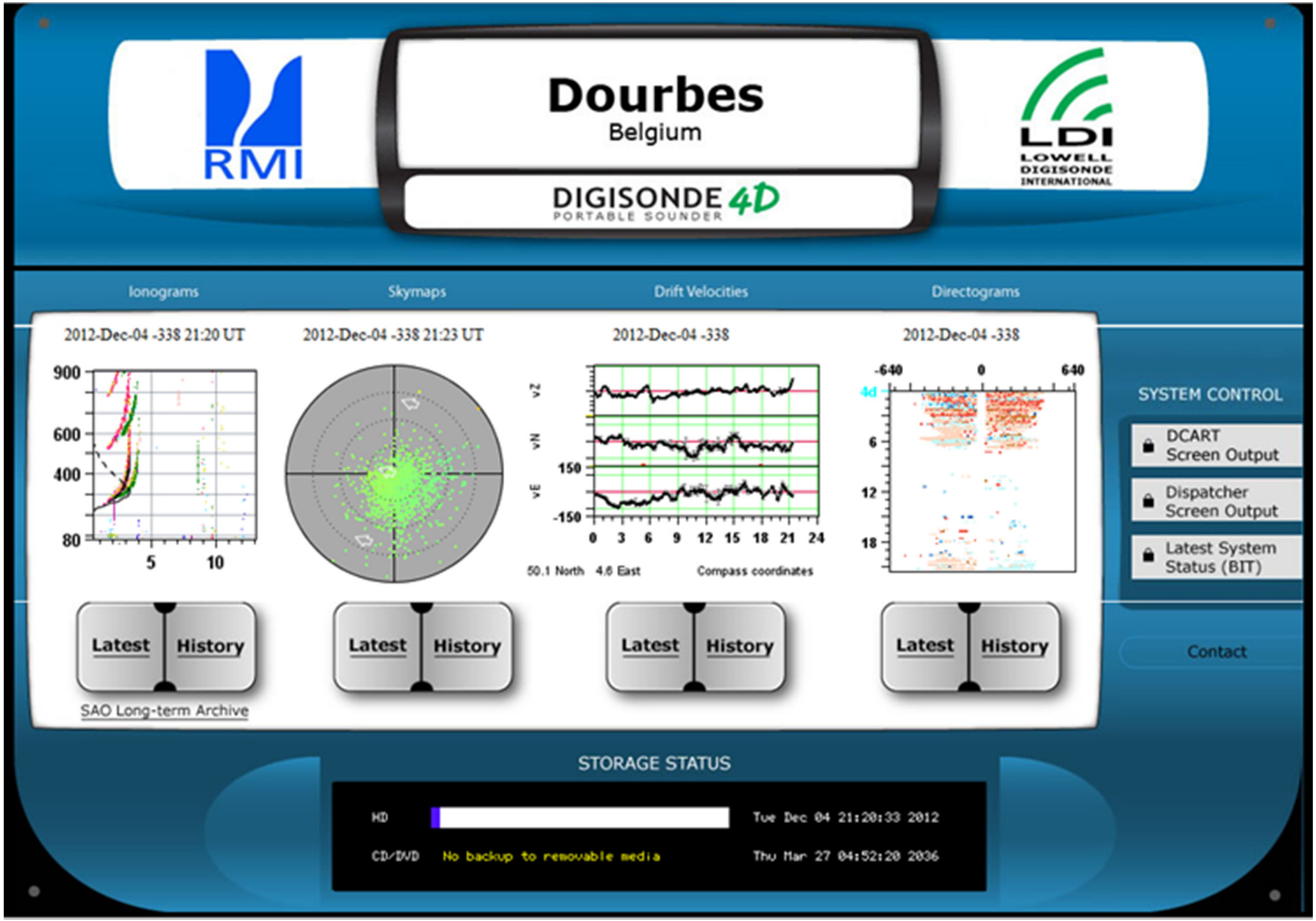


2011 - Digisonde-4D



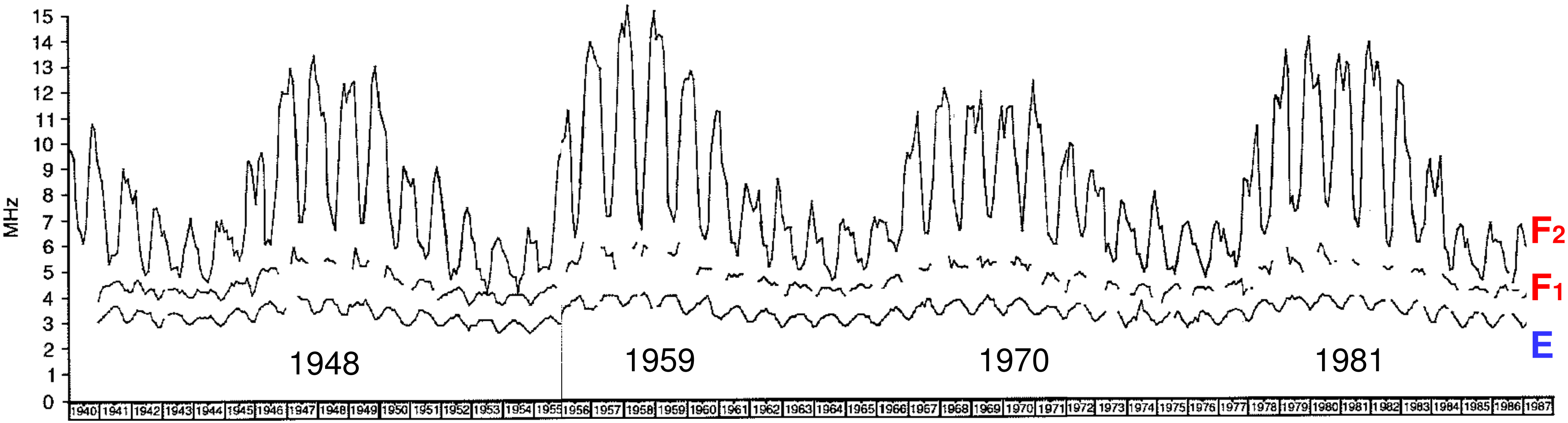


Ionosonde Measurements



Ionosonde Measurements

monthly median critical frequencies, 1200LT, Wash (39N,77W)



- general increase in the critical frequencies with solar activity
- foF1 and foE in phase w/ the solar zenith angle
- foF2 in antiphase w/ the solar zenith angle (*the F2 winter anomaly*)
- F1 may disappear in winter
- mid lats: foF2 diurnal max – at midday in winter, late afternoon in summer
- low lats: foF2 diurnal max – may also occur in the evening

Rush et al. (1974): The relative daily variability foF2 and hmF2 … Radio Sci..

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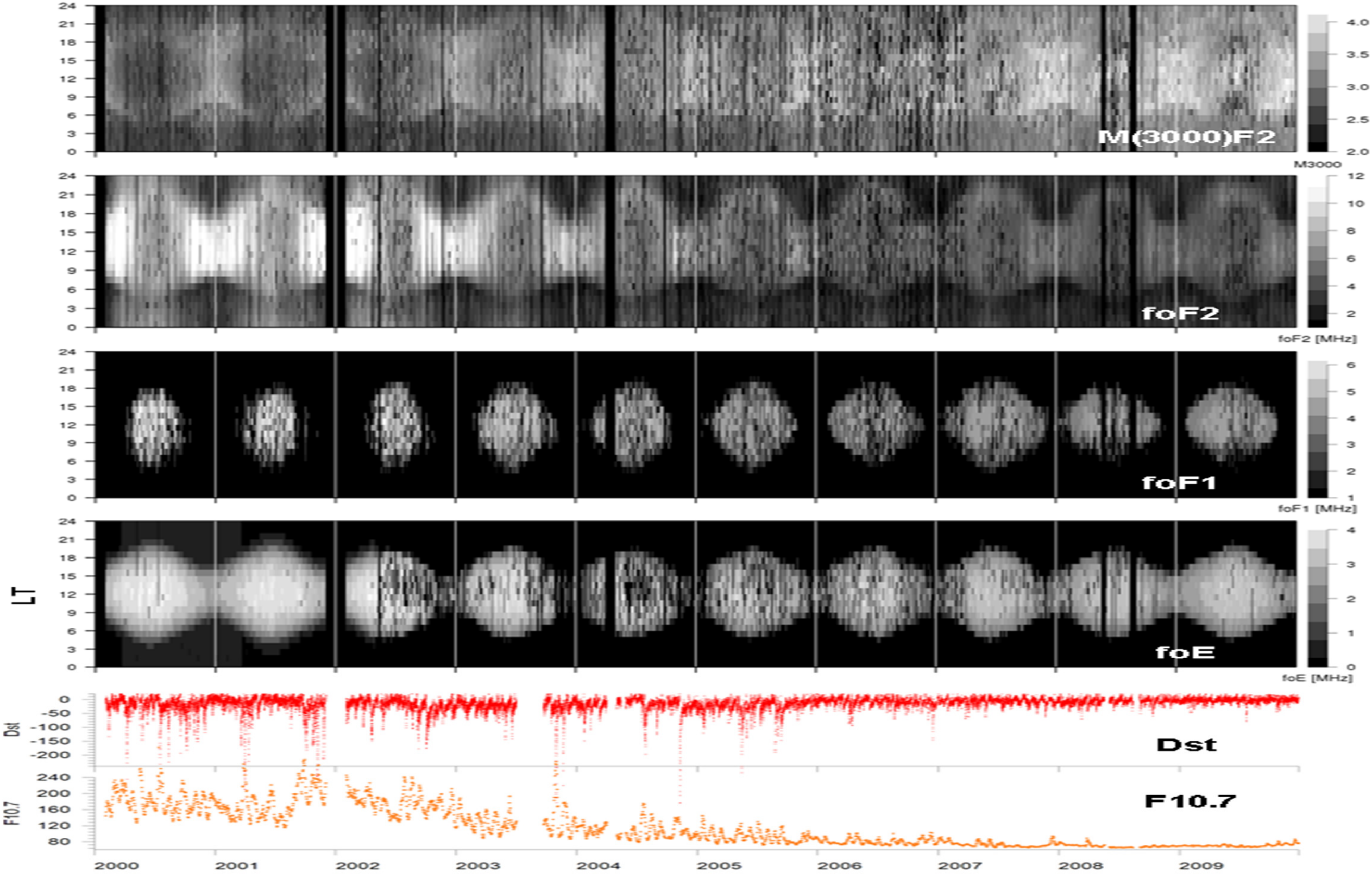
Ionosonde Measurements

STCE



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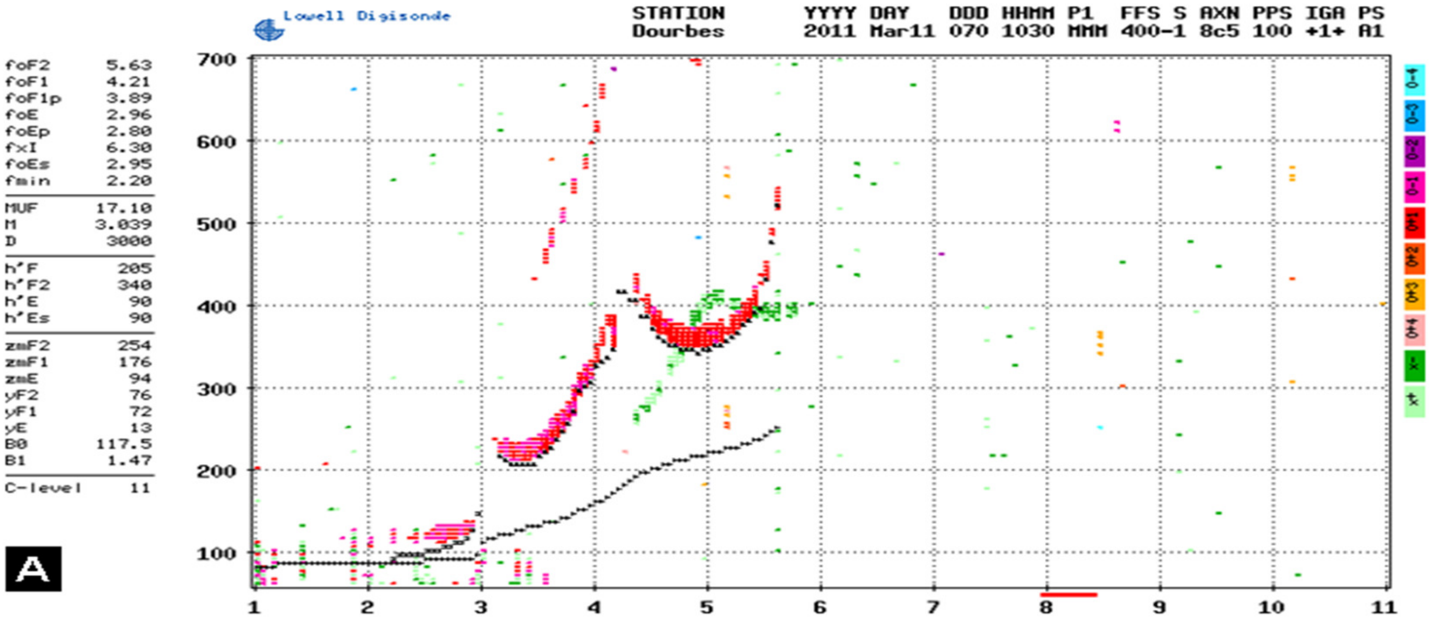
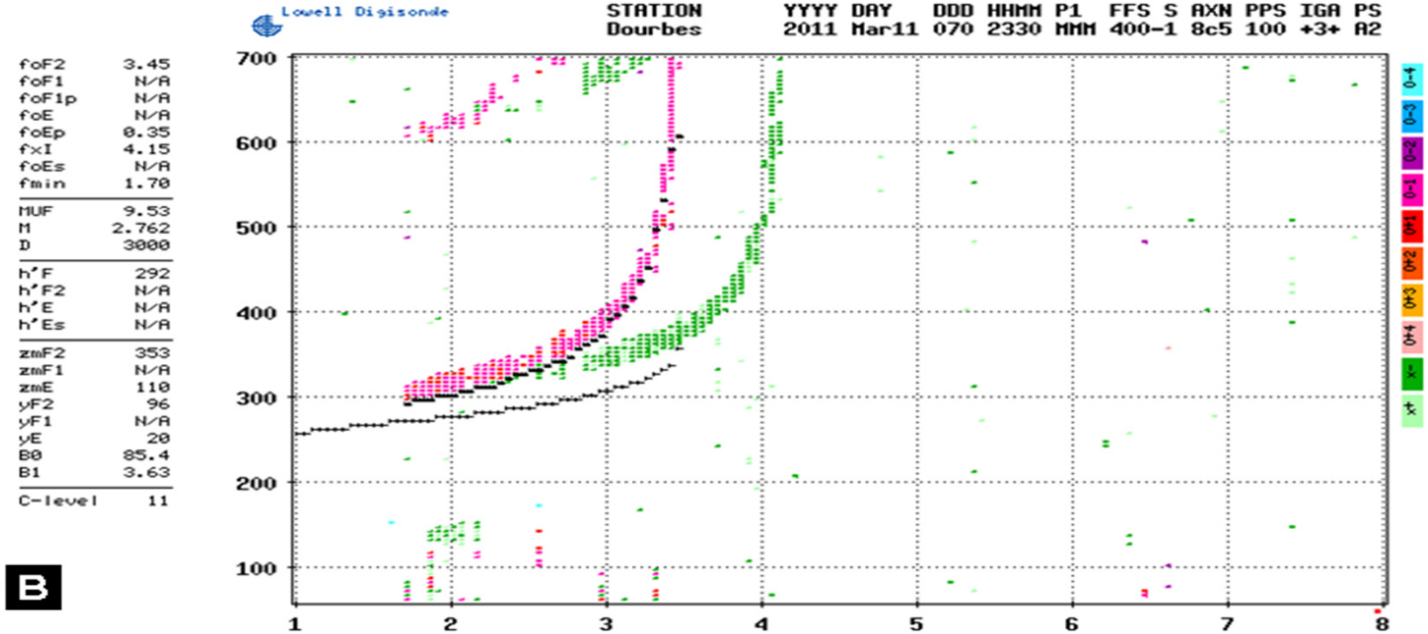
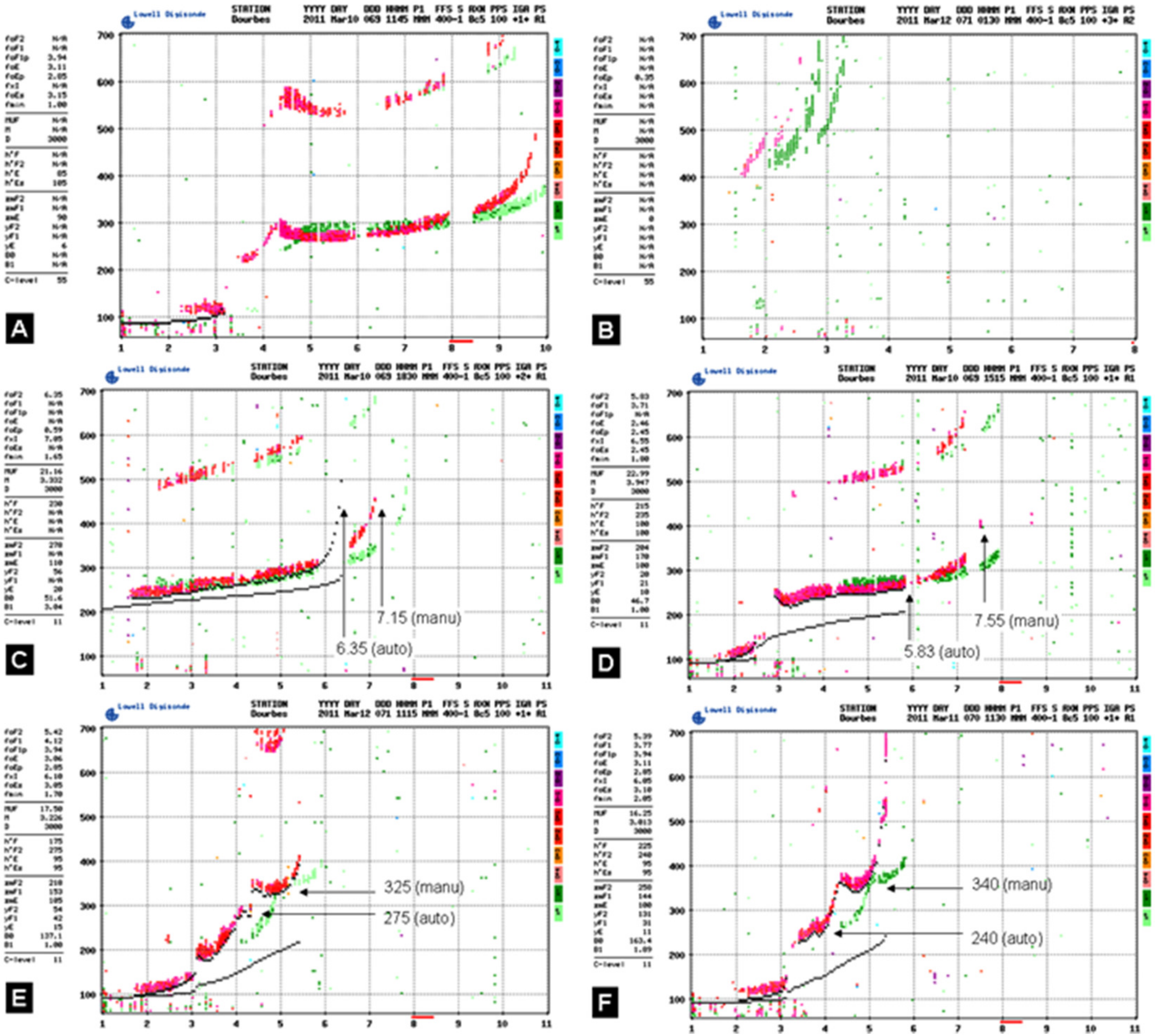
Performance Evaluation





(**A**/**B**): Successfully autoscaled ionograms

Performance Evaluation



(**A**/**B**): Autoscaling failures – (A) partial, E-layer parameters only scaled, and (B) completely unscaled, an example of severely depleted ionosphere during a geomagnetic storm.

(**C**/**D**): Gap occurrence (due to interference) - smaller gaps successfully ignored/interpolated, larger gaps falsely inter-/extra-polated resulting in the automatic layer trace being truncated prematurely (D).

(**E**/**F**): Incorrect autoscaling of the h'F2 virtual height.

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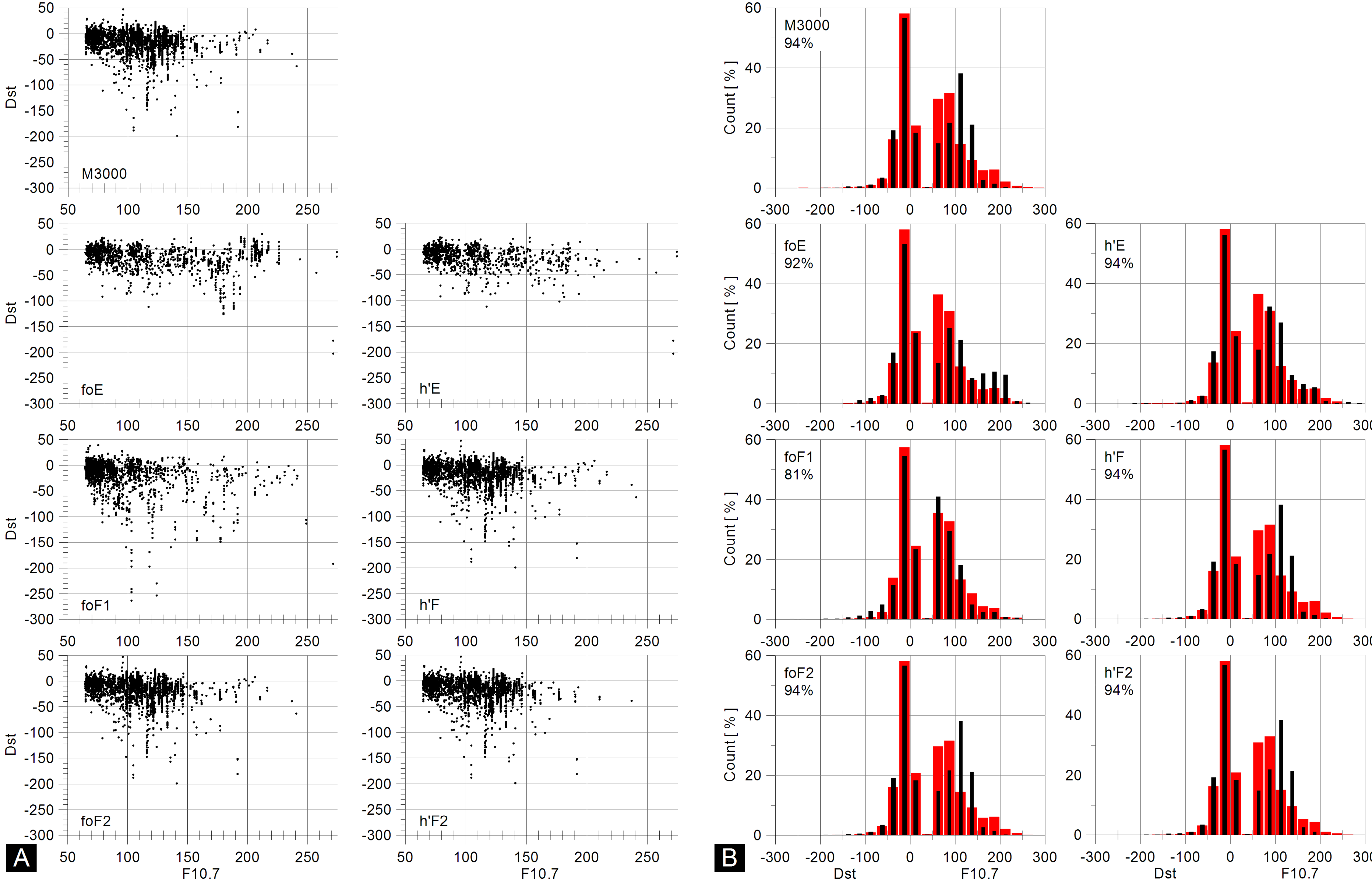
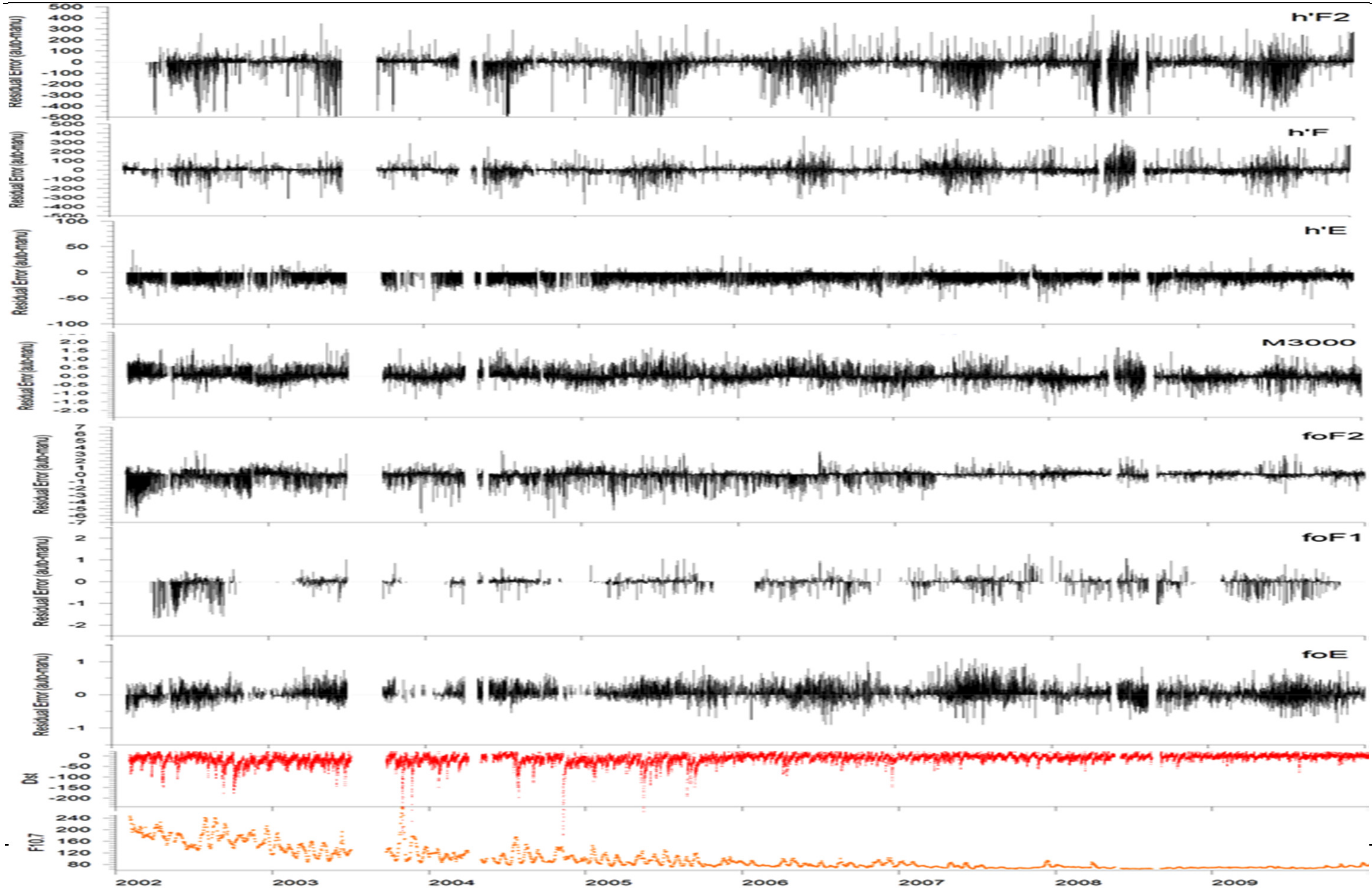
Performance Evaluation

STCE



Performance Evaluation



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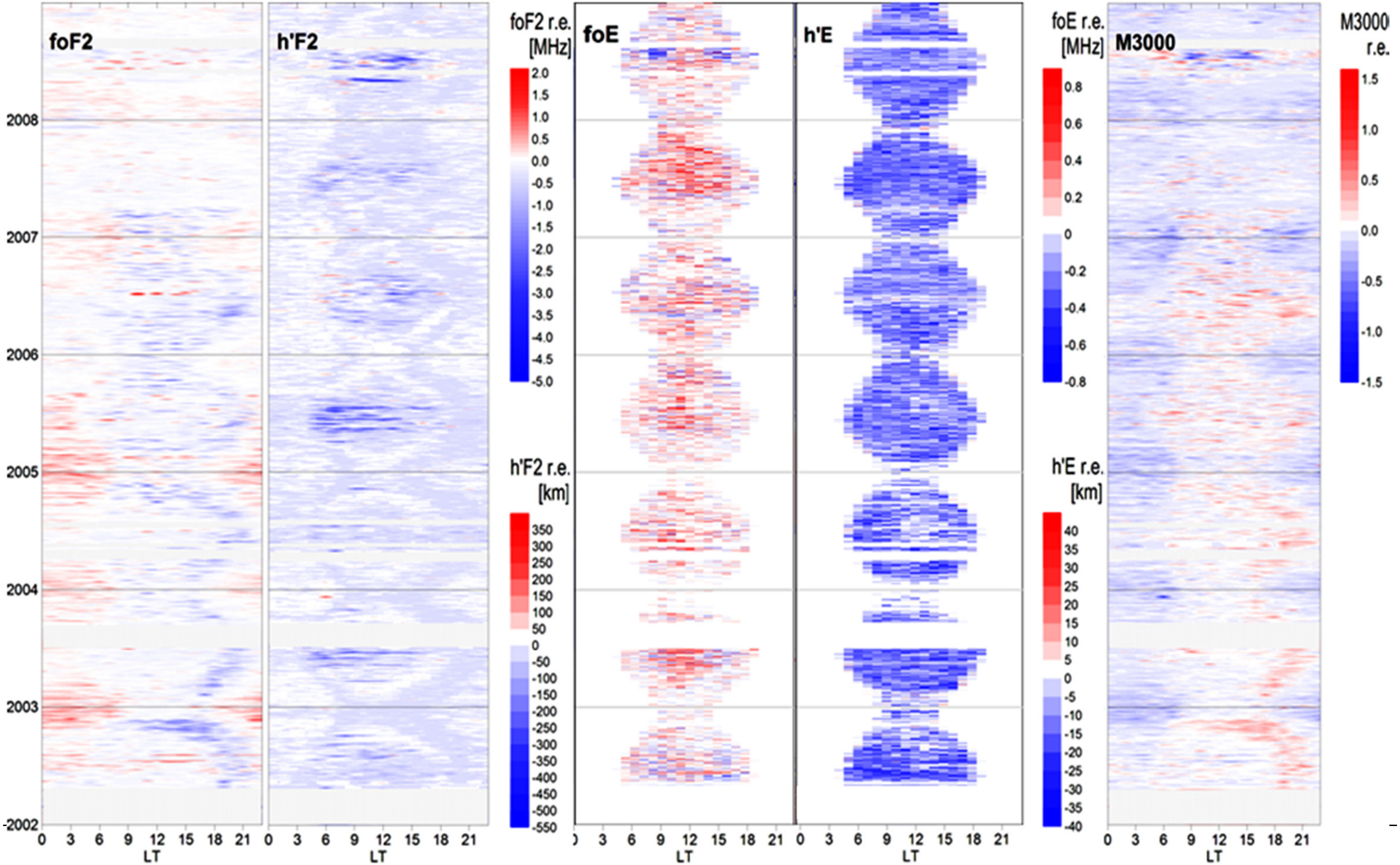
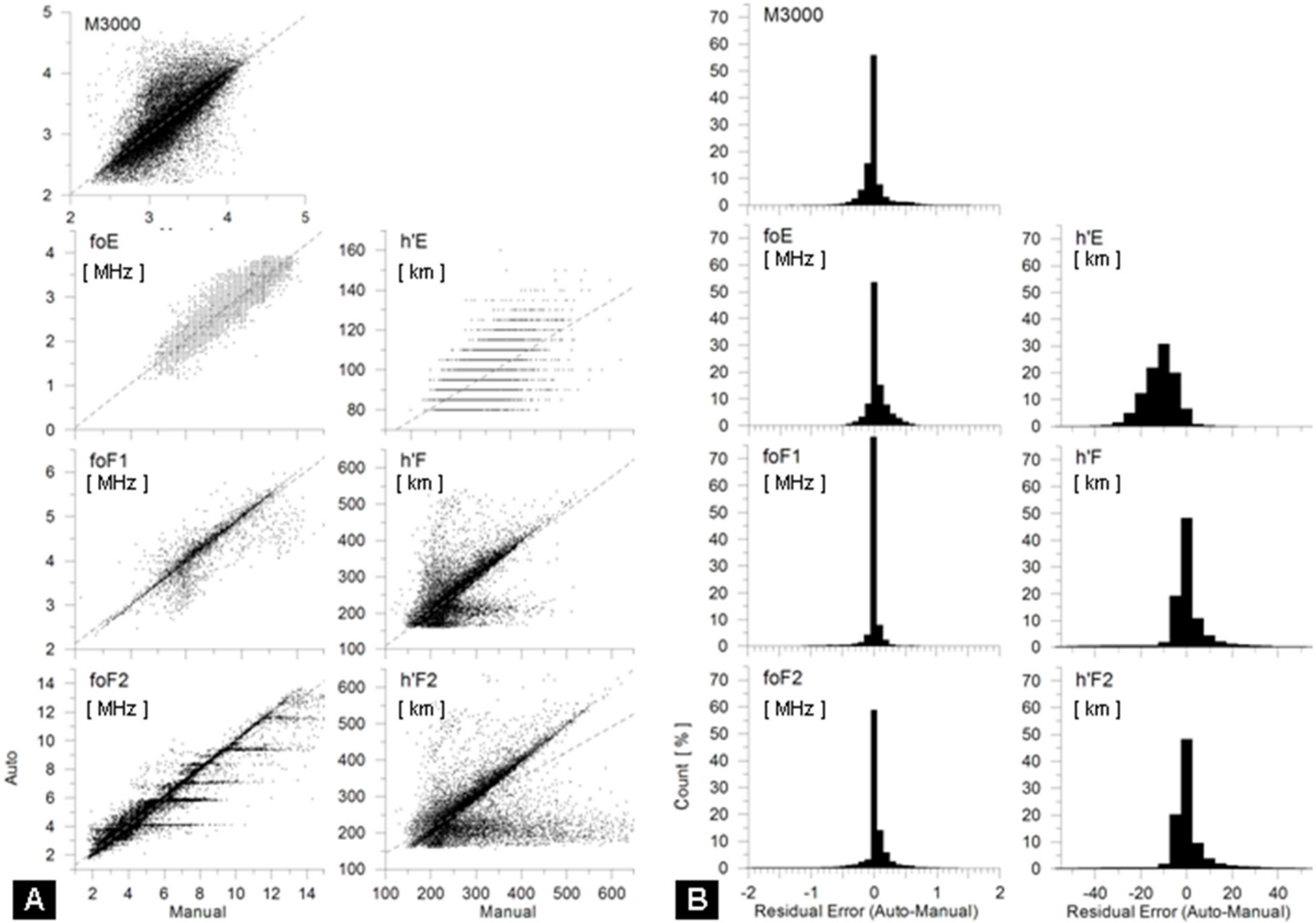
Performance Evaluation

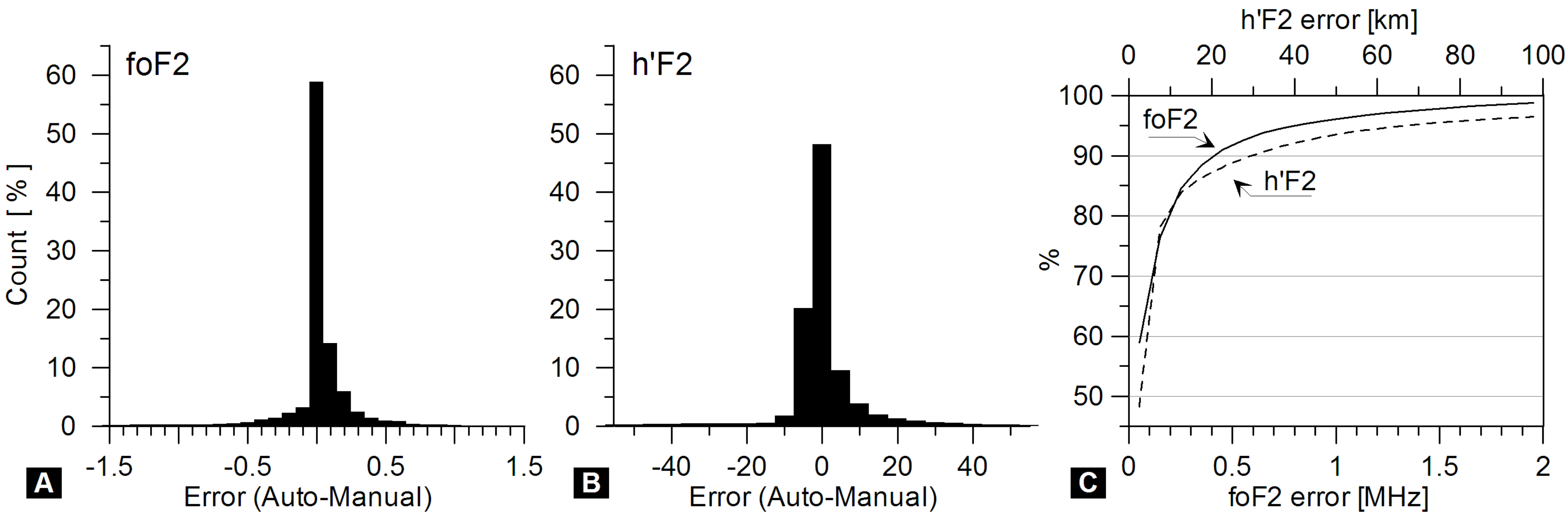
STCE



Performance Evaluation



Performance Evaluation



(A/B): Histograms of the foF2 and h’F2 errors. (C): Relative cumulative foF2 and h’F2 error distributions.

Error bounds (95% probability):
foF2 (-0.75,+0.85), foF1(-0.25,+0.35), foE(-0.35,+0.40),
h’F2(-68,+67), h’F(-38,+32), h’E(-26,+2) ,
M3000F2(-0.55,+0.45)

Performance Evaluation

- **Automatic scaling availability**

available in **94-98**% cases for all characteristics except foF1 (89%)

- **Autoscaling accuracy**

for some characteristics (most notably for foF2 and M3000F2) the magnitude of the residual error (autoscaled minus manually-scaled values) **varies in local time, season and solar activity**

- **Influence of geomagnetic activity/storms**

Although geomagnetic storms seem to affect the autoscaling, the overall results about the influence of geomagnetic activity remain **inconclusive**

*

Overall, the automated ionogram processing/scaling has demonstrated **sufficiently good performance** that allows the utilisation of the instantaneous ionospheric sounding data for operation of a monitoring system

Physical & Mathematical background

$\Im_i(h) = \Im_i(H_i, N_{mi}, h_m F_2; h)$ ← ion density profile (topside)

The height profile of the electron density calculated via the following 'reconstruction' formula:

$\Im_e(h) = \Im_{O+}(H_{O+}, N_{mO+}, h_m F_2; h) + \Im_{H+}(H_{H+}, N_{mH+}, h_m F_2; h)$ ← plasma density profile (topside)

The unknowns $(H_{O+}, H_{H+}, N_{mO+}, N_{mH+})$ determined from the following system of equations:

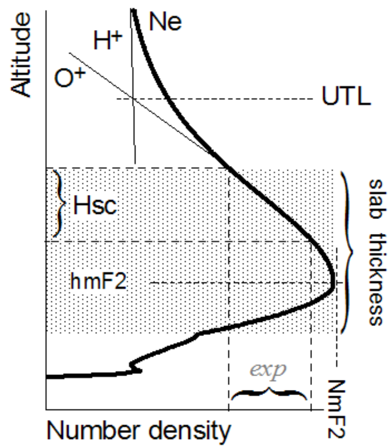
$N_{mO+} + N_{mH+} = N_m F_2$ ← plasma quasi-neutrality (peak)

$H_{H+} = (\mu_{O+} / \mu_{H+})\, \xi\, H_{O+}$ ← O^+/H^+ scale heights relation

$\Phi_t = \aleph_{O+}(H_{O+}, N_{mO+}, h_m F_2) + \aleph_{H+}(H_{H+}, N_{mH+}, h_m F_2)$ ← integrated topside densities

$\Im_{O+}(H_{O+}, N_{mO+}, h_m F_2; h_{tr}) = \Im_{H+}(H_{H+}, N_{mH+}, h_m F_2; h_{tr})$ ← O^+/H^+ ion transition level

H_{O+}, H_{H+} - the O^+ and H^+ ion scale heights
N_{mO+}, N_{mH+} - the O^+ and H^+ ion maximum densities
μ_{O+} - the O^+ ion mass (atomic mass = 15.9994 amu, $2.6567625437\times10^{-26}$ kg)
μ_{H+} - the H^+ ion mass (atomic mass = 1.00794 amu, $1.6737235385\times10^{-27}$ kg)
ξ - the vertical 'scale height' corrector, $\xi = \sin[\arctan(2\tan\varphi)]$, φ - geom. latitude
h_{tr} - the upper, O^+/H^+ ion transition level
Φ_t - the measured topside TEC (above hmF2)
$\aleph_{mO+}$, $\aleph_{mH+}$ - the integrated topside O^+ and H^+ ion densities



Stankov et al. (2003): A new method for reconstruction of the vertical electron density distribution in the upper ionosphere and plasmasphere. Journal of Geophysical Research, 108(A5), 1164, doi:10.1029/2002JA009570.

Local ionospheric plasma density specification in real time

Royal Meteorological Institute (RMI) — STCE

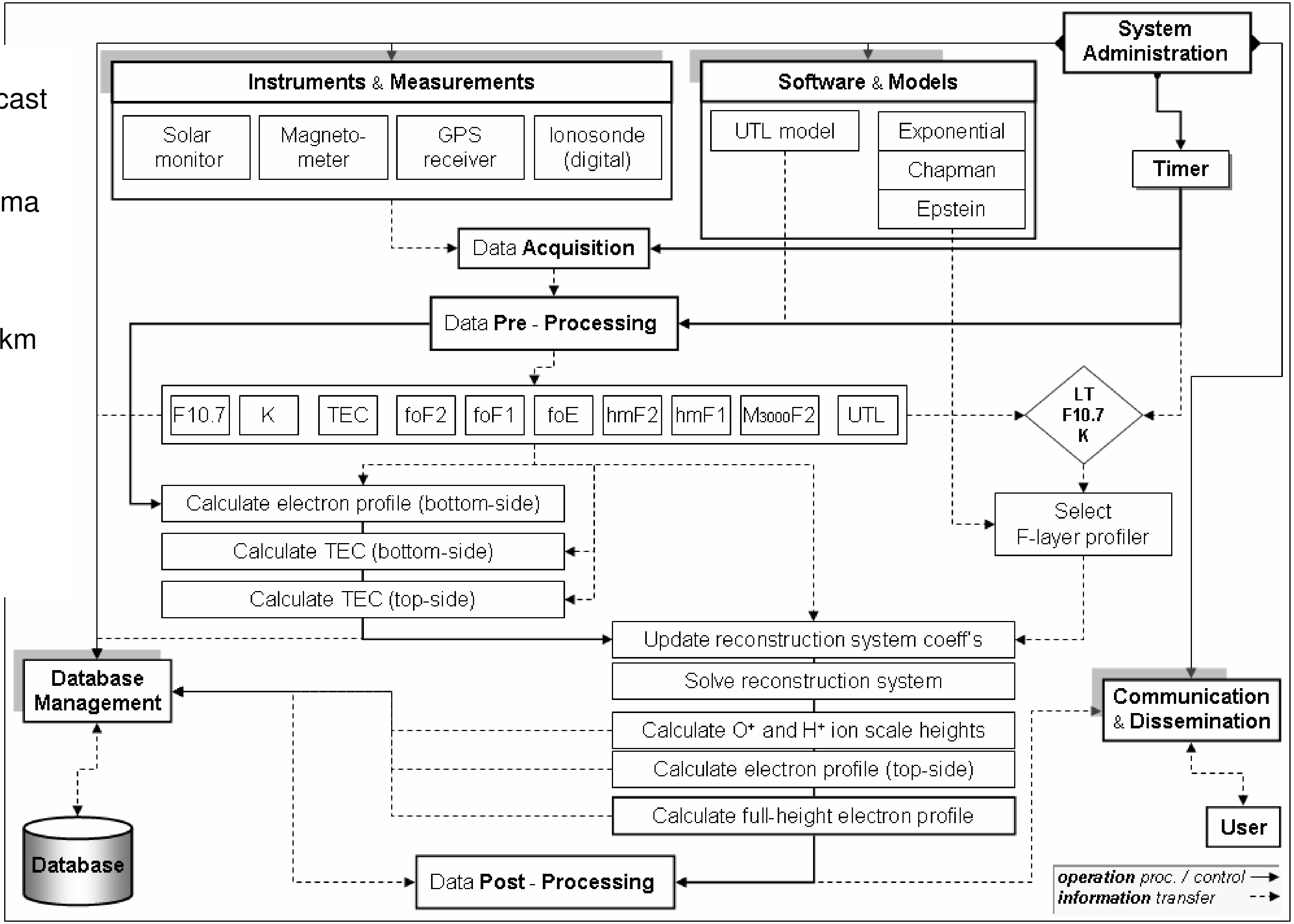
Type:
- operational nowcast

Output:
- ionospheric plasma density/frequency

Altitude range:
- from 90 to 1100 km

Time resolution:
- 5 min

Latency:
- less then 3 min



Stankov et al. (2011): Local ionospheric electron density profile reconstruction in real time. Adv. Space Res. 47(7), 1172-1180.

LIEDR – Local Ionospheric Electron Density Reconstruction

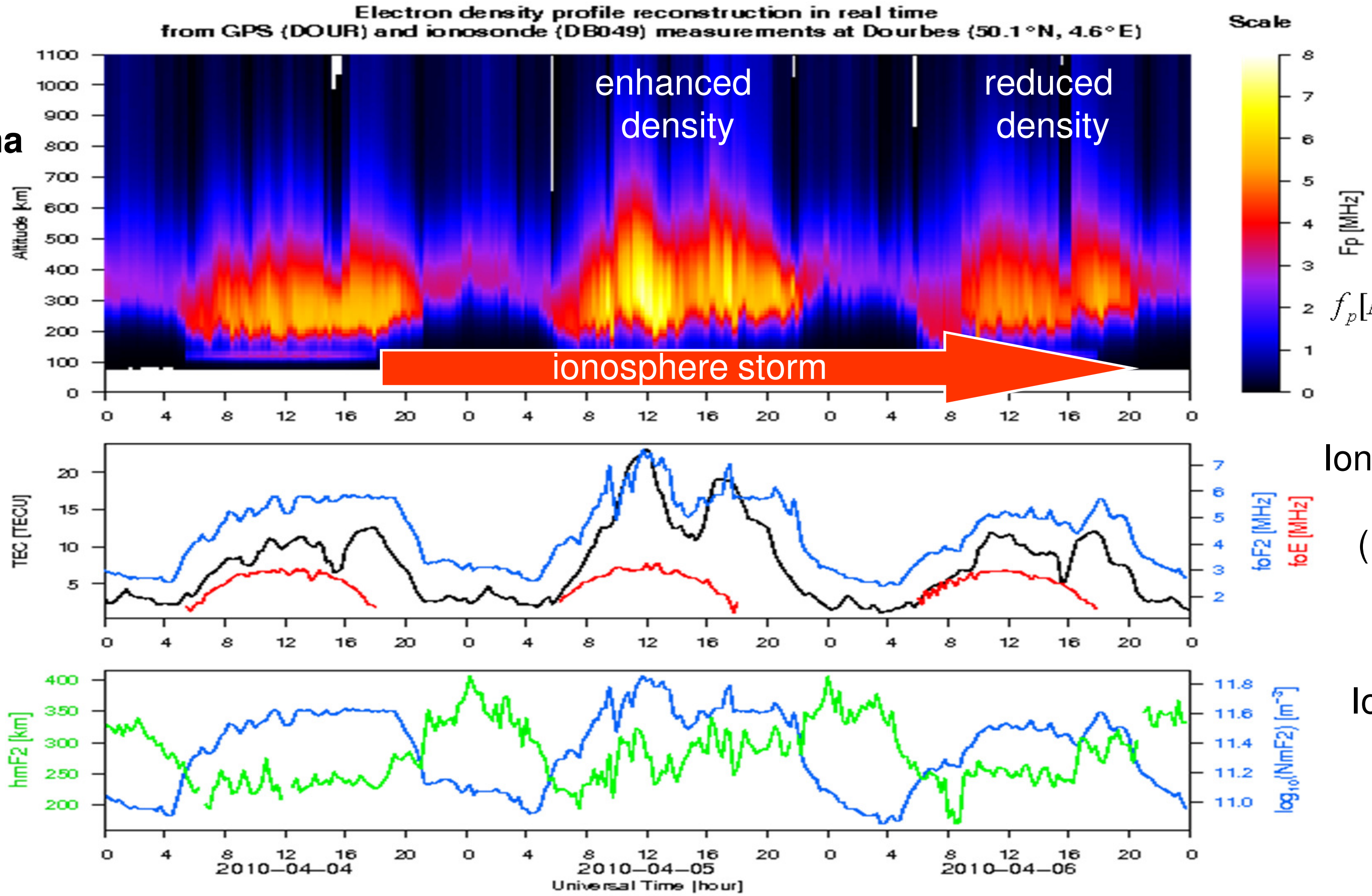
Ionospheric plasma density specification in real time

Development:
Type – operational nowcast, Output – ionospheric plasma density/frequency, Altitude range – from 90 to 1100 km, Time resolution – 15 min, Latency – less then 3 min.

Ionosphere Plasma Frequency

Ionosphere Total Electron Content (TEC)

Ionosphere peak density altitude (hmF2)



$f_p[MHz] \approx c_p\, N_e^{0.5}[el/m^3]$

$c_p = 0.898 \times 10^{-5}$

Ionosphere Critical Frequencies (F2 layer - foF2 , E layer - foE)

Ionosphere Peak Density (NmF2)

http://swans.meteo.be/ionosphere/liedr

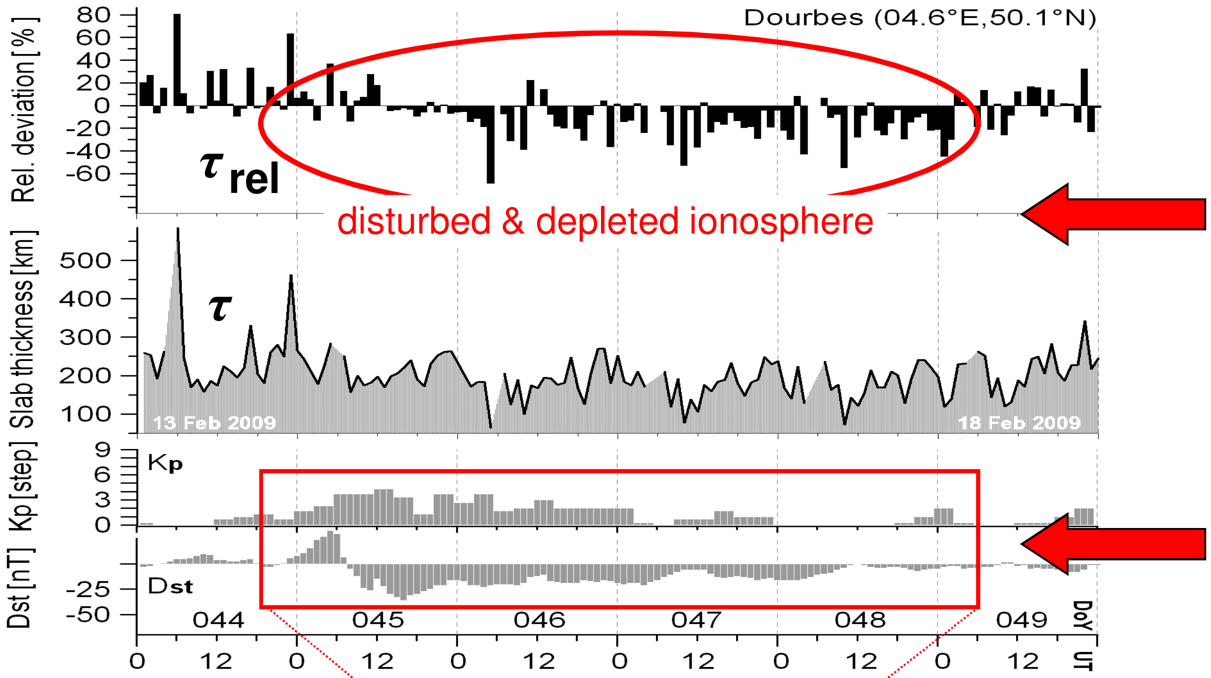
Stankov et al. (2011): Local ionospheric electron density profile reconstruction in real time. Adv. Space Res. 47(7), 1172-1180.

LIEDR – Local Ionospheric Electron Density Reconstruction

Ionospheric
slab thickness
relative deviation
from non-disturbed
behaviour

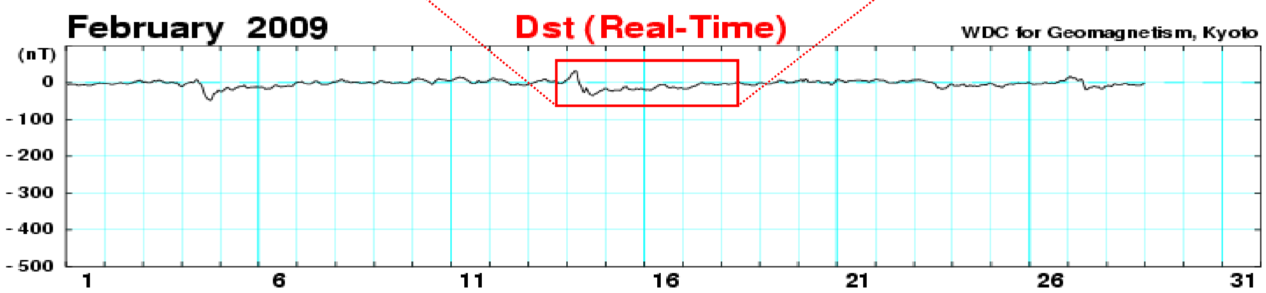
Ionospheric
slab thickness

Geomagnetic
activity indices
Kp and Dst



Ionospheric
slab thickness
behaviour
during
geomagnetically
disturbed
conditions

Geomagnetically
disturbed
conditions



http://swans.meteo.be/ionosphere/liedr

Stankov et al. (2009): Ionospheric slab thickness – analysis, modelling, and monitoring. Advances in Space Research, 44, 1295–1303.

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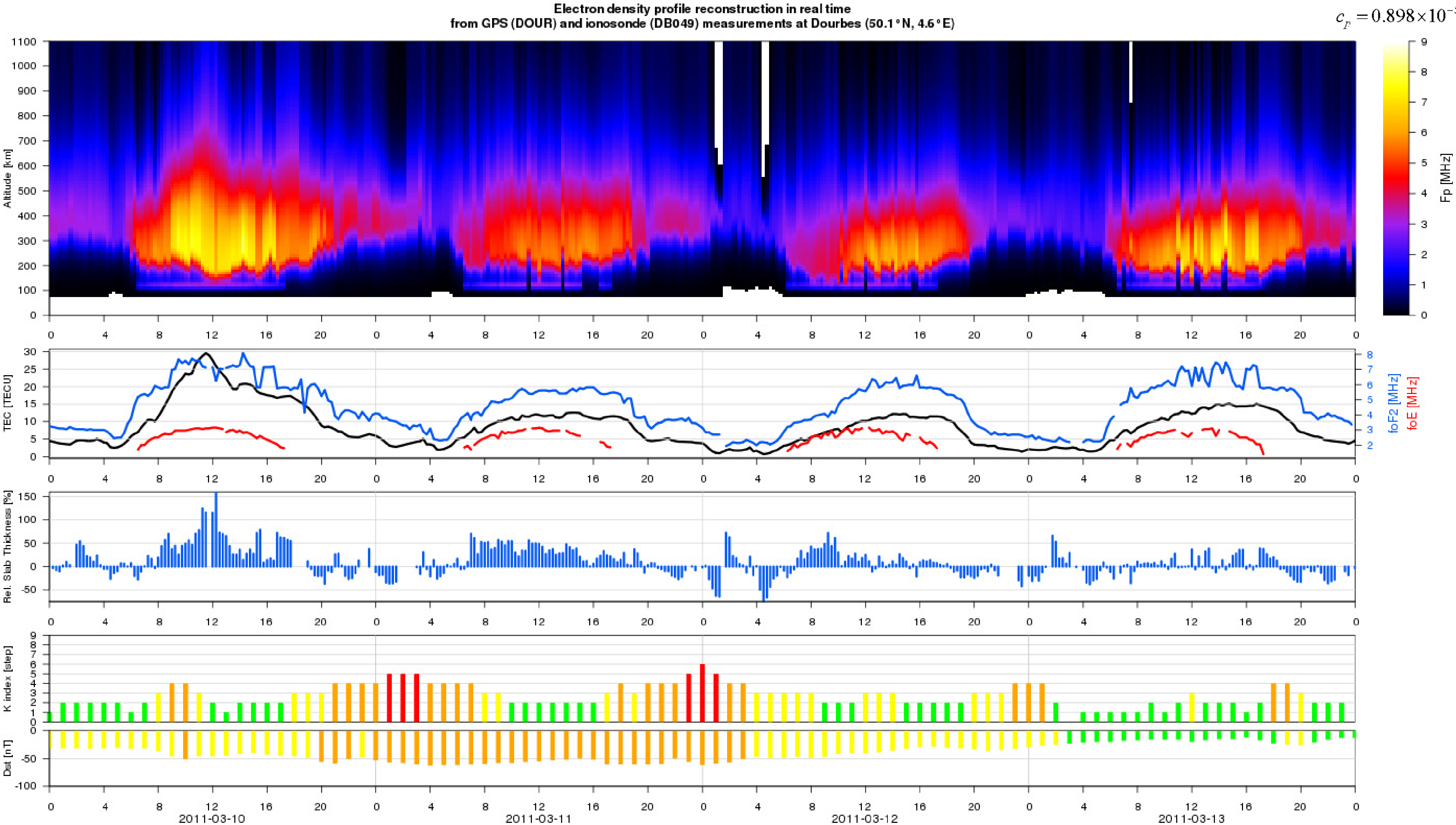
Local ionospheric plasma density specification in real time

STCE

$$f_p[MHz] \approx c_p \, N_e^{0.5}[el/m^3]$$

$$c_p = 0.898 \times 10^{-5}$$



http://swans.meteo.be/ionosphere/liedr

Summary and Outlook

- Modern GNSS-based applications demand high precision – **simultaneous real-time observation of several characteristics essential** (incl. solar/geomagn. activity and 'derivative' measures e.g. ionospheric slab thickness)

- **Electron density reconstruction technique** - **reliable, easy to maintain and upgrade**. It is important that new measurements can be obtained and processed rapidly, which in turn provides higher resolution in the results. Possibilities for **extension to regional ionosphere monitoring** (for regions with dense ionosonde networks, e.g. Europe; alternatively, using empirical/model foF2 maps)

- **Research applications**: further understanding the ionospheric morphology, validating existing ionospheric models. Suitable for investigating **local ionospheric storm-time development**. However, for better identifying and observing a storm, it is necessary to include geomagnetic measurements

- **Operational applications**: ionospheric/space weather monitoring, research & modelling -- to improving comm/nav systems performance (incl. HF propagation and ray tracing, adverse ionospheric effects warnings/mitigation)

- **Further developments** – reconstruction using variable scale height profilers, improving the ion transition height model