The Abdus Salam
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Workshop on Science Applications of GNSS in Developing Countries (11-27 April), followed by the: Seminar on Development and Use of the Ionospheric NeQuick Model (30 April-1 May)

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The Ionosphere

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The Ionosphere

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Workshop on Science Applications of GNSS in Developing Countries
(11-27 April 2012)

This lecture

- The importance of the Ionosphere for systems depending on radio signals
- The atmospheric system
- Formation of the ionosphere
- Ionospheric structure
- Ionospheric variations

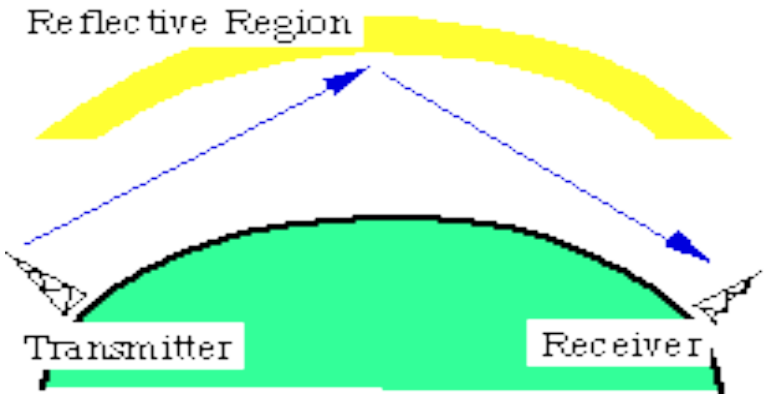
The importance of the Ionosphere for systems depending on radio signals

The beginning

- In 1864 James Clerk Maxwell published a theory of electromagnetic waves.
- In 1899 Guglielmo Marconi invented the first practical radio telegraph system sending signals across the English Channel.
- In 1901 he demonstrated transatlantic radio communications. He was awarded the Noble Prize in Physics in 1909.

The question raised by Marconi's experiment

- How can the radio signals reach a distant receiver if radio waves should travel along straight lines?
- In 1902 Oliver Heaviside and Arthur Kennely came out with the explanation:



Implications to the radio communications (1)

For the most of the 20 century radio communications relied on HF frequencies (3-30 MHz) that used the ionosphere as reflector.

The applications included:

- **Radio Broadcasting**
- **Civilian point-to-point communications**
- **Military communications and surveillance**
- **Ship-to-shore communications**
- **Trans-oceanic aircraft links**
- **Jamming**

Implications to the radio communications (2)

In the 21 century:

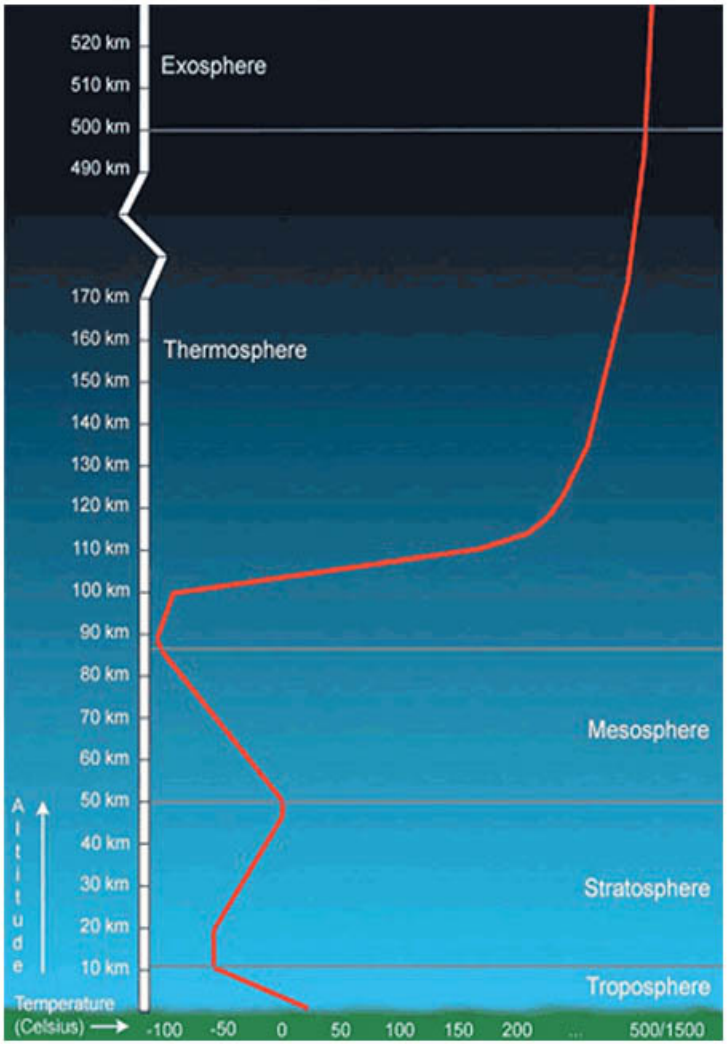
The applications are mostly related to trans-ionospheric radio links including civilian and military satellite communications and satellite navigation systems.

The atmospheric system

The study of the atmospheric system: a word of warning

- **The atmospheric system is not normally studied as a *system* but taking only into account one particular element of the system as its temperature or ionization.**
- ***This approach reduces the possibilities of a full understanding of the atmospheric system behavior as a whole*.**

Atmospheric structure: temperature



The *termal structure* is described as a number of layers (-spheres) separated by -pauses which are defined as the inflection points in the temperature profile.

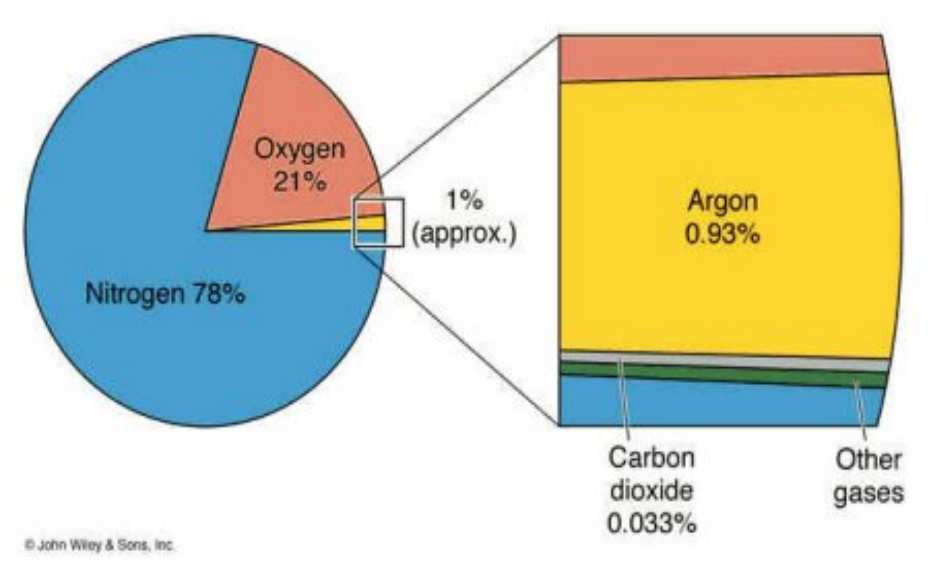
As an example: the *tropopause* defines the top of the troposphere where the temperature gradient turns over from negative to positive.

Why this thermal structure ?

- **The *troposphere* is heated mainly by the ground, which absorbs solar radiation and re-emits it in the infra-red.**
- **The *stratosphere* above the troposphere has a positive temperature gradient due to heating from the *ozone* which absorbs the solar ultra-violet radiation that penetrates down to these altitudes.**
- **In the *mesosphere*, above 50 km, the density of ozone drops off faster than the increase in incoming radiation can compensate for and the temperature decreases with altitude.**
- **The *thermosphere* is heated mainly by absorption of EUV and XUV radiation through dissociation of molecular oxygen.**

Atmospheric composition: ground level

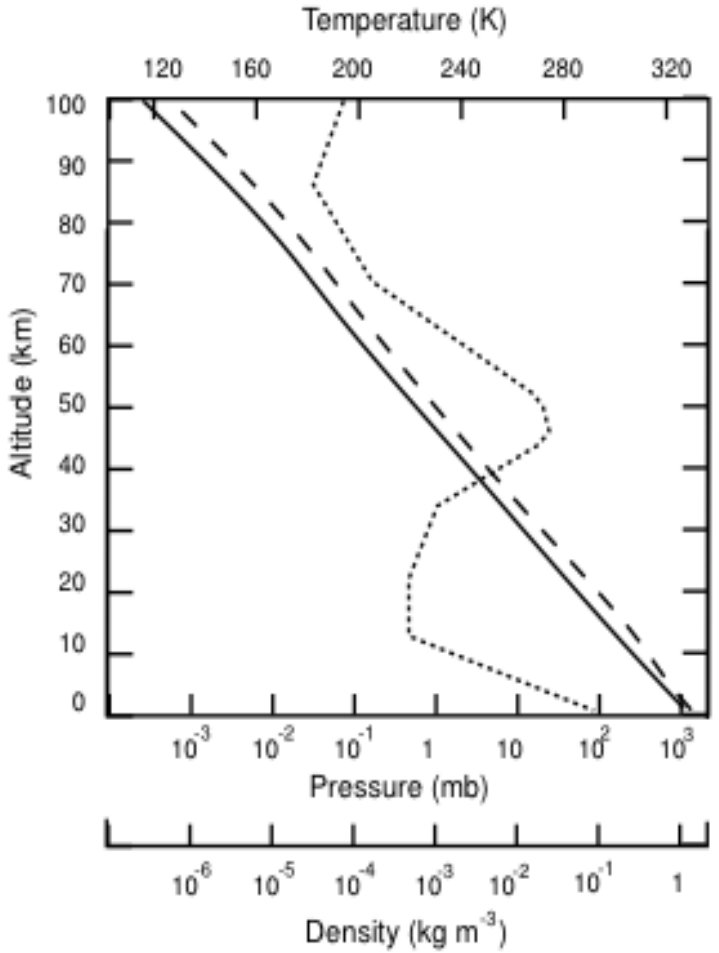
- **By mass**
  - **Nitrogen: ~ 76%**
  - **Oxygen: ~ 23 %**
  - **Argon: ~ 1%**
- **By volume**
  - **Nitrogen: ~78%**
  - **Oxygen: ~21%**
  - **Argon: ~1%**



Atmospheric composition as a function of height

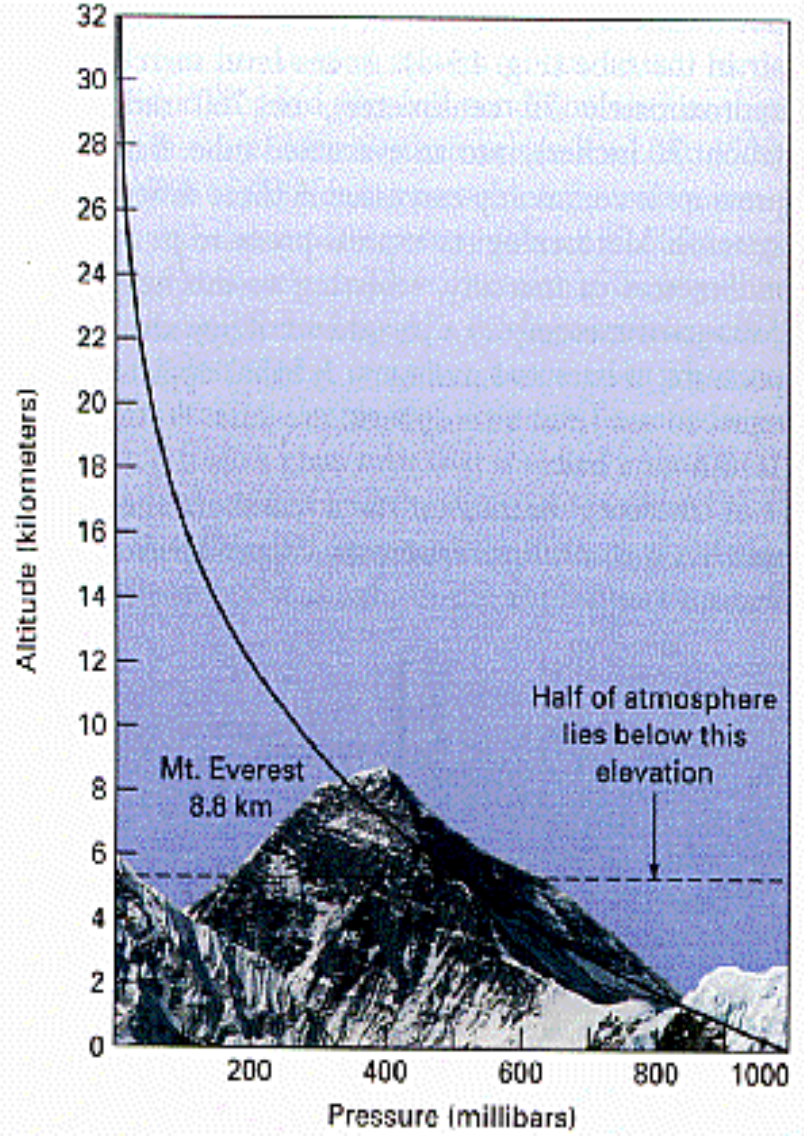
Mixing and molecular diffusion:

- **Turbulent mixing:** ***lower and middle atmosphere***
  - **Does not depend on molecular weight.**
  - **Composition tends to be independent o height**
- **Diffusion:** ***upper atmosphere***
  - **Mean molecular weight of mixture gradually decreases with height.**
  - **Only lightest gases are present at highe levels.**
  - **Each gas behaves as if it were alone.**
  - ***Density drops-of exponentially with height***

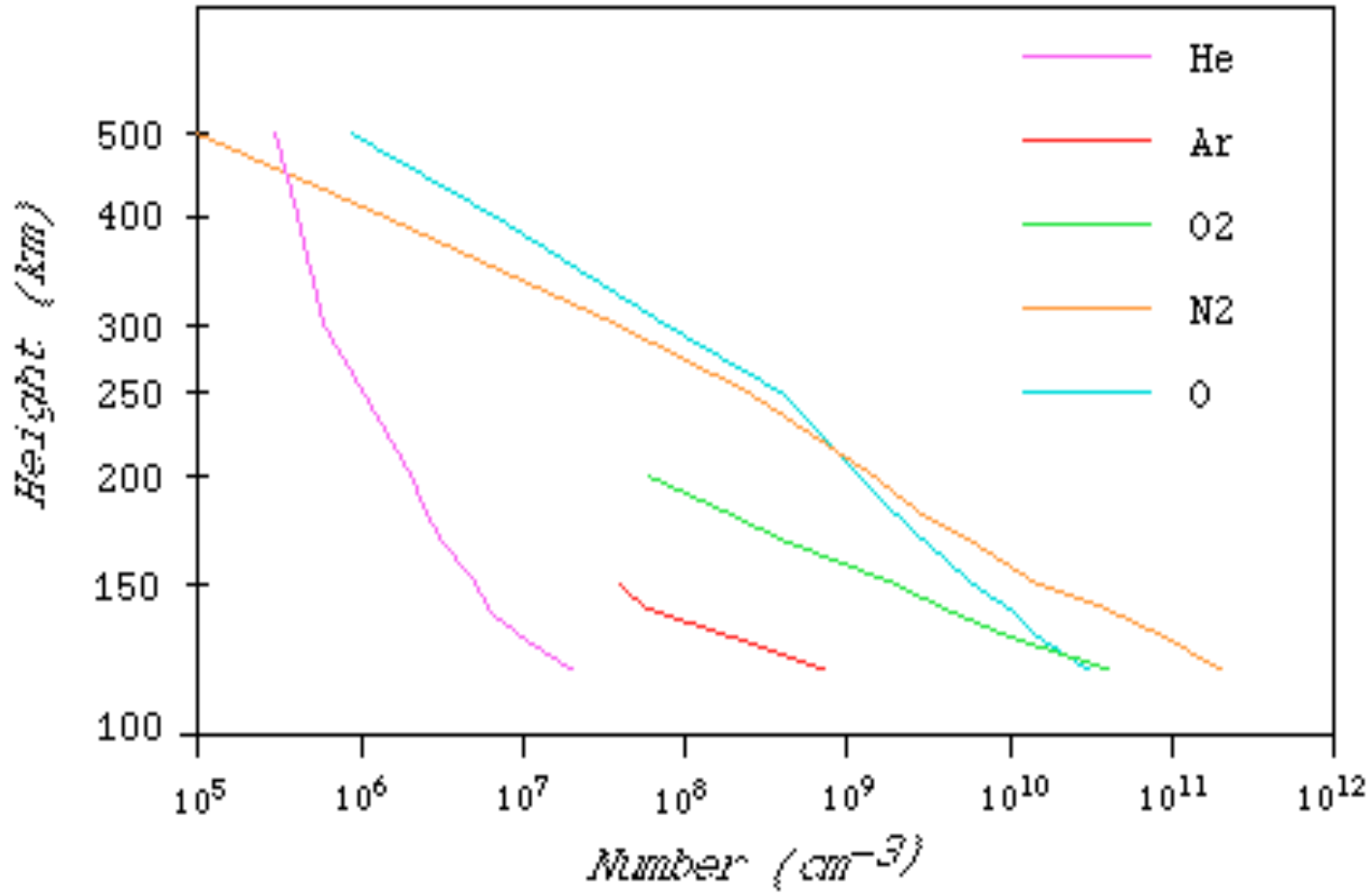


Near 100km: diffusion = turbulent mixing.

A closer look to the atmospheric pressure



Neutral atmosphere composition in the upper atmosphere



Atmospheric Hydrostatic Equilibrium

Pressure Gradient: $\frac{dp}{dz} = -g(z)\rho$ height derivative of pressure equals acceleration of gravity times density

Perfect Gas Law: $p = nkT = \frac{\rho}{M}kT$

Approximation: If g and T are not functions of z, then:

$$\frac{dp}{dz} = -p\frac{Mg}{kT} = -\frac{p}{H} \qquad H = \frac{kT}{Mg}$$

H = scale height (e-folding distance)

$$\frac{dp}{p} = -\frac{dz}{H} \qquad p(z) = p(z_0)\exp\left[-\frac{z - z_0}{H}\right]$$

Scale Height

In various scientific contexts, a "Scale Height" is a distance over which a quantity decreases by a factor of *e*.

The "scale height" defined in the previous slide is the "*pressure scale height*" that, considering the perfect gas law and the troposphere composed mostly by N_2 (m=2 x 14 x 1.66×10^{-27} kg):

$m = 4.65 \times 10^{-26}$ kg
$g = 9.8$ m/s^2
and
T ~ 300 K,
we get:

$$H = 9 \times 10^3 \text{ m} = 9 \text{ km}$$

Formation of the ionosphere

Photochemical processes in the atmosphere

- **The atmosphere of the Earth is made up of a large number of chemical constituents.**
- **We have seen that the most abundant or major constituents are N_2, O_2 and Ar, but many more constituents are produced in the atmosphere itself by *photochemical processes* or at the surface by different natural processes and human activity.**
- ***Photochemical processes play a fundamental role in the middle and upper atmosphere including the ionosphere*.**

Main photochemical absorption processes of solar radiation

Photodissociation $AB + h\nu \rightarrow A + B$

(wavelenght > 130 nm)

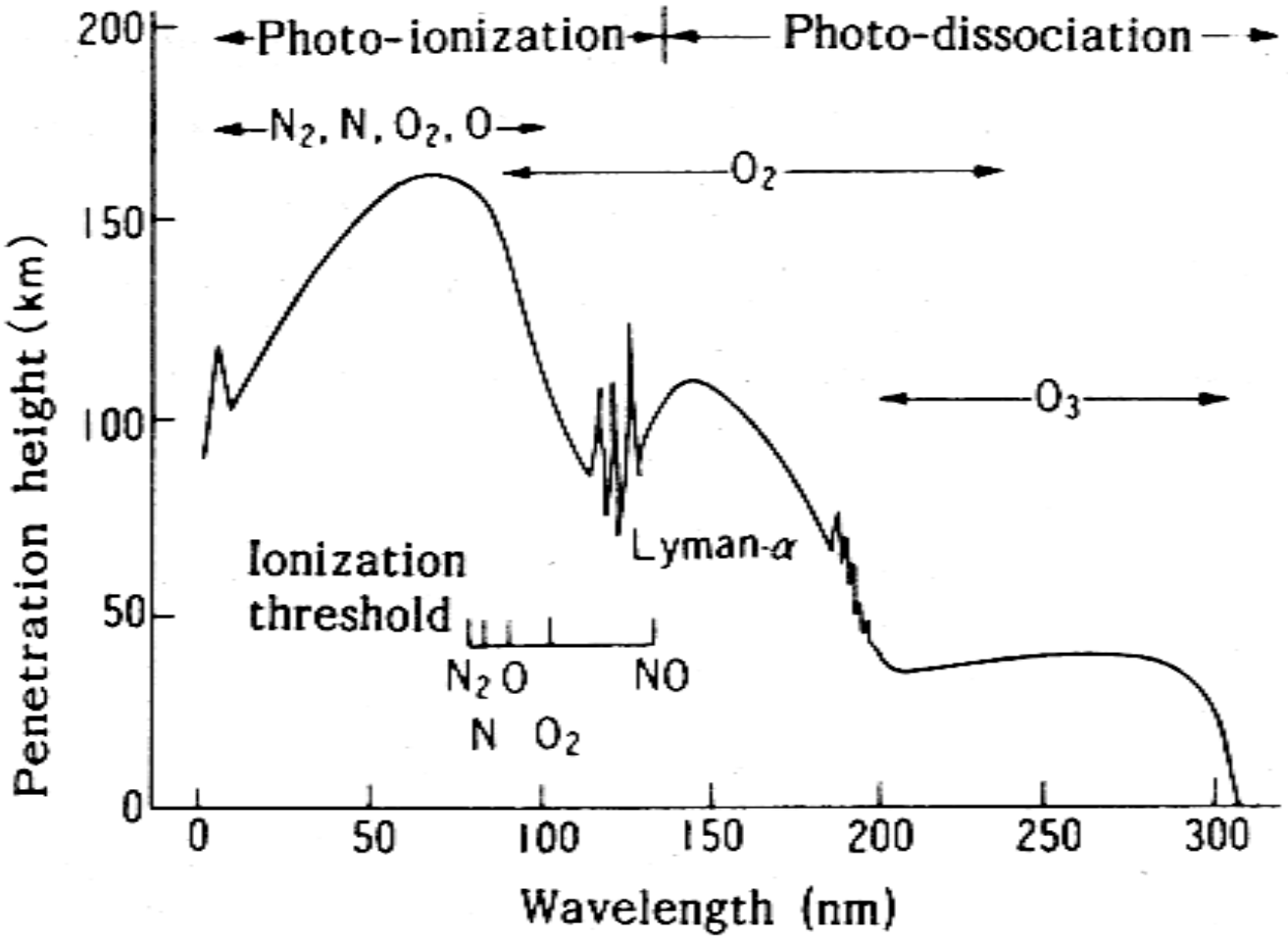
Photoexcitation $AB + h\nu \rightarrow AB^{*}$

(wavelenght < 130 nm)

Photoionization $A + h\nu \rightarrow A^{+} + e$

(wavelenght < 100 nm)

Solar radiation penetration heights



Ionic species recombination processes

Radiative recombination $X^+ + e \xrightarrow{\alpha_R} X + Y$

Dissociative recombination $XY^+ + e \xrightarrow[\alpha_i]{\alpha_D} X + Y$

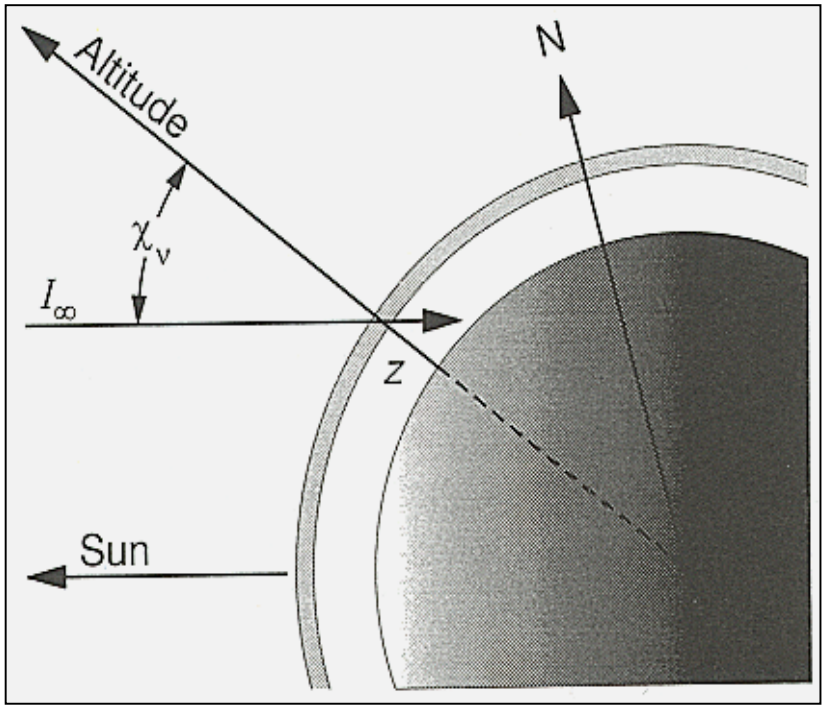
Ion-Ion recombination $XY^+ + Z^- \rightarrow$ **neutrals**

Formation of the Ionosphere

Solar UV and X radiation impinges at angle χ_v,

It is absorbed in the upper atmosphere and ionizes the neutral atmosphere

I_∞ is the flux on top of the layer.



Basic equations of solar radiation absorption in the atmosphere (1)

H **is the scale height,**

$H = k_B T_n / m_n g$,

with *g* being the gravitational acceleration at height *z* = 0, where the density is n_0.

$$n_n(z) = n_0 \exp(-z/H)$$

According to radiative transfer theory, the incident solar radiation diminishes with altitude along the ray path in the atmosphere.

$$dI = \sigma_\nu n_n \frac{dz}{\cos \chi_\nu} I$$

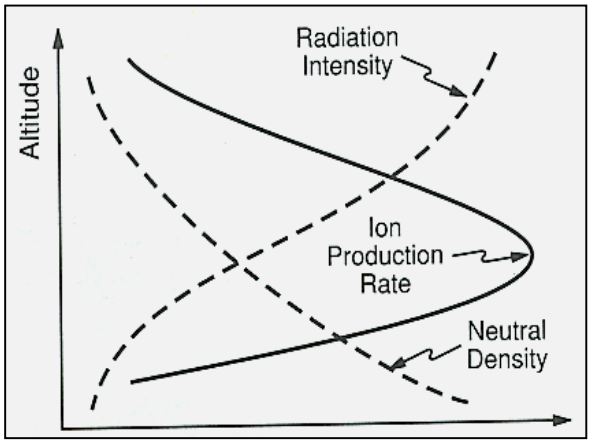
σ_ν **is the radiation absorption cross section for radiation (photon) of frequency** ν**.**

Basic equations of solar radiation absorption in the atmosphere (2)

Solving for the intensity yields:

$$I(z) = I_\infty \exp\left[-\frac{\sigma_\nu n_0 H}{\cos\chi_\nu}\exp(-z/H)\right]$$

The figure shows the exponential decrease of the intensity with height, the decrease of neutral density and the resulting ion production given analitically by the next equation



Basic equations of solar radiation absorption in the atmosphere (3)

$$q_\nu(z) = \kappa_\nu \sigma_\nu n_0 I_\infty \exp\left[-\frac{z}{H} - \frac{\sigma_\nu n_0 H}{\cos\chi_\nu}\exp(-z/H)\right]$$

The number of electron-ion pairs locally produced by the solar radiation, the photoionization rate per unit volume $q_\nu(z)$, is proportional to the ionization efficiency, κ_ν , and absorbed radiation: $q_\nu(z) = \kappa_\nu \sigma_\nu n_n I(z)$.

This equation describes the formation of the Chapman layer and represents the basis of the theory of the photochemical processes in the atmosphere.

Basic equations of solar radiation absorption in the atmosphere (4)

Recombination, with coefficient α_r, and electron attachment, β_r, are the two major loss processes of electrons in the ionosphere.

In equilibrium quasi-neutrality applies:

$$n_e = n_i$$

Then the continuity equation for n_e reads:

$$\frac{dn_e}{dt} = q_{\nu,e} - \alpha_r n_e^2 - \beta_r n_e$$

Chapman layer theory

***A theoretical distribution of ionization as a function of height produced solely by the absorption of solar radiation by a single atmospheric constituent*.**

Named for Sydney Chapman, who first derived the shape of such a distribution mathematically.

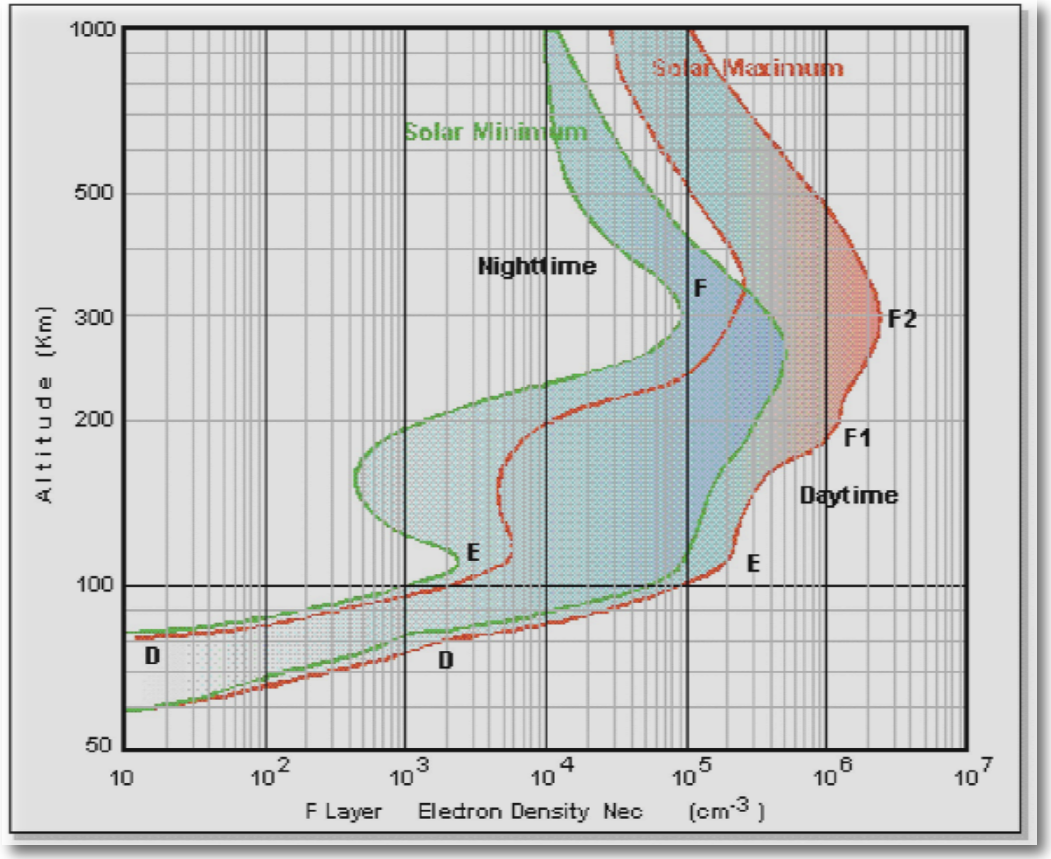
Some of the basic assumptions used to develop the equation were that

- ***The ionizing radiation from the sun is monocromatic,***
- ***The single neutral constituent to be ionized is distributed exponentially (i.e., with a constant scale height),***
- ***There is equilibrium between the creation of free electrons and their loss by recombination.***

Ionospheric structure

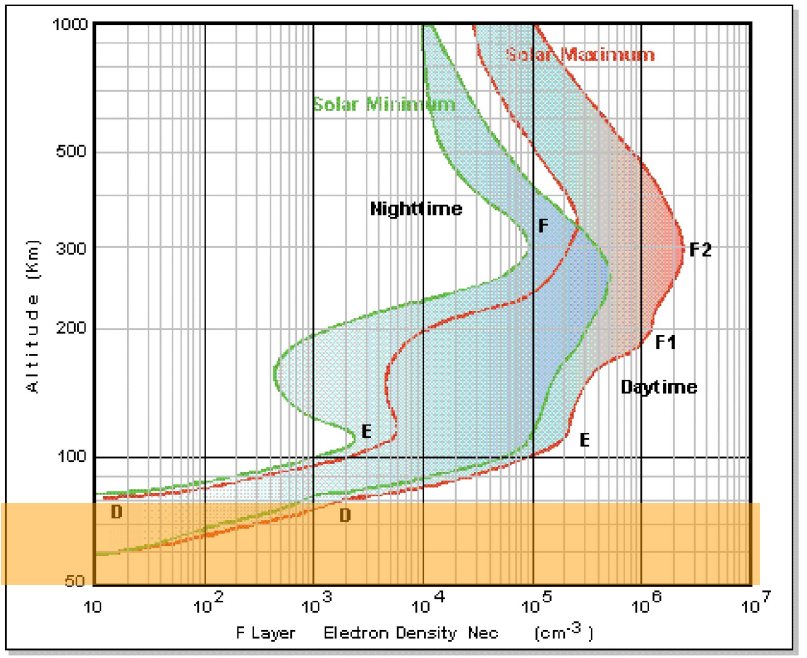
A layered structure

Due to *different ionization production and loss processes* the electron density profile with altitude shows a layered structure.



D region

- D-region (about 60 to 90 km altitude)
  Production: daytime ionization of nitric oxide (NO) by solar Lyman alpha (121 nanometer wavelength) and of nitrogen and oxygen (N2, O2) by solar X-rays (less than 20 nm). Molecular ions react with water vapor to produce water cluster ions.
  Loss: electrons recombine rapidly with water cluster ions and also attach to molecules to make negative ions (but rapidly detach again in daylight).
  Balance: layer disappears at night (within several minutes) as production essentially ceases and electrons undergo rapid recombination and attachment.

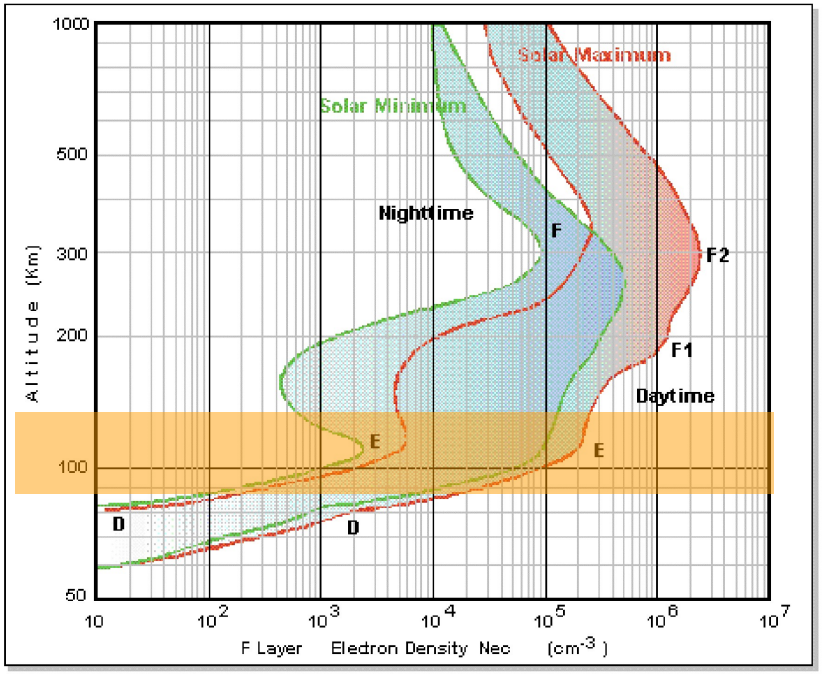


E region

- E-region (about 90 to 140 km altitude)
  Production: daytime ionization of molecular oxygen (O2) by extreme ultraviolet solar radiation (90-103 nm), ionization of meteoric vapors.
  Loss: electrons recombine with molecular ions (O2+ and NO+).
  Balance: layer persists, although diminishes, during night due to slower recombination (than in D-region) and presence of atomic metallic ions such as Na+ (sodium) and Fe+ (iron). Electrons recombine with atomic ions (such as Na+ or O+) very inefficiently.

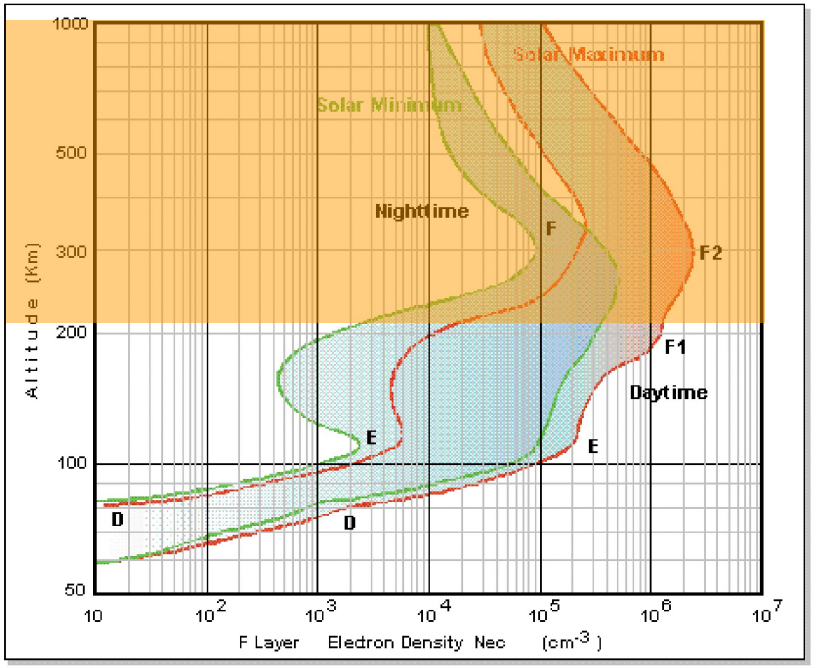
  E region behaves as a Chapman layer.

  At the E region heights sporadic thin layers can be formed that can have electron densities well above the background values.



F region

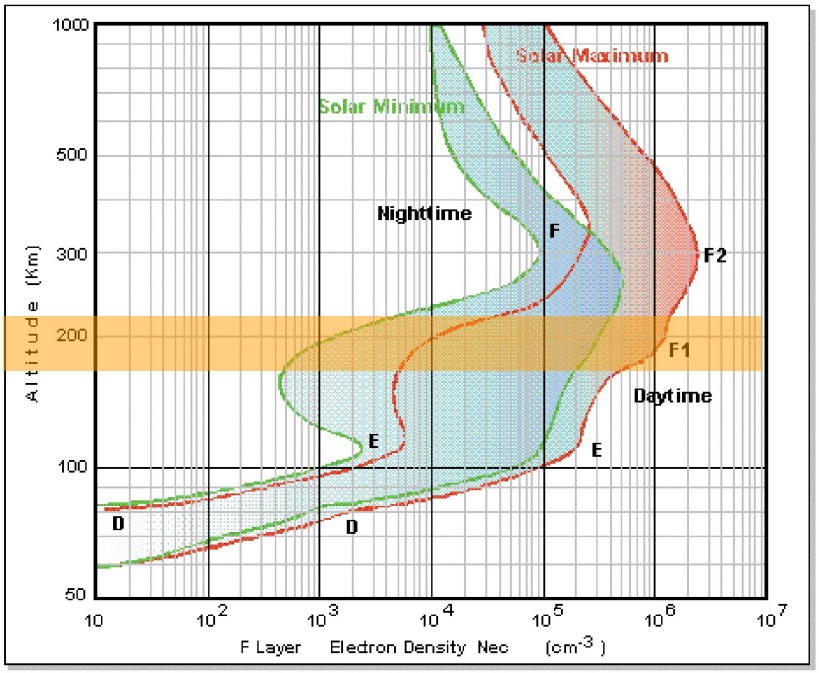
- F-region (above 140 km altitude)
  Production: daytime ionization of atomic O by extreme ultraviolet (EUV) solar radiation (20 - 90 nm). O+ converted to NO+ by molecular nitrogen (N2)



F1 layer

- F1-layer (about 140 to 200 km altitude)
  Loss: controlled by recombination of NO+ ions with electrons.
  Balance: layer diminishes at night as electrons recombine with NO+.

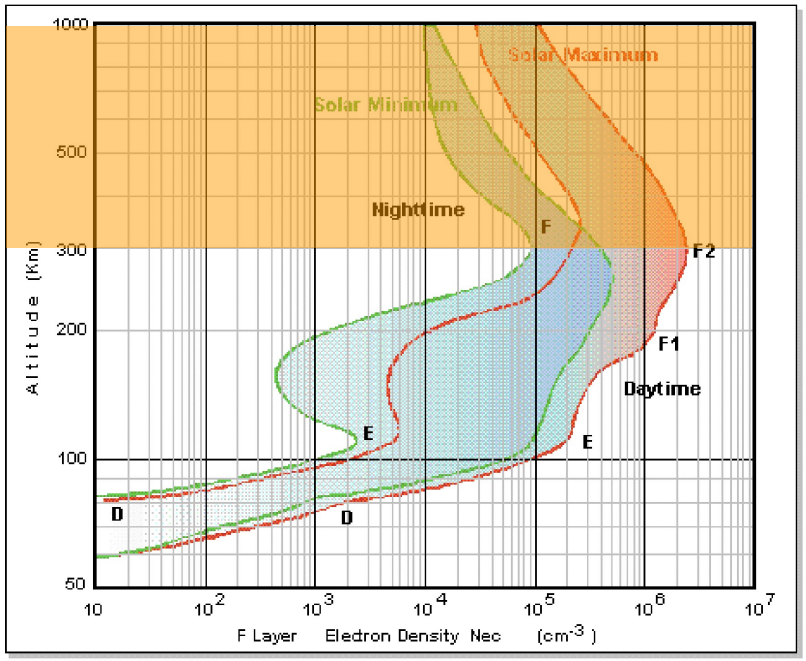
  F1 layer behaves as a Chapman layer



F2 layer

- F2-layer (peak about 300 to 400 km altitude)
  Loss: controlled by O+ reaction with molecular nitrogen (N2), electrons recombine quickly with ion product (NO+) as it is created.
  Balance: layer persists through night (becoming simply the F-region) since the small supply of N2 leads to slow conversion of O+ to NO+ and hence only a small reduction in the number of electron.

  Transport processes become important in the F2 and upper F regions, including ambipolar diffusion and wind-induced drifts along B, and and electrodynamic drifts across B.



F2 region chemistry

The recombination process is two-stage:

$O^+ + N_2 \rightarrow NO^+ + N$ (attachment like) **rate $\propto \beta$ $[O^+]$**

- ***controls the rate at high altitudes***

$NO^+ + e \rightarrow N + O$ **rate $\propto \alpha$ $[NO^+][Ne]$**

- ***controls the rate at low altitudes***

$$\frac{dn_e}{dt} = q_{\nu,e} - \alpha_r n_e^2 - \beta_r n_e$$

Continuity equation and Ion transport in the F region

Ions and electrons, once formed (P), will tend to recombine (L) but they are also affected by transport with a plasma drift V.

Ions and electrons will be influenced by the vertical pressure gradient, and the heavier ions will tend to 'settle'. But, the resultant separation will form an electric field which will tend to restore the system.

$$\frac{\partial n_e}{\partial t} = P - L - div(n_e V)$$

$$\frac{\partial n_e}{\partial t} = q - \beta n_e - div(n_e V)$$

F region in summary

- The lowest region (F1), where photochemistry dominates.
- The transition region from chemical to diffusion (lower F2).
- The upper region, or topside, where diffusion dominates
- In the F2, including the topside, the presence of transport processes influenced by the geomagnetic field became important.

Ionospheric variations

Ionospheric variations

- ***The Earth's ionosphere shows marked variations with altitude, latitude, longitude, universal time, season, solar cycle, and magnetic activity.***
- **This variation is reflected in all ionospheric properties: electron density, ion and electron temperatures, and ionospheric composition and dynamics.**
- **This is primarily a result of the ionosphere's coupling to the other regions in the solar-terrestrial system: the sun, the interplanetary medium, the magnetosphere, the thermosphere, and the mesosphere**
- **Variations are of two general types:**
  - **(1) *(more or less) regular*, occurring in cycles and that can be predicted in advance with reasonable accuracy (*quiet ionosphere*)**
  - **(2) *irregular*, mostly due to the irregular behavior of the sun and that cannot be easily predicted in advance (*disturbed ionosphere*)**

Both regular and irregular variations have important effects on radio wave propagation.

Introduction to the topic

- We will concentrate on the regular variations mostly of the F2 layer and in the variability of two parameters that are related to the peak electron density and the electron content in the ionosphere.
- The starting point will be a mention to the experimental techniques used to derive these parameters

The ionosonde and the ionogram

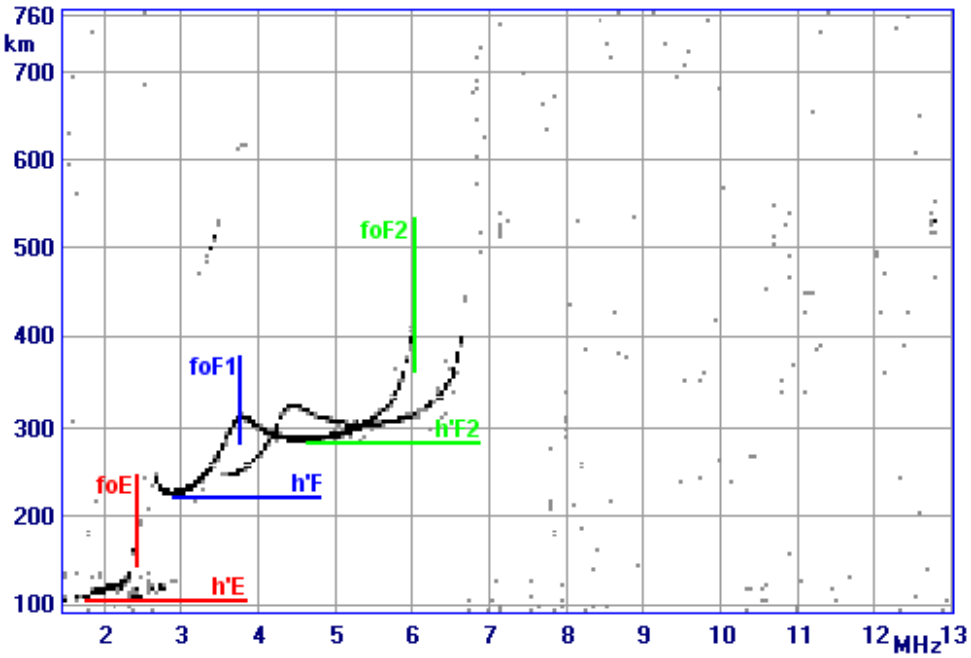
- An ionosonde is essentially a radar that transmits pulses of a sweep of frequencies, usually in the range of 0.1 to 20 MHz.

- As the frequency increases, each wave penetrates further in the ionized layer before it is reflected.

- Generally, a frequency is reached that enables the wave to penetrate the layer without being reflected.

- For *o* mode waves, this occurs when the transmitted frequency just exceeds the peak plasma frequency of the layer.

- In the case of the *x* wave, the magnetic field has an additional effect, and reflection occurs at a frequency that is higher than the ordinary wave.



Critical frequencies

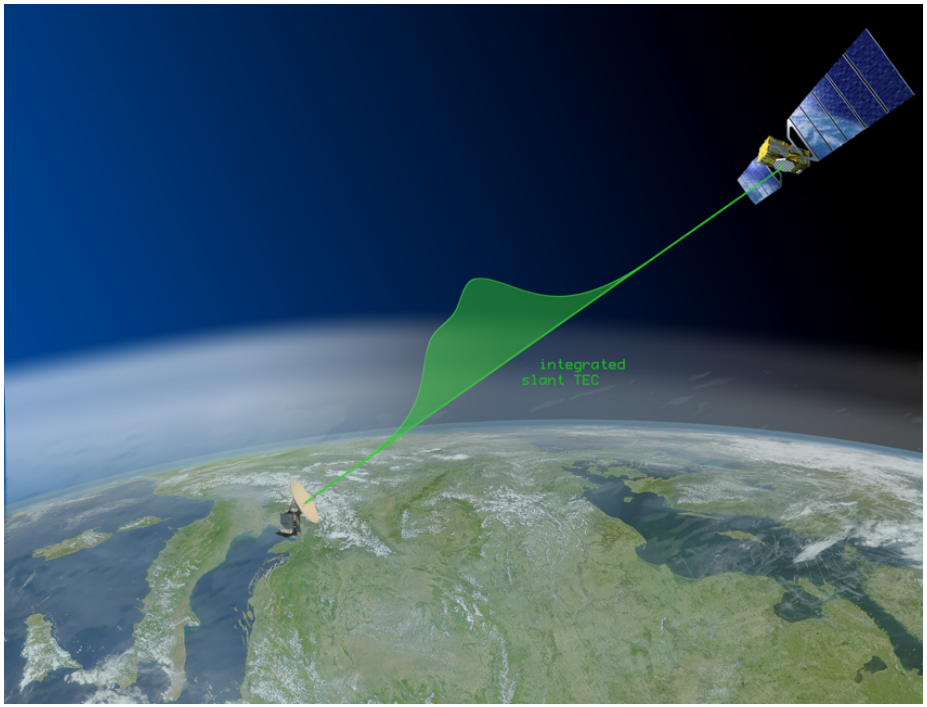
The frequency at which a wave just penetrates an ionospheric layer is known as the critical frequency of that layer. The critical frequency is related to the electron density by the simple relation:

$$N = 0.124 \times 10^{11} \left(f\right)^2$$

$$N\left[m^{-3}\right] \quad f\left[MHz\right]$$

Total electron content

The total electron content (TEC) is the number of electrons in a column of one metre-squared cross-section along a trans-ionospheric path. It can be obtained by different means, mainly from GNSS and satellite born altimeters signals



$$N_T = \int_S N(s)\, ds \qquad 1\,TEC = 10^{16}\, m^{-2}$$

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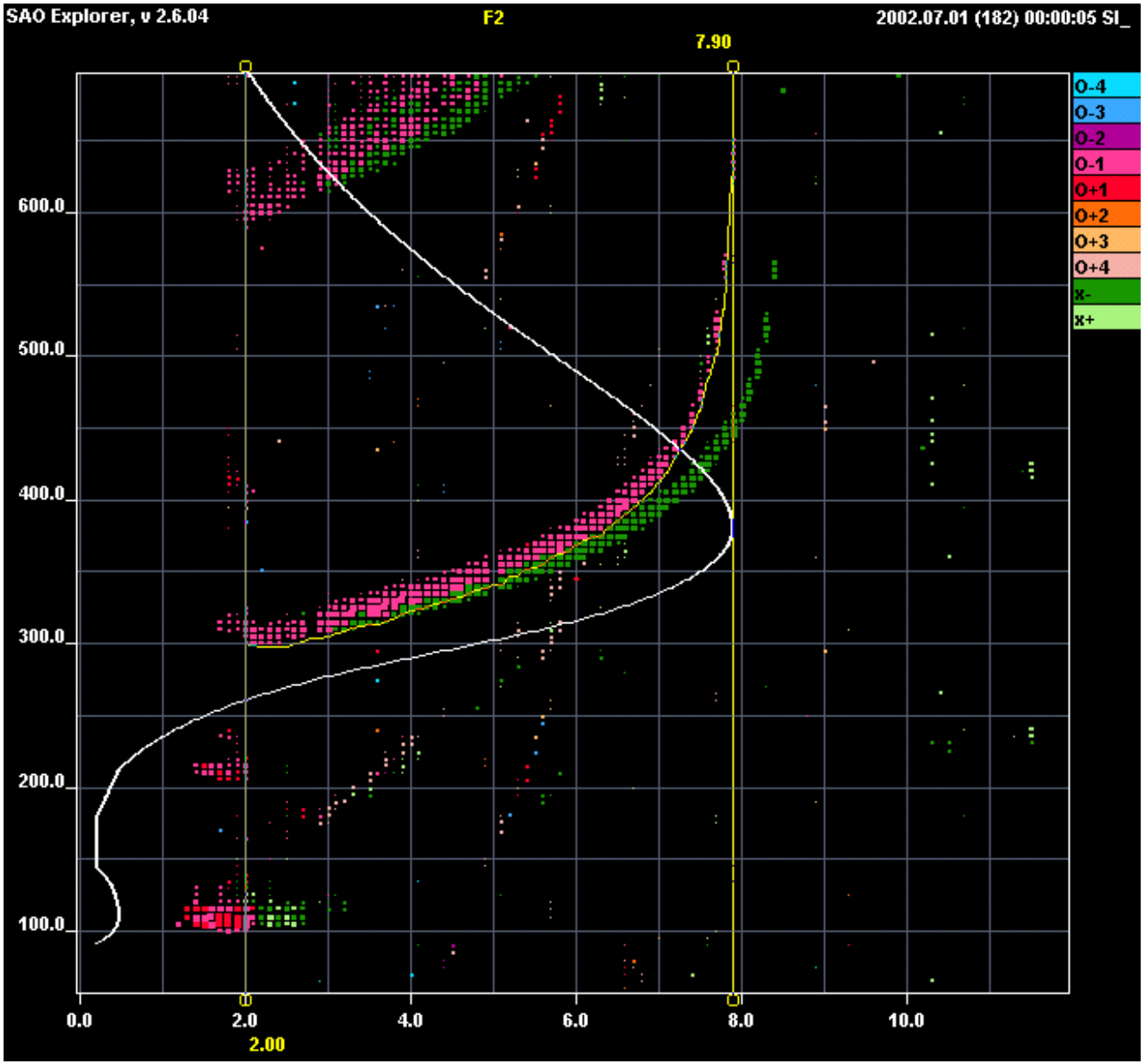
Diurnal variations



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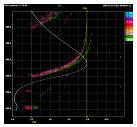
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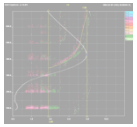
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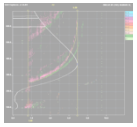
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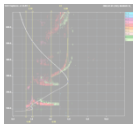
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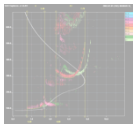
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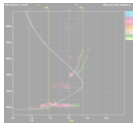
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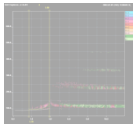
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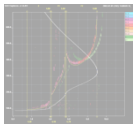
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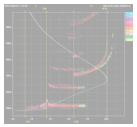
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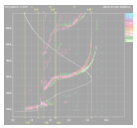
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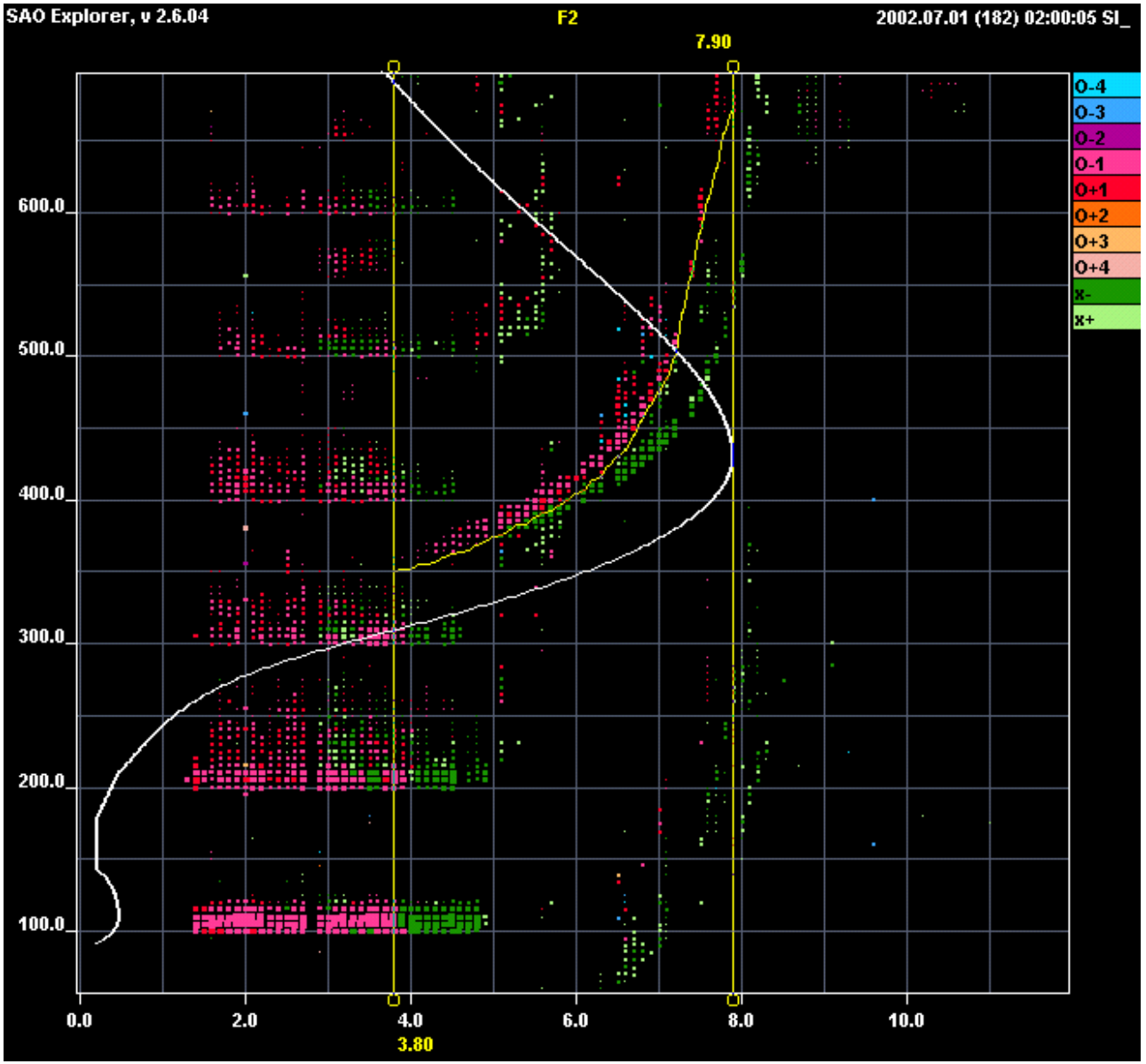

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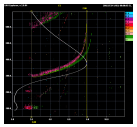

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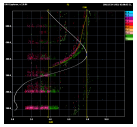

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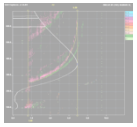

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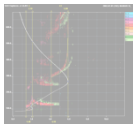

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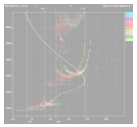

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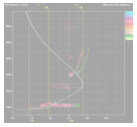

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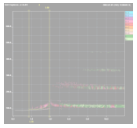

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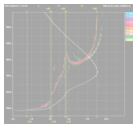

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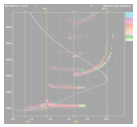

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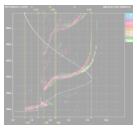

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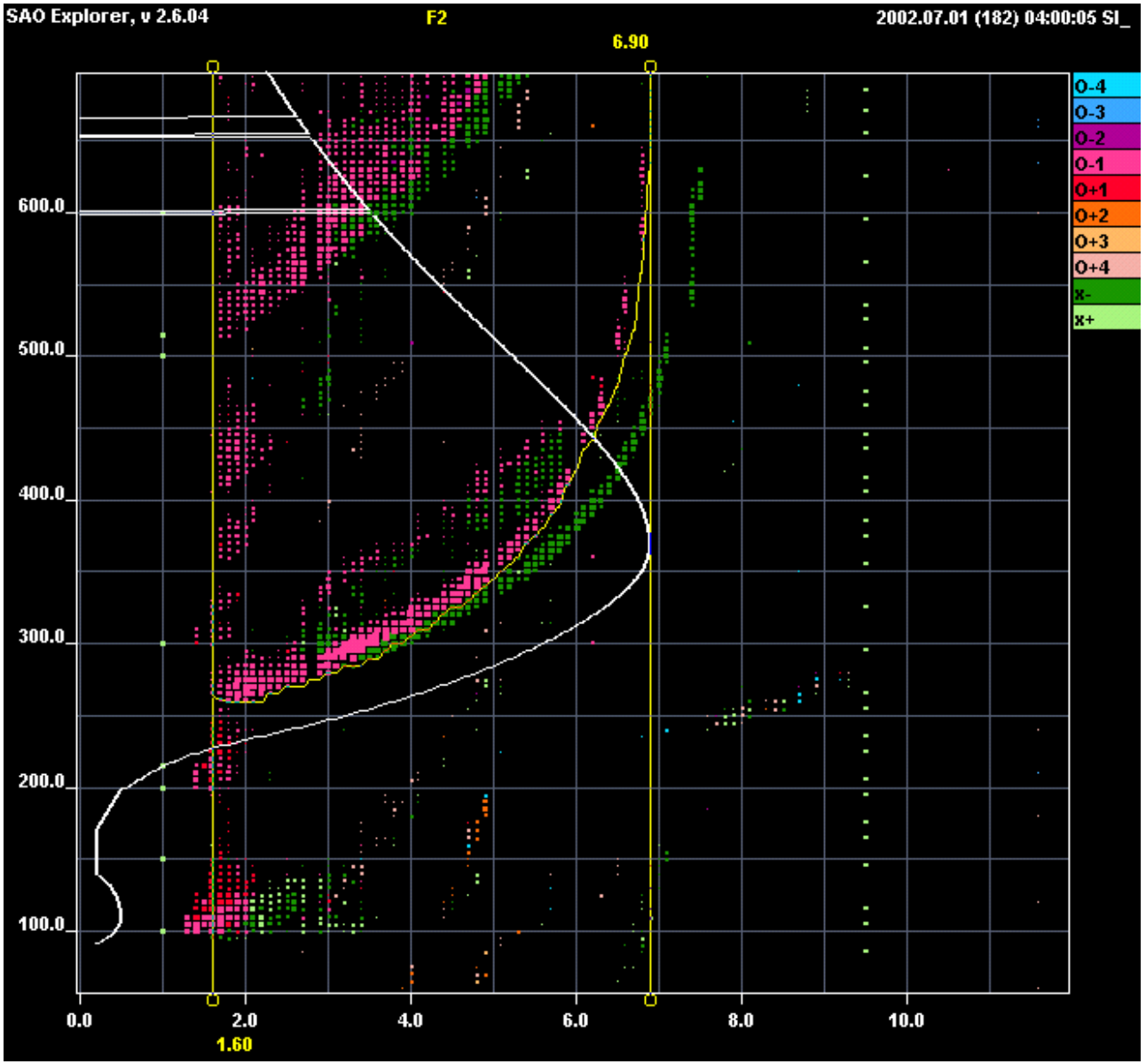

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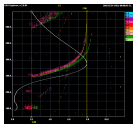

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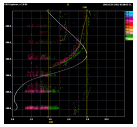

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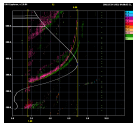

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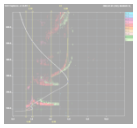

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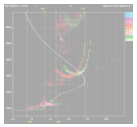

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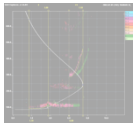

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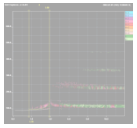

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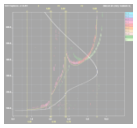

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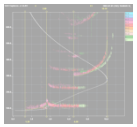

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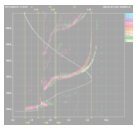

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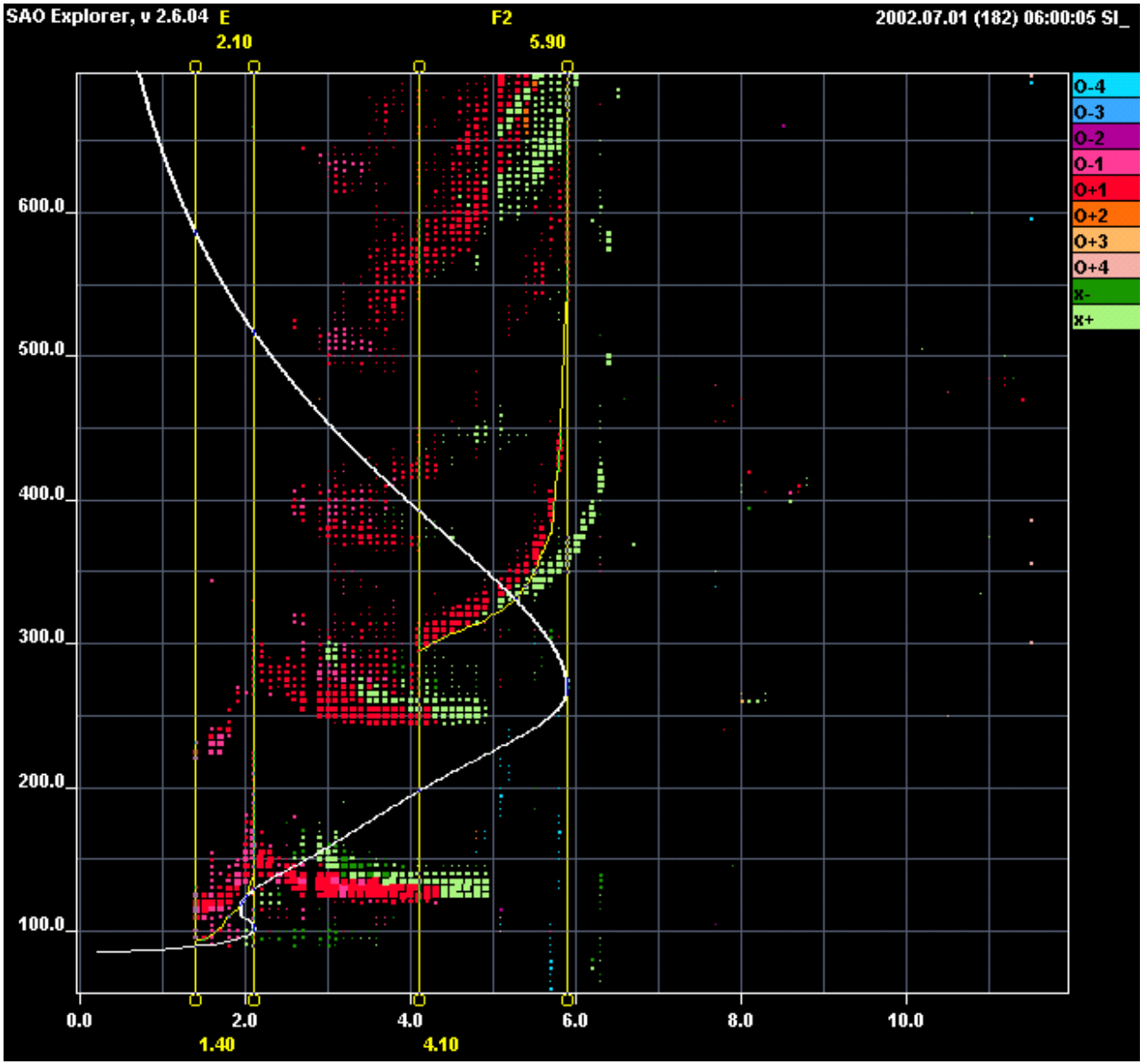

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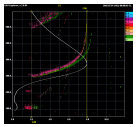

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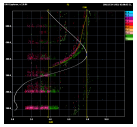

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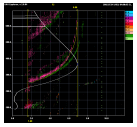

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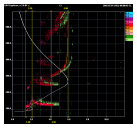

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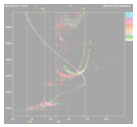

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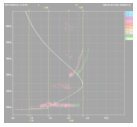

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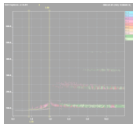

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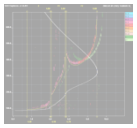

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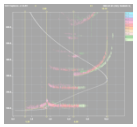

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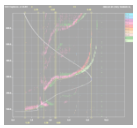

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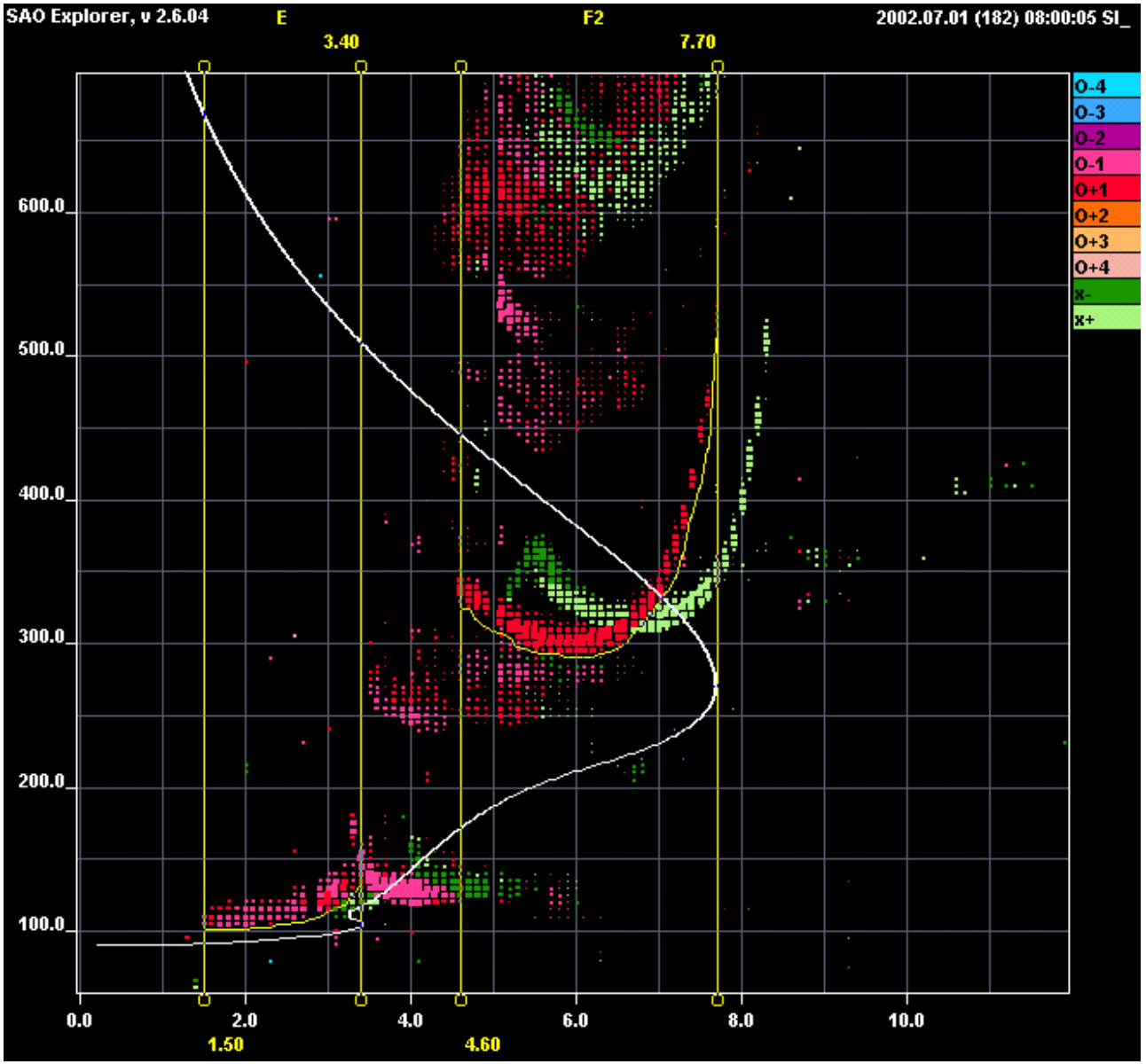

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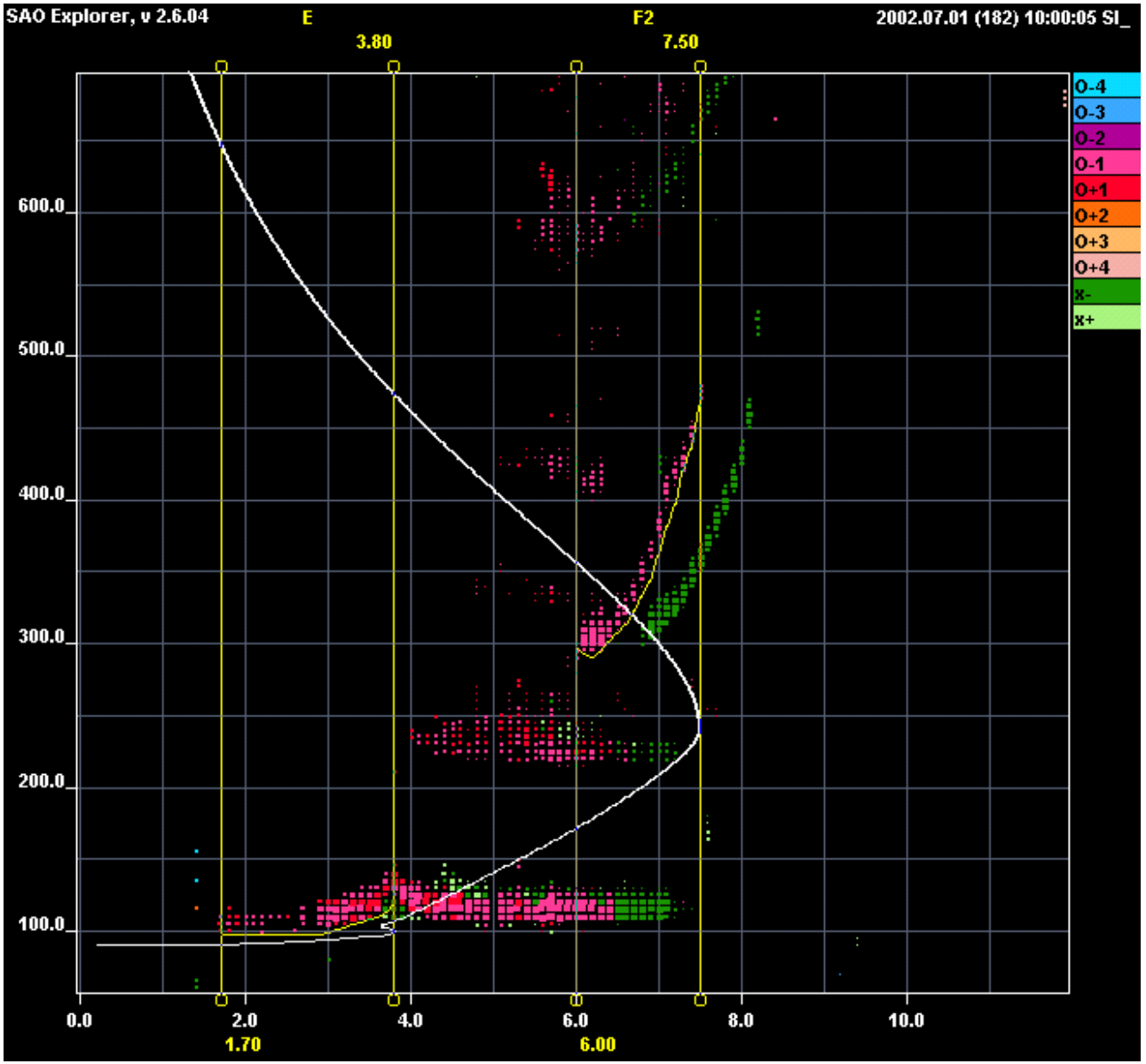

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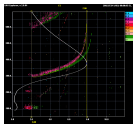
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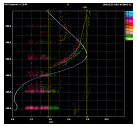
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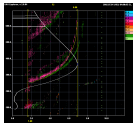
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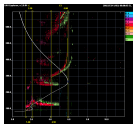
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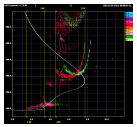
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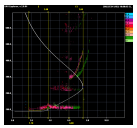
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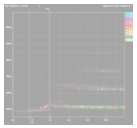
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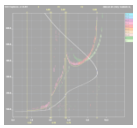
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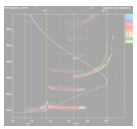
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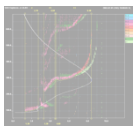
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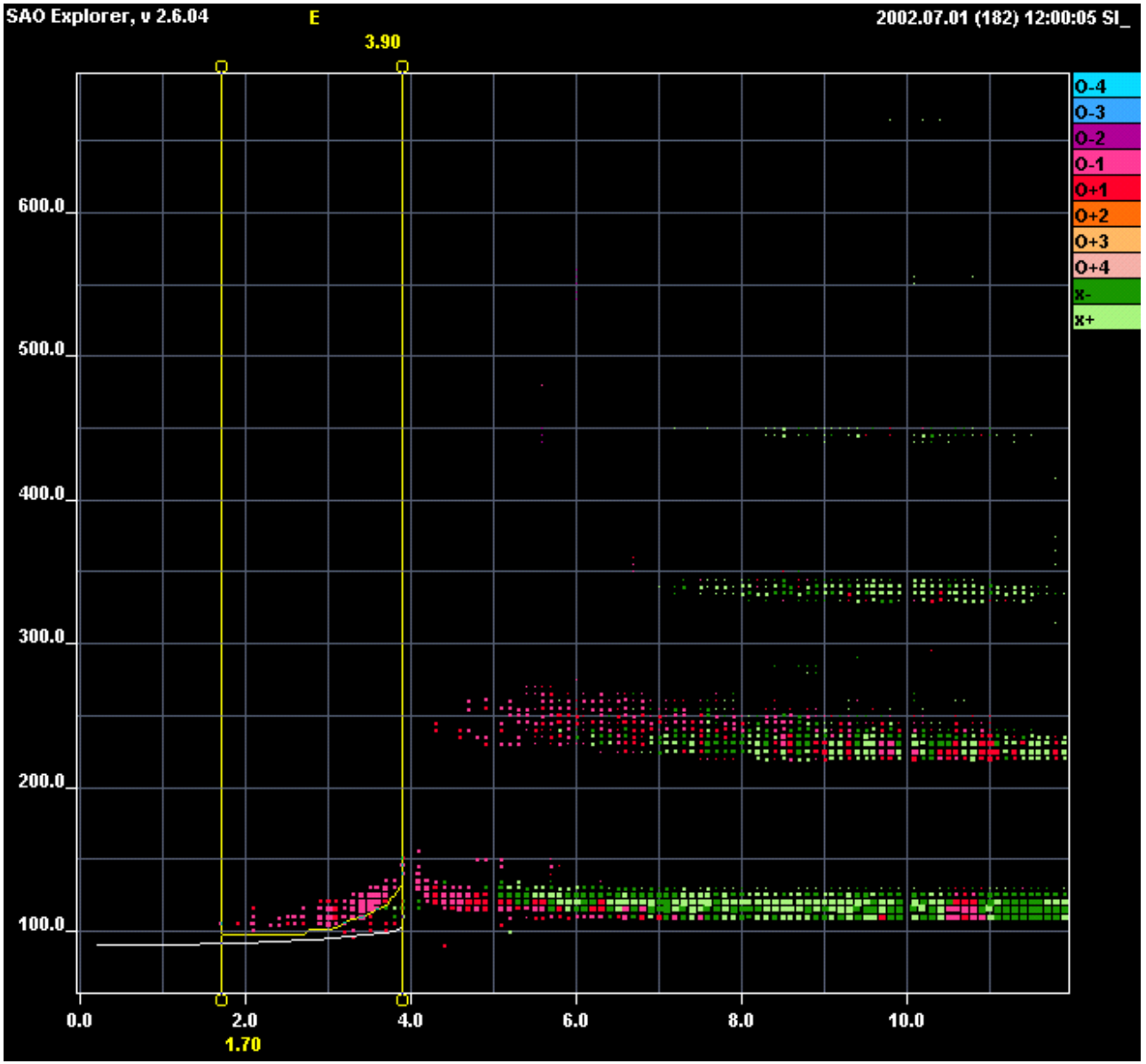

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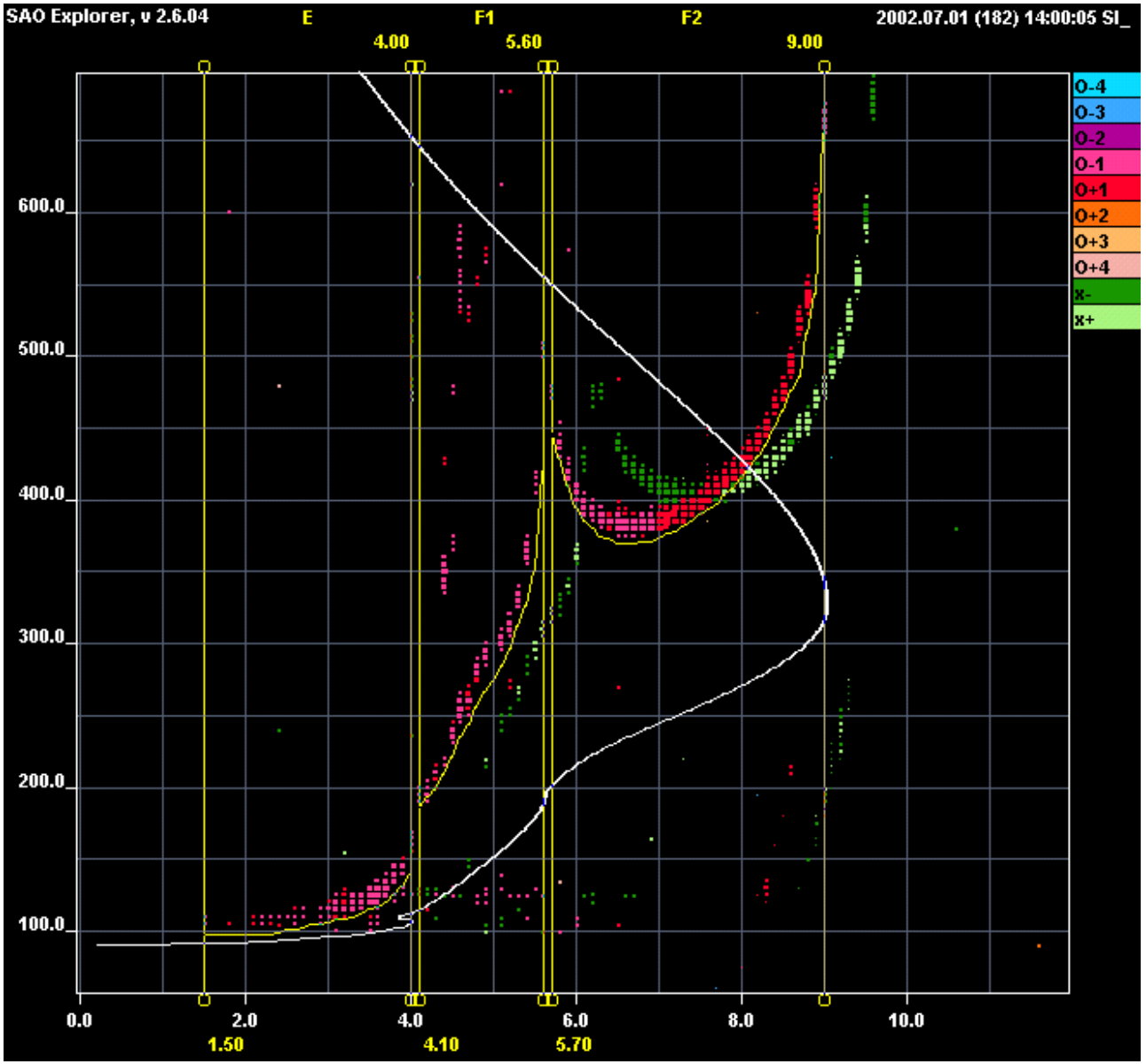

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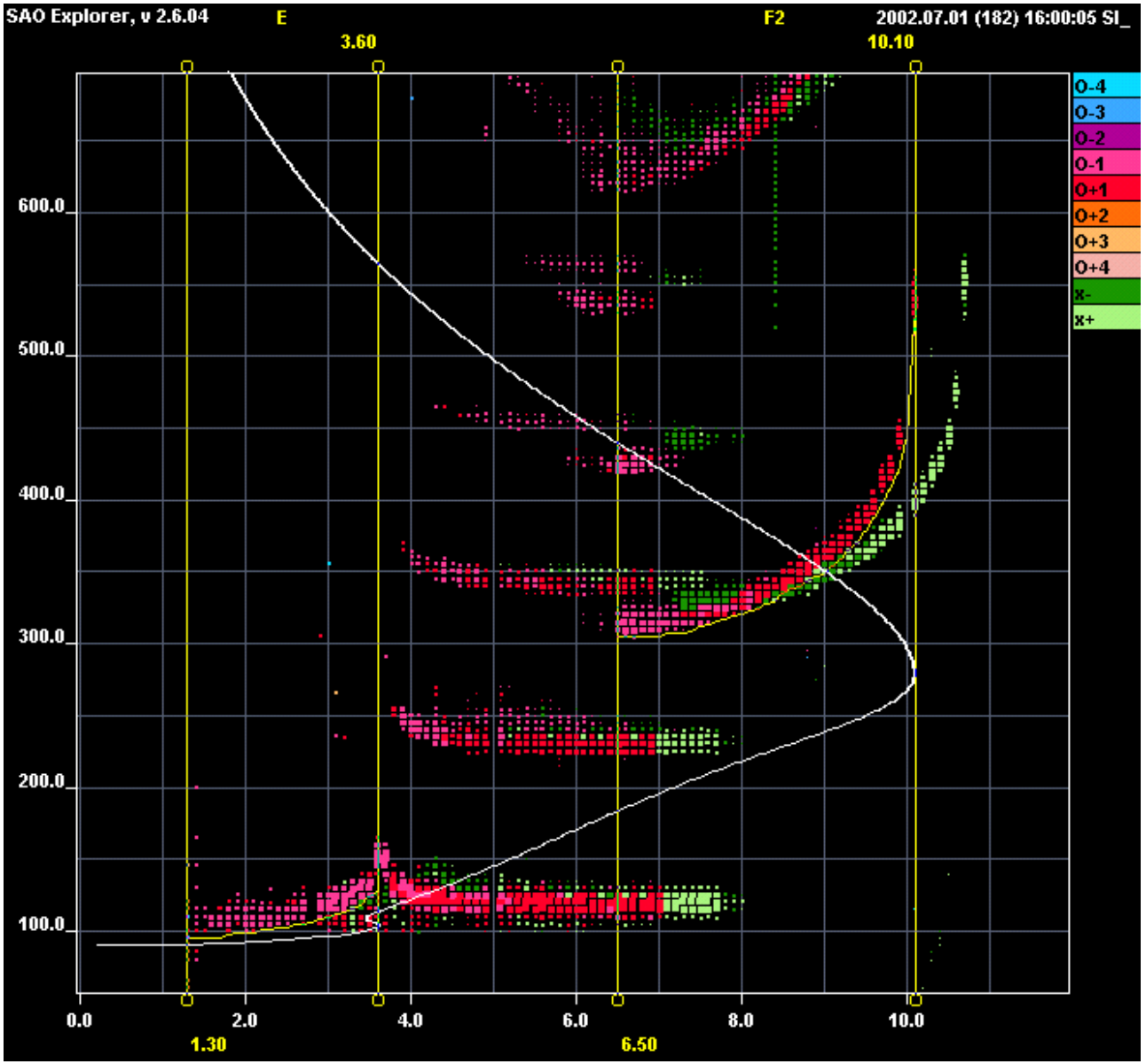

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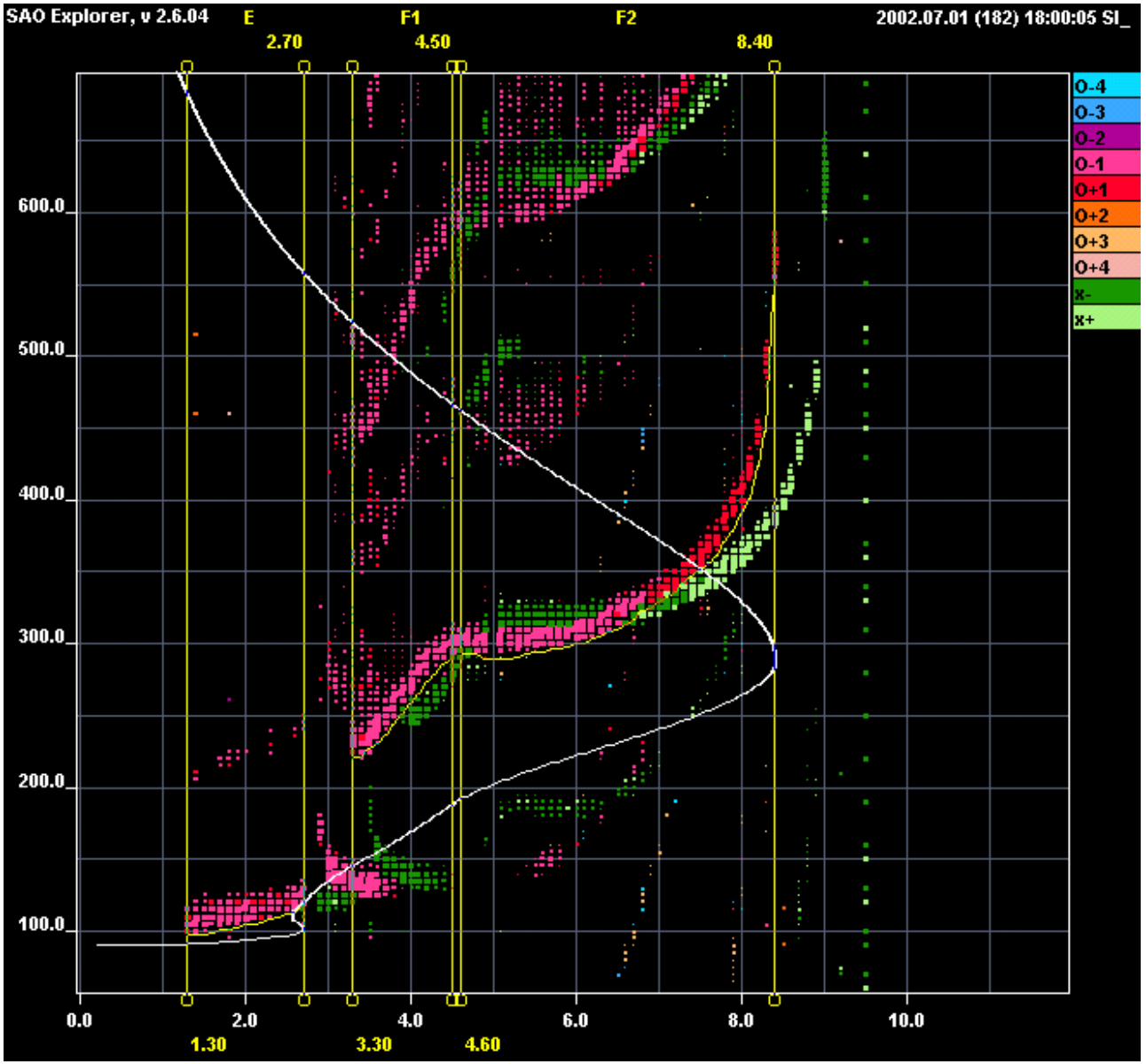

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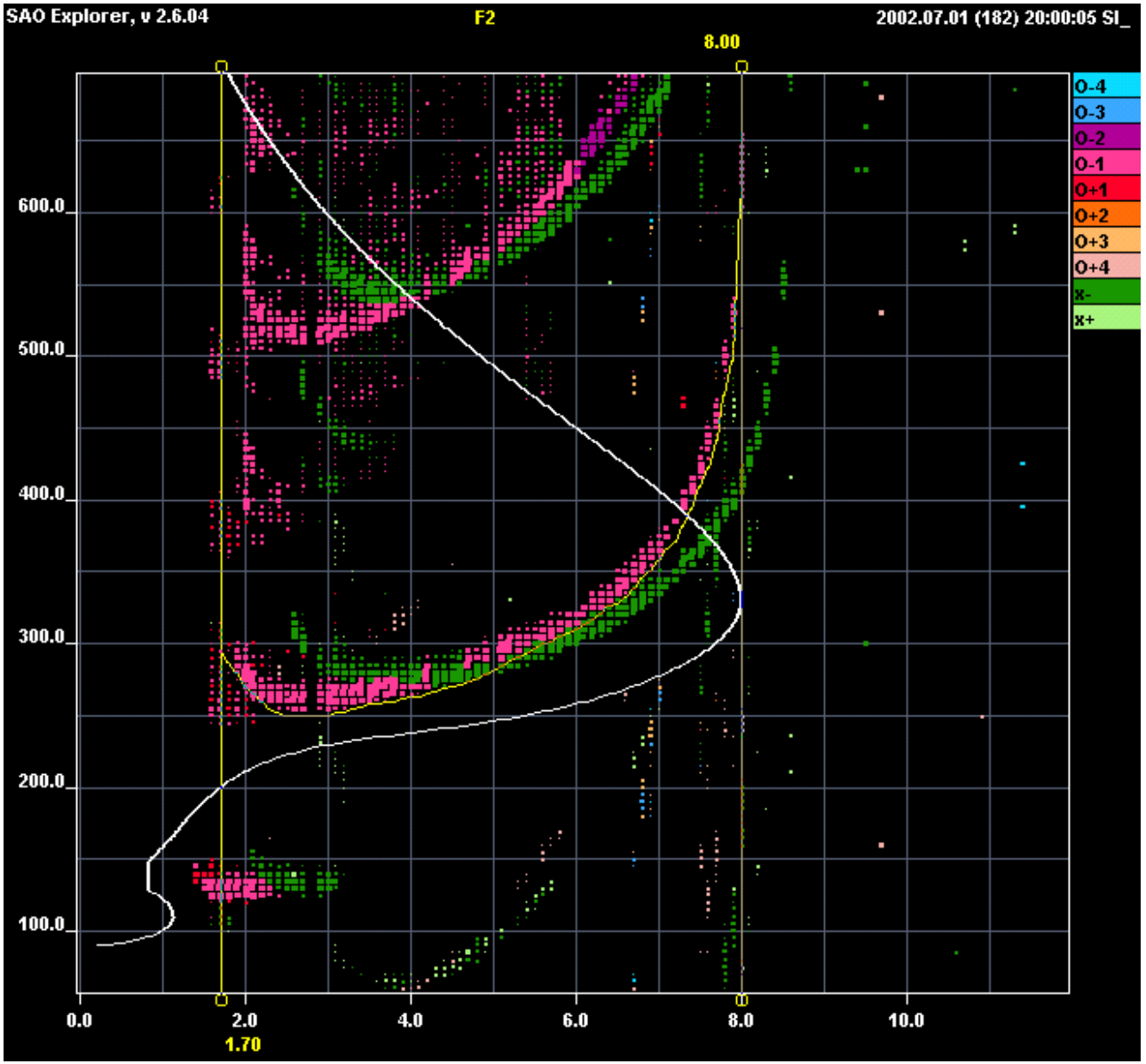

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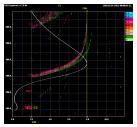

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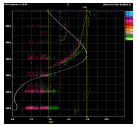

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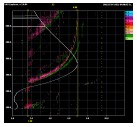

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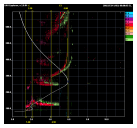

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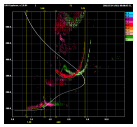

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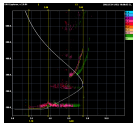

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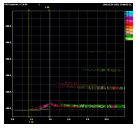

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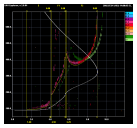

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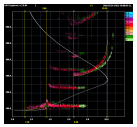

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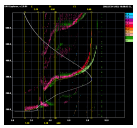

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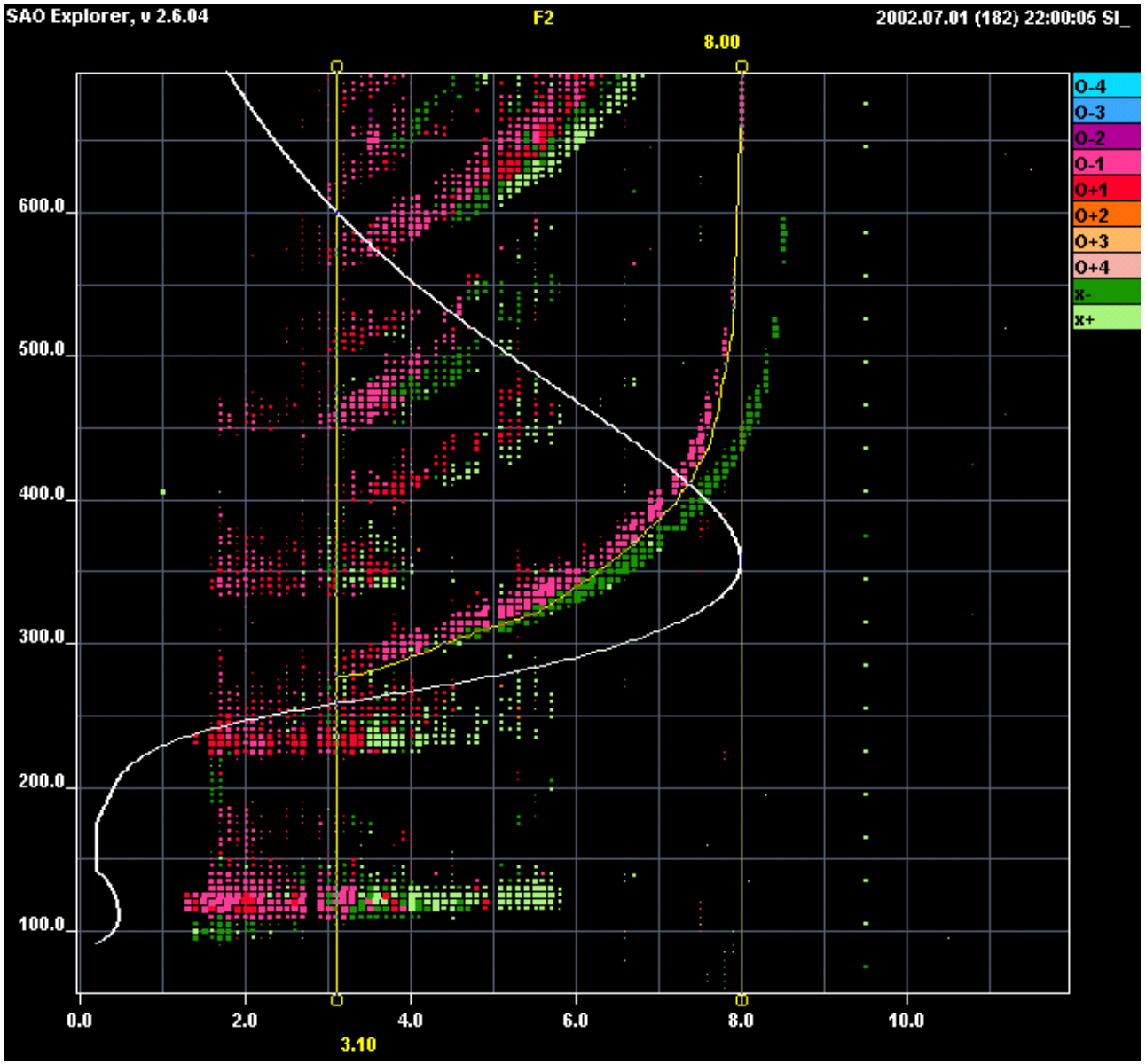
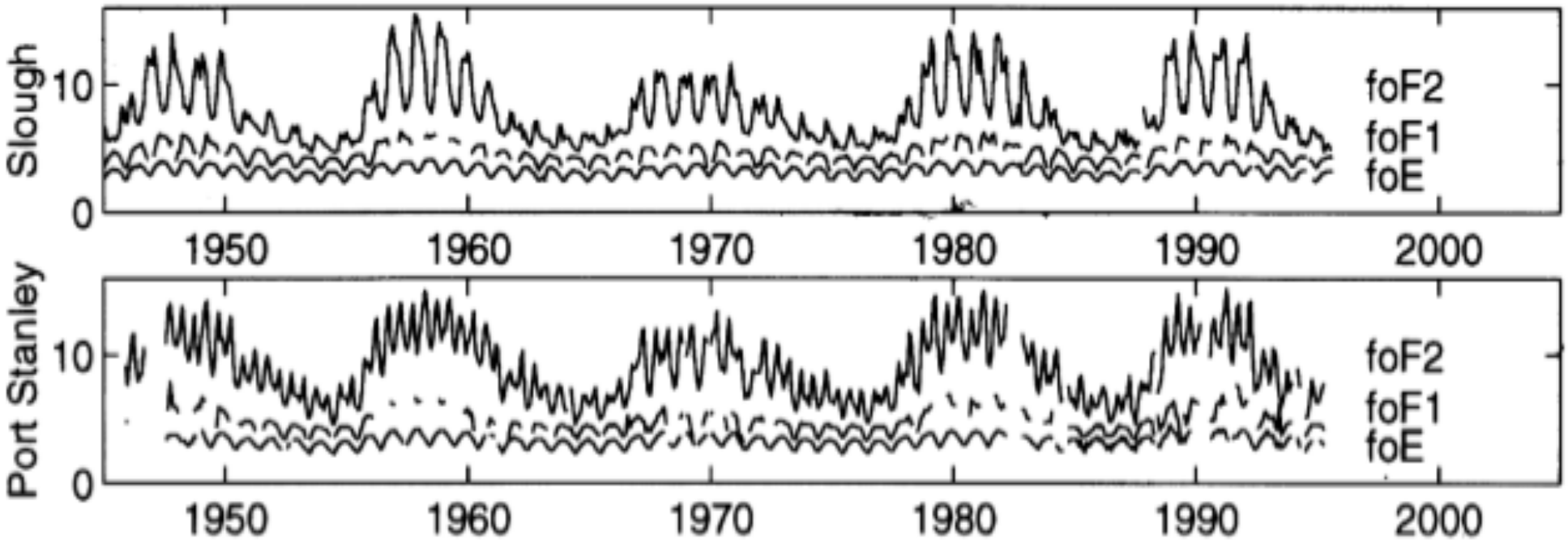


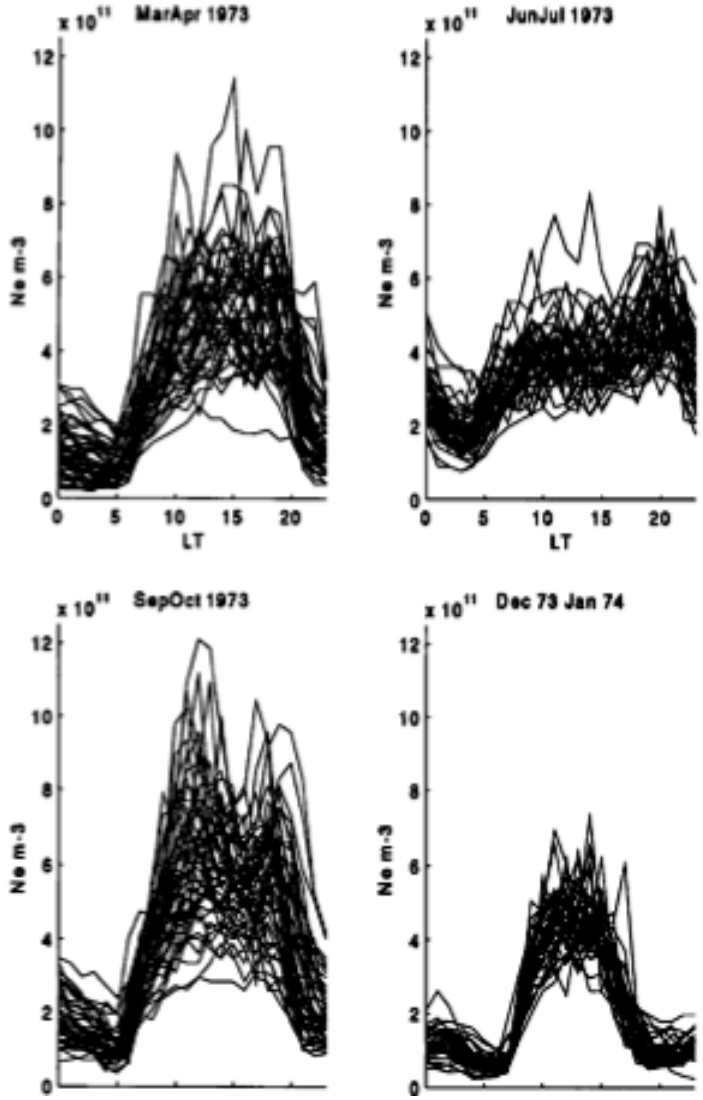
Ionospheric median critical frequencies variations



Rishbeth, H., Journal of Atmospheric and Solar-Terrestrial Physics, 60 p.1385-1402 (1998)

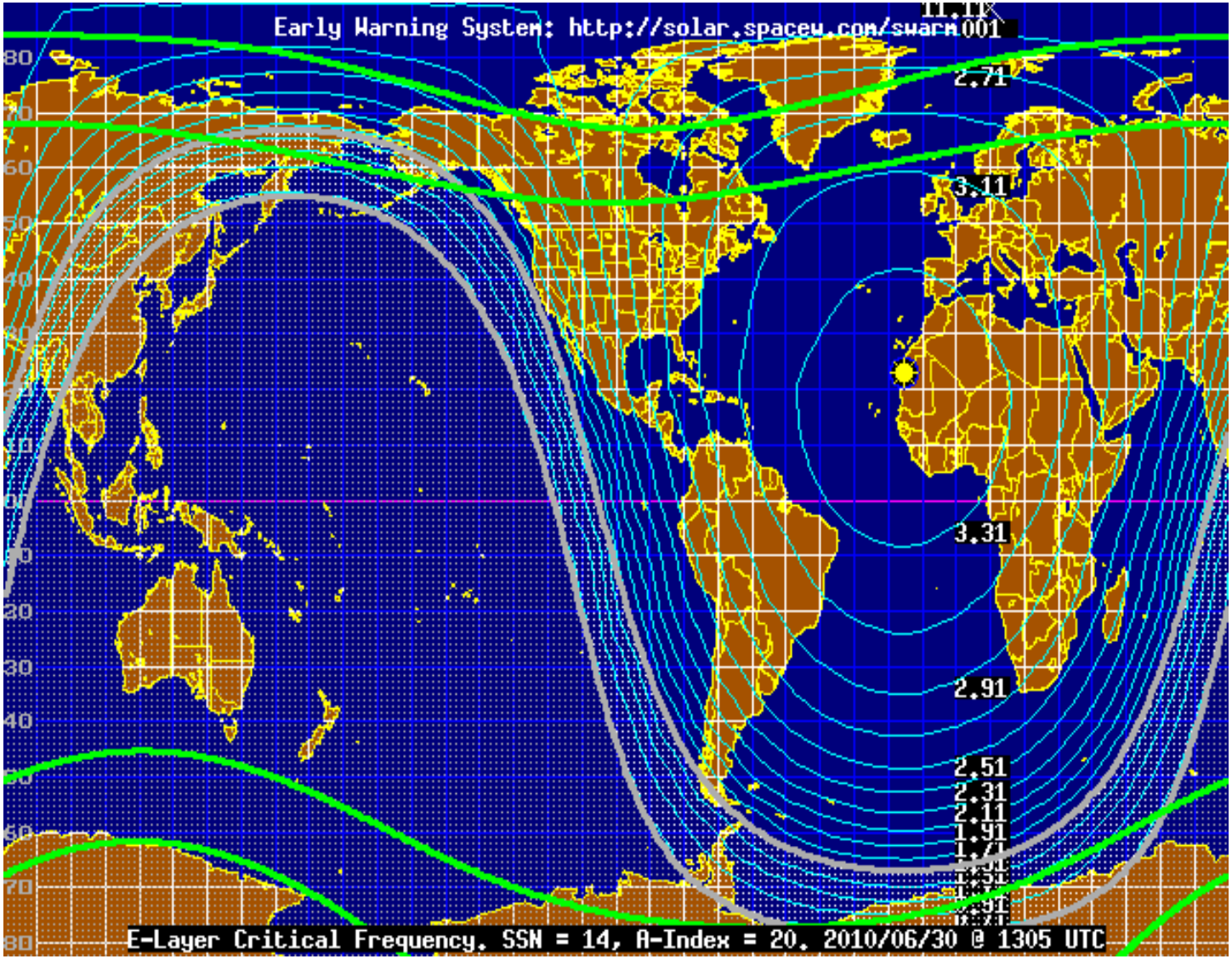
Diurnal and day-to-day variability of NmF2

Variation of NmF2 at Slough for every day during four 2-month periods in 1973-1974.

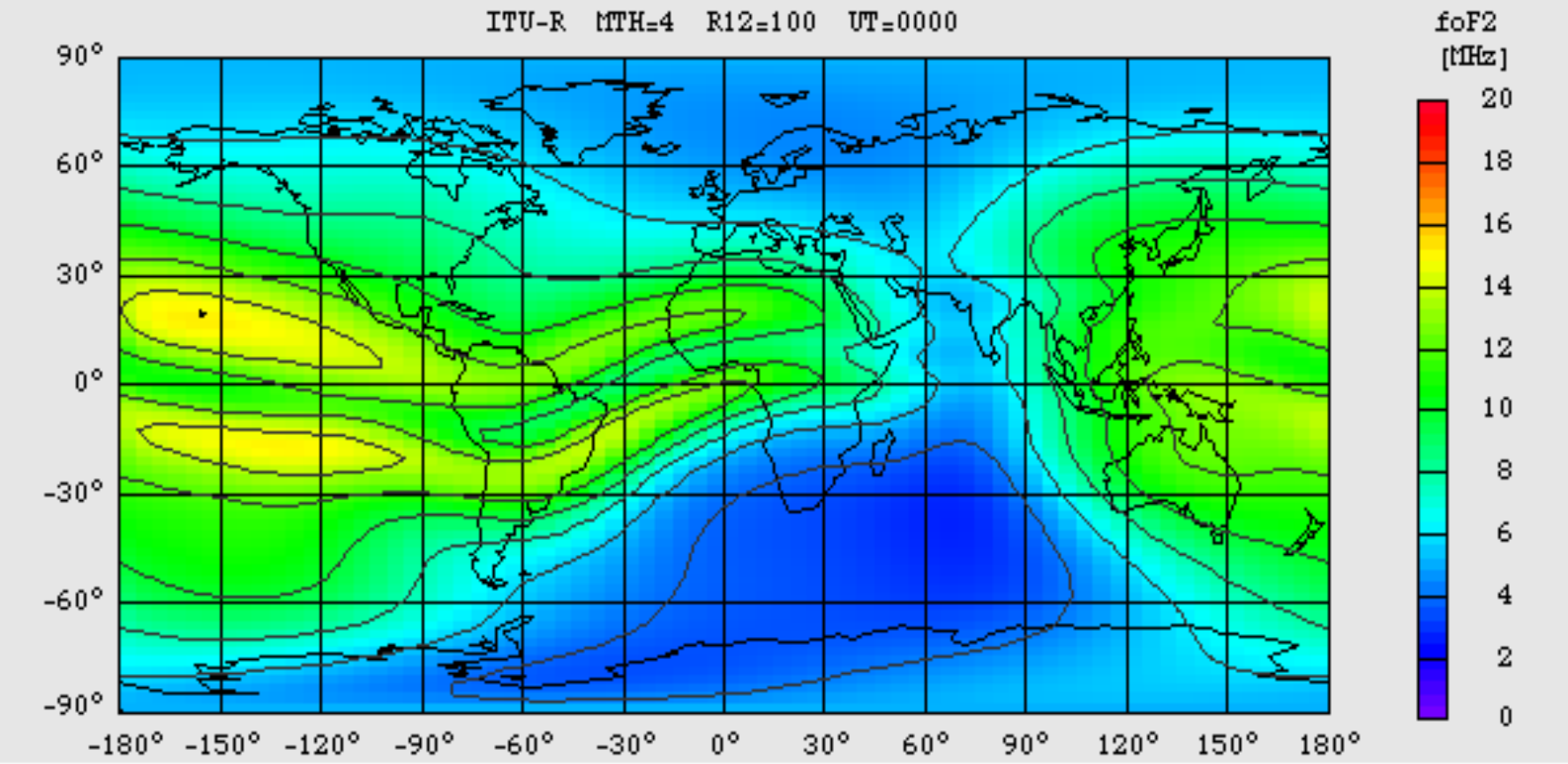


H. Rishbeth, M. Mendillo / Journal of Atmospheric and Solar-Terrestrial Physics 63 (2001) 1661–1680

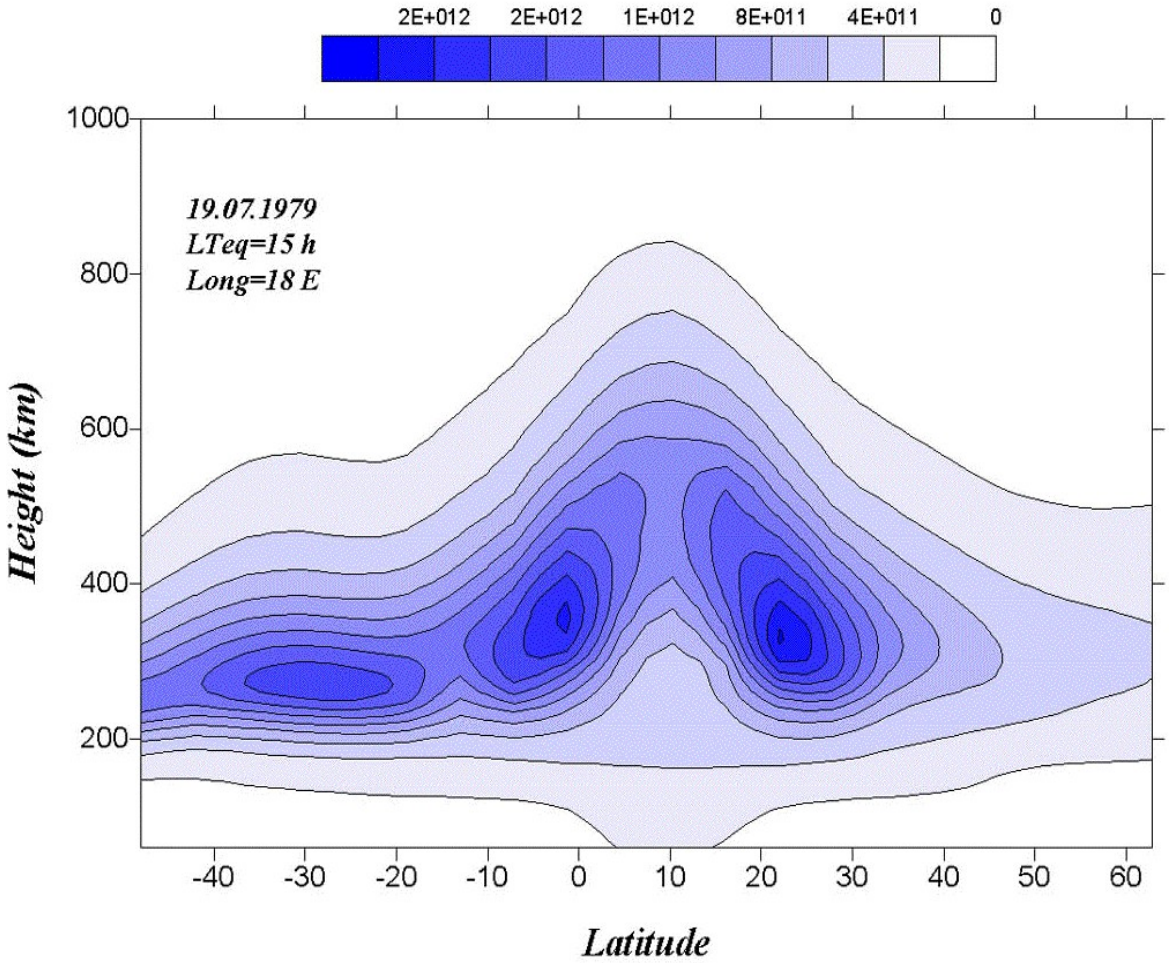
E region global Variations: a well behaved Chapman layer



Global variations of foF2 April (R12=100)



Geographical variations: the equatorial anomaly

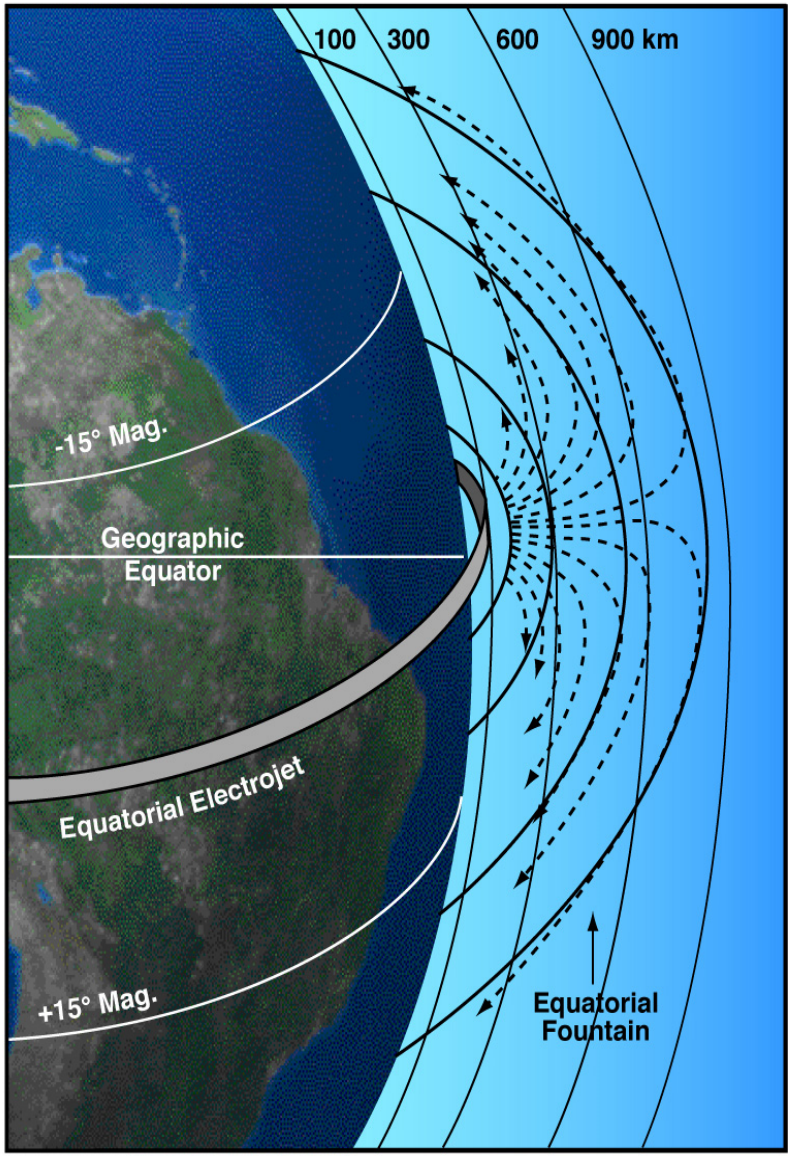


Nava B., Radicella S.M., Pulinets S. and Depuev V. "Modelling bottom and topside electron density and TEC with profile data from topside ionograms", Advances in Space Research, V. 27, pp. 31-34, 2001.

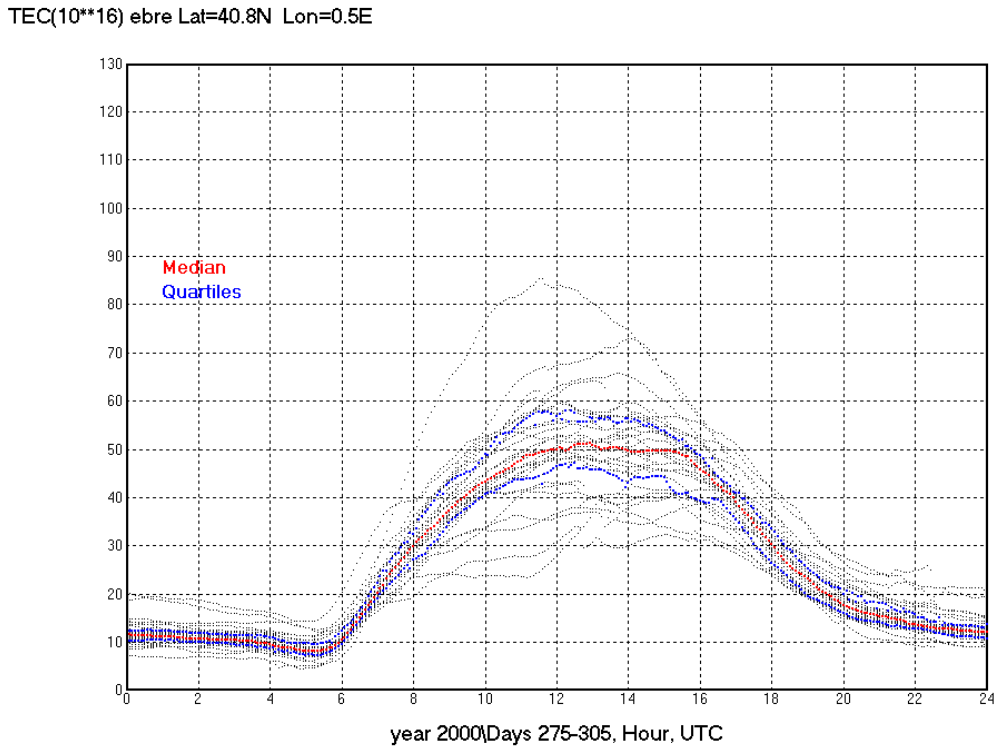
From the Chapman theory it can be expected that the electron density maximises over the geographic equator at equinox. However, it actually maximises ~ 10-20 degrees of geomagnetic latitude N and S, with a small minima at the equator due to the effect of the geomagnetic field: the 'fountain effect'.

The “fountain effect”

The Equatorial Electrojet drives the F-region motor. E-field is zonal, magnetic field is meridional, so plasma drift is vertically upwards. Plasma then descends down the magnetic field lines either side of the geomagnetic equator.

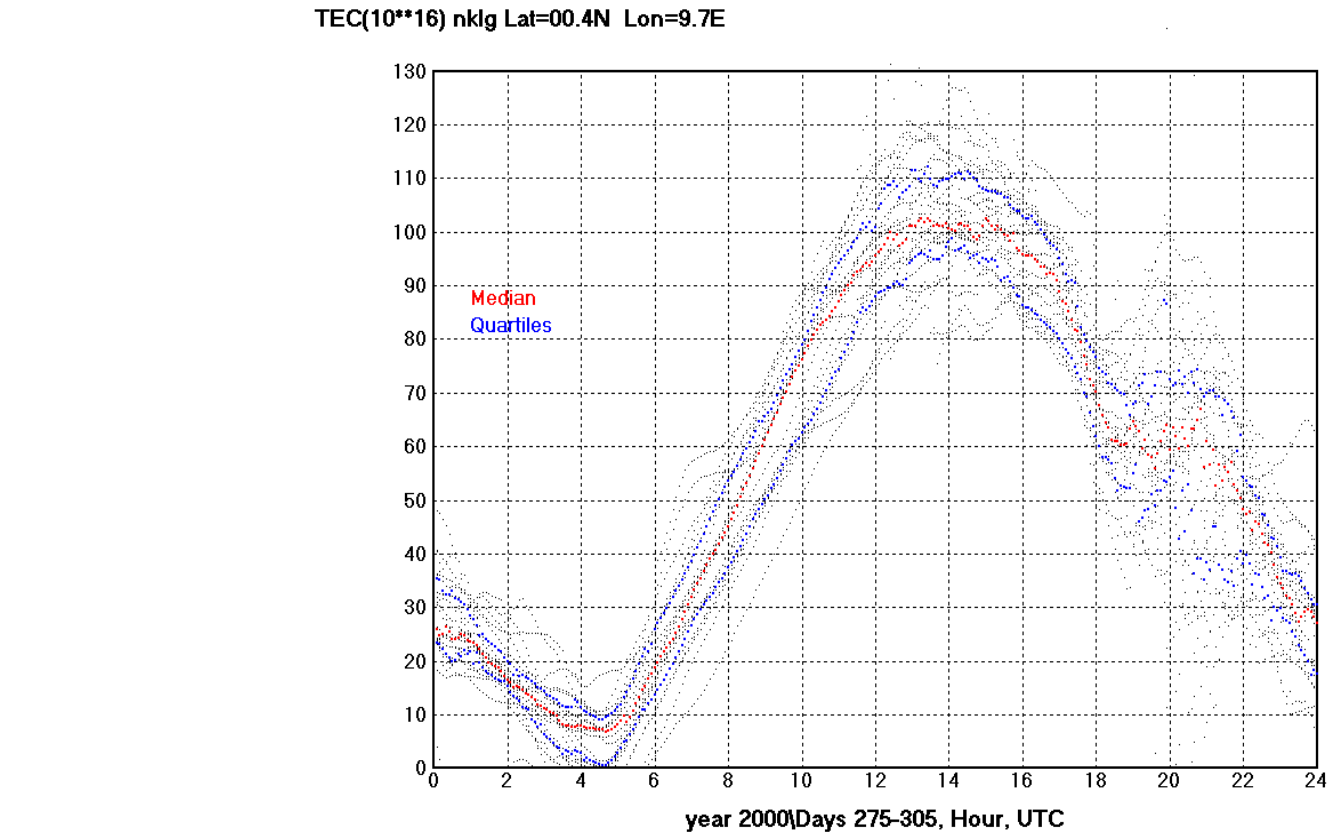


Vertical TEC diurnal and day-to-day variations (1)



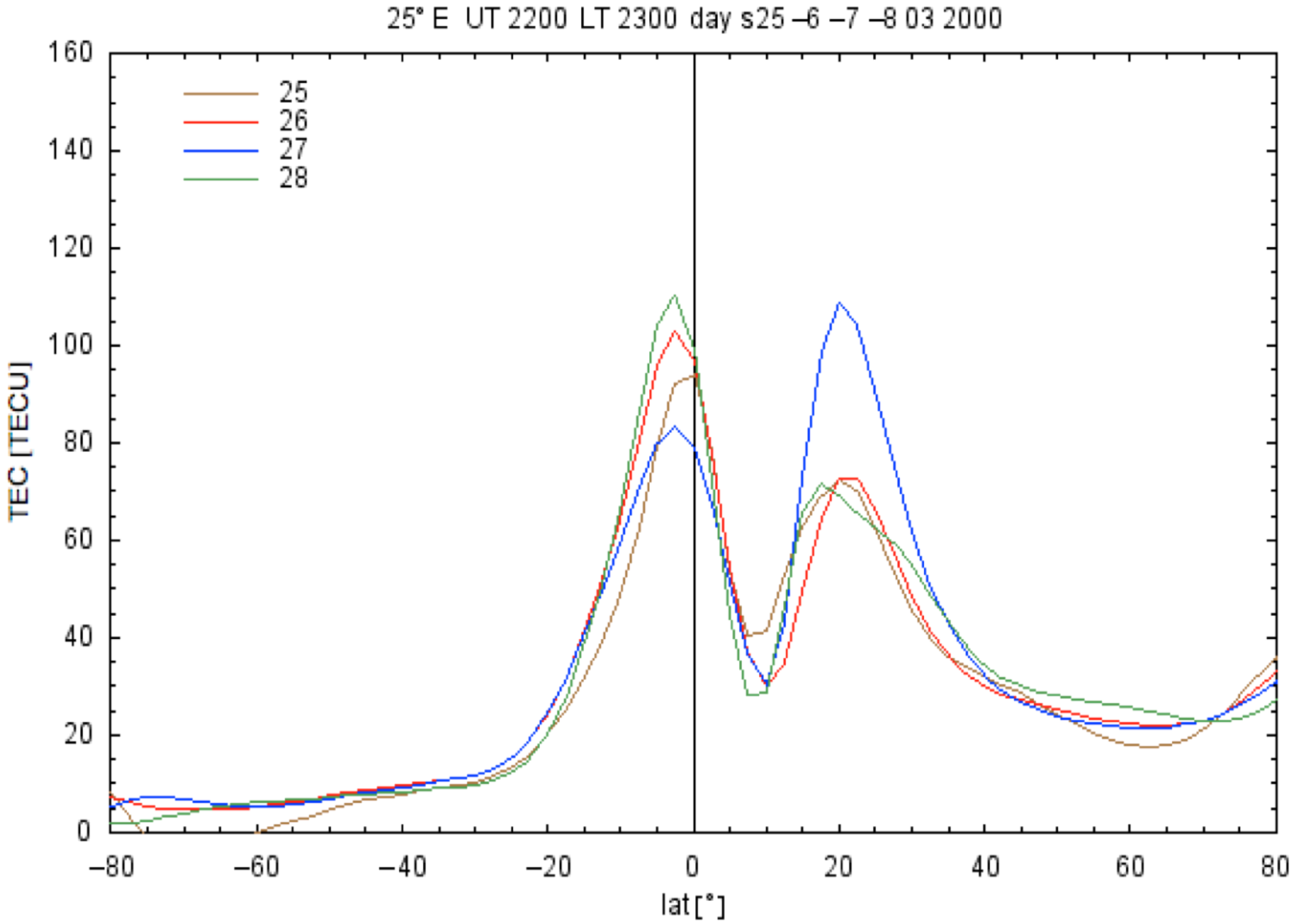
GPS derived vertical TEC at 5 min interval for Roquetes (Lat. 40.8°, Lon. 0.5° E,Mag. Dip 57°), October 2004

Vertical TEC diurnal and day-to-day variations (2)



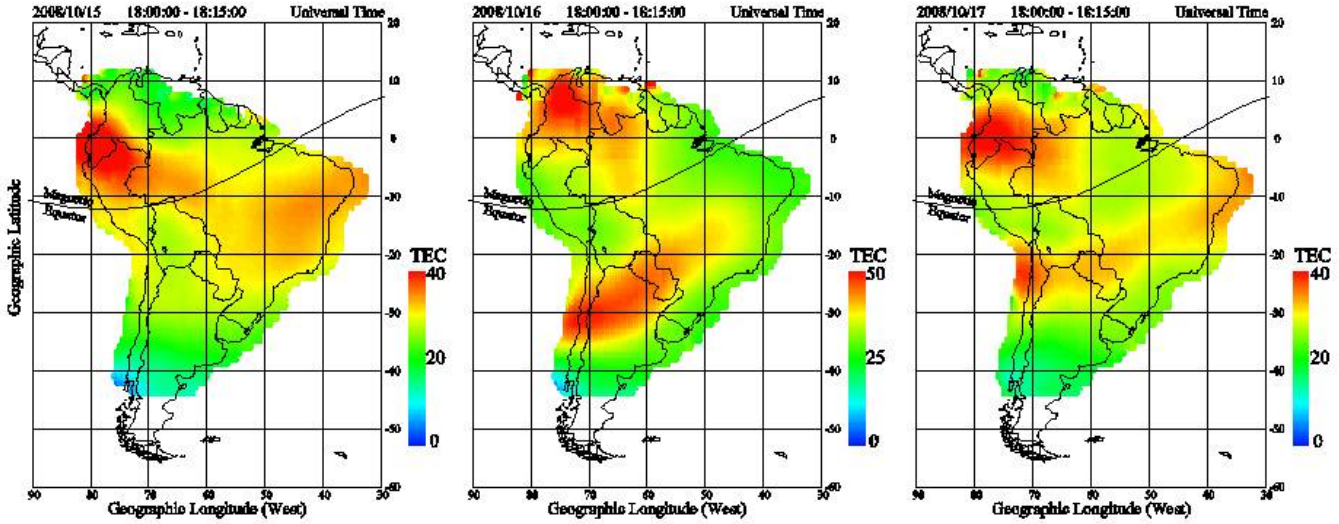
GPS derived vertical TEC at 5 min interval for Libreville (Lat. 0.4° N, Long. 9.7° E, Mag. Dip –25°), October 2000.

Vertical TEC Meridional cross section and day-to-day Variations



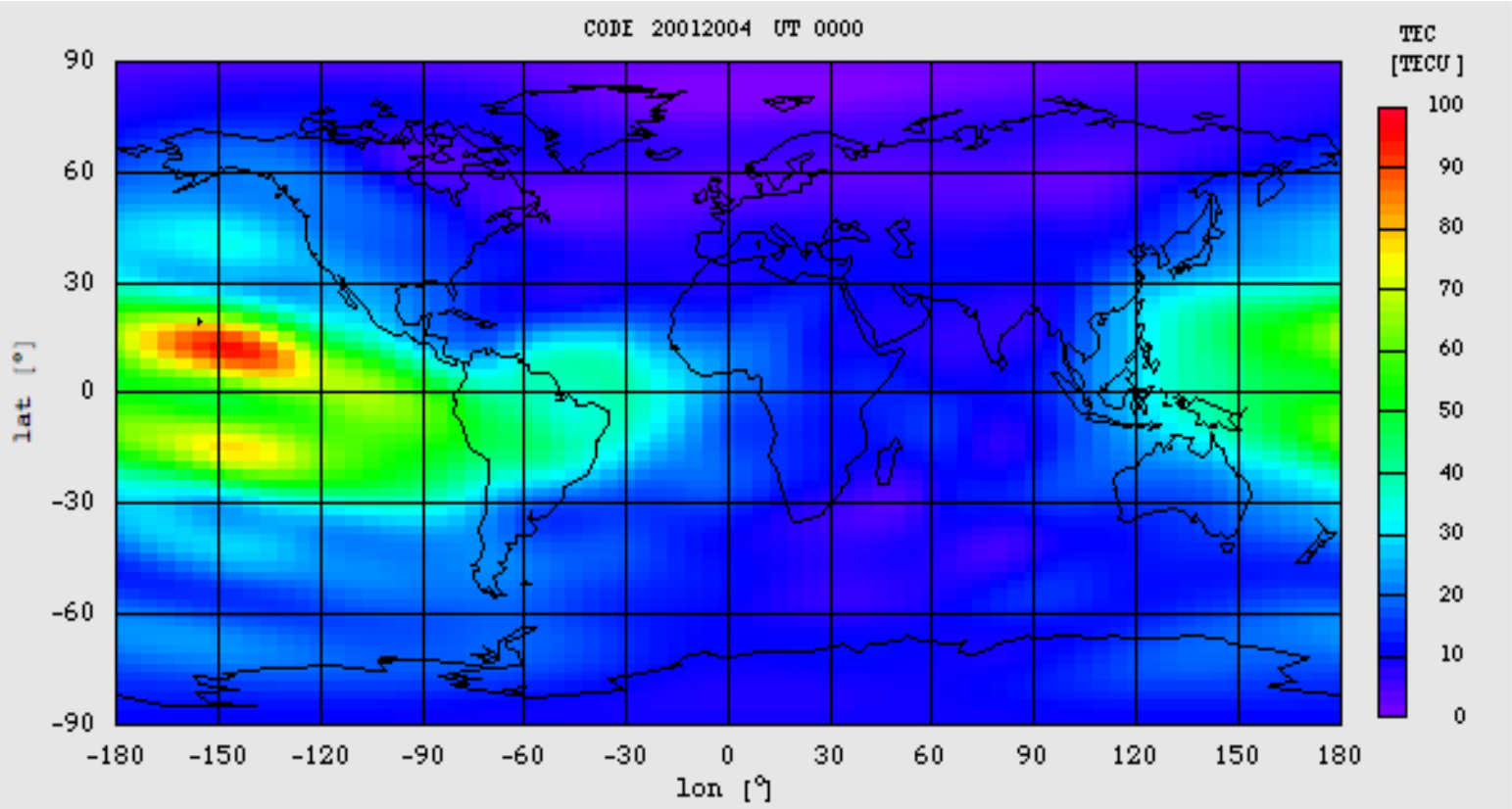
Day-to-day regional TEC Variabilitv

Characterize TEC variability in a regional Context: TEC values observed on 3 consecutive days (Oct 15-18, 2008) at same local time (2 PM at 60° W)



Courtesy of P. Doherty and C. Valladares

Global vertical TEC



This lecture indicates only in a pale way the complexity of the ionosphere but, at the same time, I hope it awakes more curiosity for this fascinating part of our environment.

THANK YOU FOR YOUR ATTENTION!