Recent upgrades in the Topside Sounders Model codes and possible links with IRI-2012

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TSM set of codes

Present profiling technique combines:

- **a core empirical model (TSM)** providing the topside scale height and upper transition (O^+- H^+) height,
- **a profiler (TSMP)** providing the shape of the vertical electron density profile in the topside and plasmasphere as a sum of O^+, H^+, and He^+ partial distributions,
- **a TSM-assisted Digisonde (TaD) profiler** ingesting Digisonde-derived parameters peak altitude, density, and topside scale height into TSMP, allowing real-time update of TSMP.

Input Parameters	Code	Output
Month, LT, glat, f10.7, Kp	TSM: Topside Sounders Model Analysis of Alouette, ISIS-1,-2 topside profiles (Bilitza, 2001)	Empirical functions of H_T: topside scale height h_T : transition height R_T: ratio H_T/h_T
H_T ($\equiv H_{O+}$), h_T, H_m, N_m and *glat*	TSMP: Topside Sounders Model Profiler Analysis of ISIS-1 topside profiles to model plasmaspheric scale height	Empirical functions of H_P: plasmaspheric scale height ($\equiv H_{H+}$) $H_P = H_T(9\cos^2 glat + 4)$ *Ne*: electron density profile in the topside ionosphere and plasmasphere $Ne = N_{O^+}(h) + gN_{O^+}(h_T)\exp\left(-\frac{\lvert h-h_T\rvert}{Hp}\right) + (1-g)N_{O^+}(h_T)\exp\left(-\frac{\lvert h-h_T\rvert}{4H_T}\right)$ and $N_{O^+}(h) = Nm\exp\left\{-\frac{1}{2}\left[\frac{h-hm}{Hm} + 1 - \exp\left(\frac{h-hm}{Hm}\right)\right]\right\}$ g is the ratio N_H+ / N_O+ at h_T
Digisonde parameters at the height of maximum density (*hmF2*, *foF2*, H_m) and vTEC (GNSS) at the Digisonde location	TaD: TSM-assisted Digisonde Profiler Calculation of the actual profile over each Digisonde location to update TSMP with current Digisonde and TEC (GNSS) parameters	$Ne = N_{O^+}(h) + gN_{O^+}(h_T)\exp\left(-\frac{\lvert h-h_T\rvert}{Hp}\right) + (1-g)N_{O^+}(h_T)\exp\left(-\frac{\lvert h-h_T\rvert}{skH_m}\right)$ where $s = H_{He+}/kH_m$ k is the correction parameter that converts H_m (the neutral scale height) to make it compliant with H_T The integral of the Ne profile can be adjusted to the measured vTEC by varying solely the correction parameter k

TSM-TSMP-TaD basic references

- Kutiev, I., and P. Marinov, Topside sounder model of scale height and transition height characteristics of the ionosphere, *Adv. Space Res.*, **39**, 759–766, 2007
- Kutiev, I., P. Marinov, A. Belehaki, N. Jakowski, B. Reinisch, C. Mayer, and I. Tsagouri, Plasmaspheric electron density reconstruction based on the Topside Sounder Model Profiler, *Acta Geophys.*, **58 (3)**, 420–431, 2009
- Belehaki, A., I. Kutiev, B. Reinisch, N. Jakowski, P. Marinov, I. Galkin, C. Mayer, I. Tsagouri, and T. Herekakis, Verification of the TSMP-assisted Digisonde (TaD) topside profiling technique, *Acta Geophys.*, **58 (3)**, 432–452, 2009
- Kutiev, I., P. Marinov, S. Fidanova, A. Belehaki, and I. Tsagouri, Adjustments of the TaD electron density reconstruction model with GNSS TEC parameters for operational application purposes, *J. Space Weather Space Clim.*, **2**, A21, 2012
- Belehaki, A., I. Tsagouri, I. Kutiev, P. Marinov, and S. Fidanova, Upgrades to the Topside Sounders Model assisted by Digisonde (TaD) and its validation at the topside ionosphere, J. Space Weather Space Clim., 2, A20, 2012

Verification of TaD at a single site location

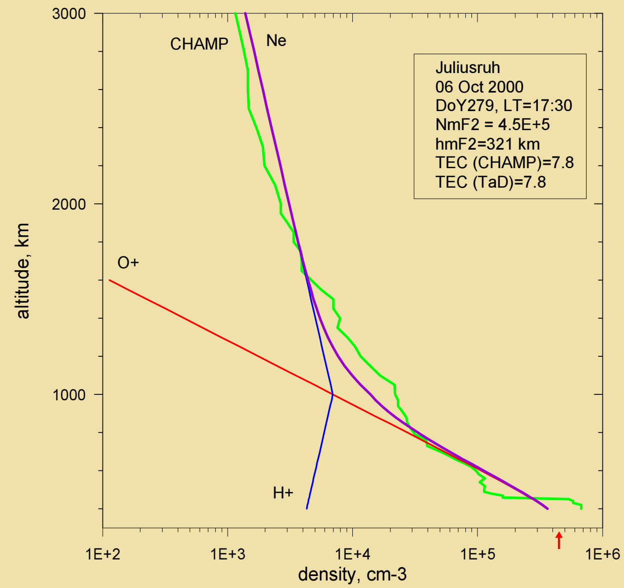
TaD is extensively tested and verified using independent observations:

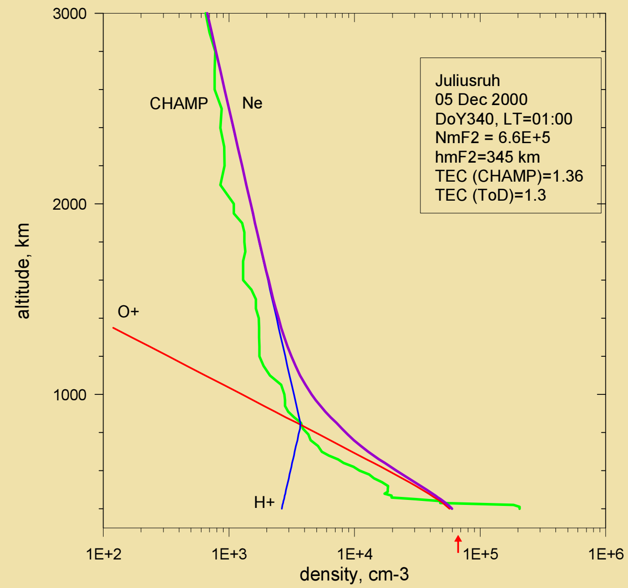
- CHAMP TEC and profiling;
- ground-based GPS-TEC;
- Malvern Incoherent Scatter Radar (ISR);
- RPI sounder on IMAGE

Latest improvement, allows adjustment of TaD integral with GPS-derived TEC, increasing the accuracy of the method.

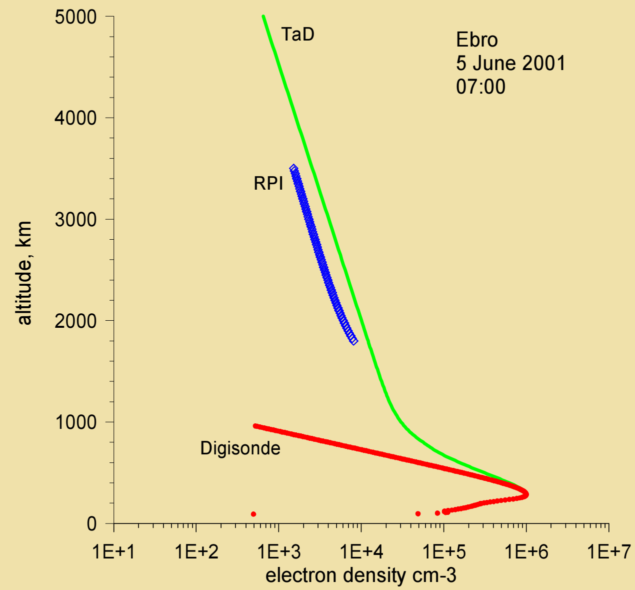
TaD verification results
Comparison with CHAMP and IMAGE/RPI derived profiles

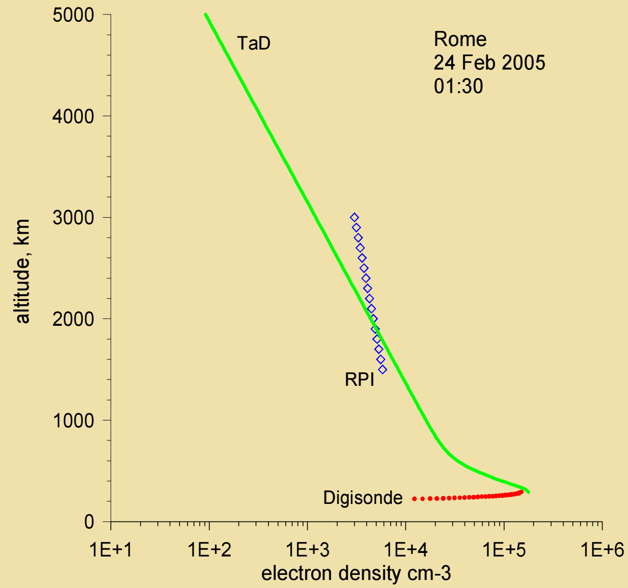
CHAMP





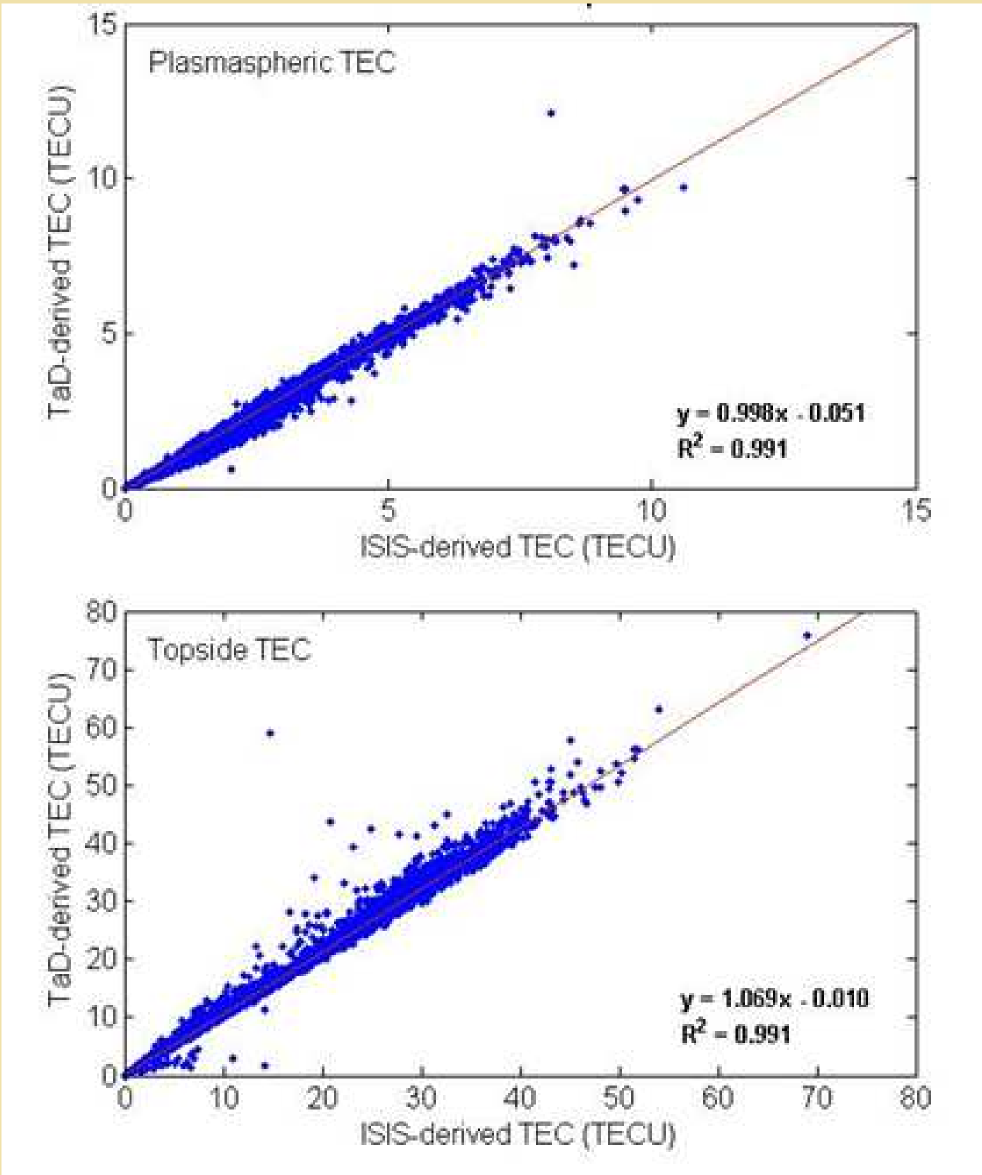
IMAGE





Belehaki et al., Acta Geo., 2009

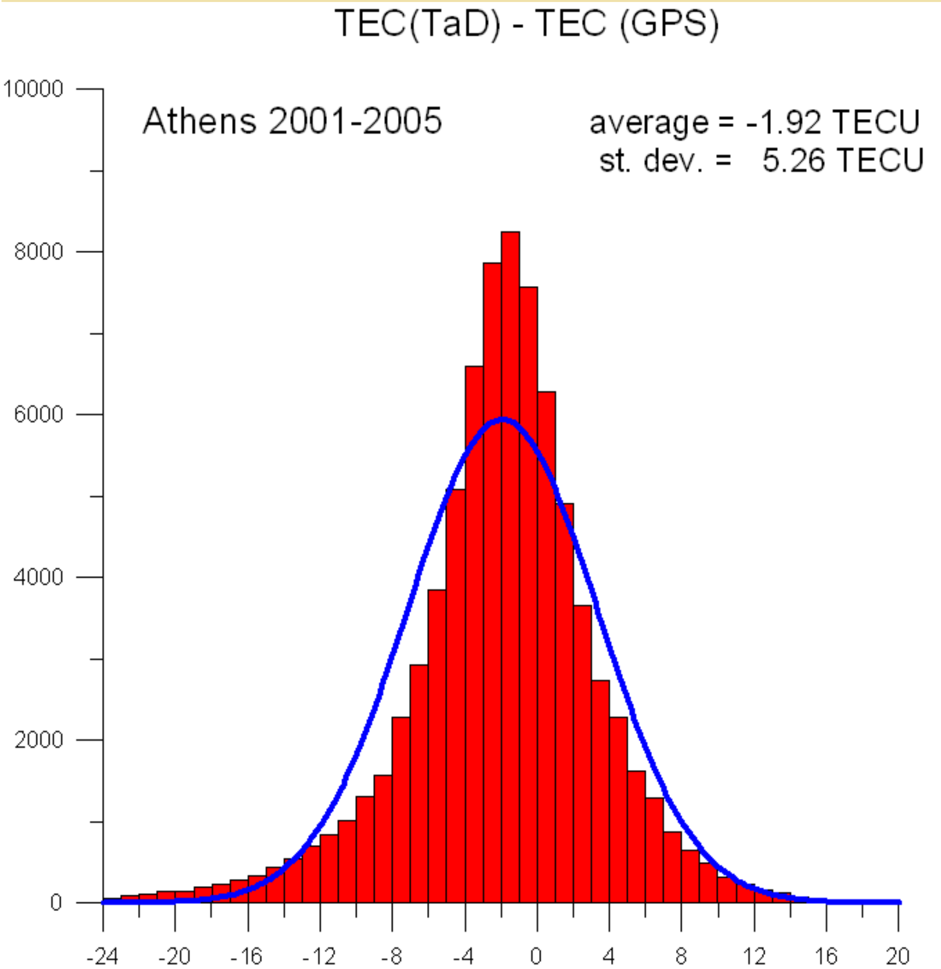
TaD verification results

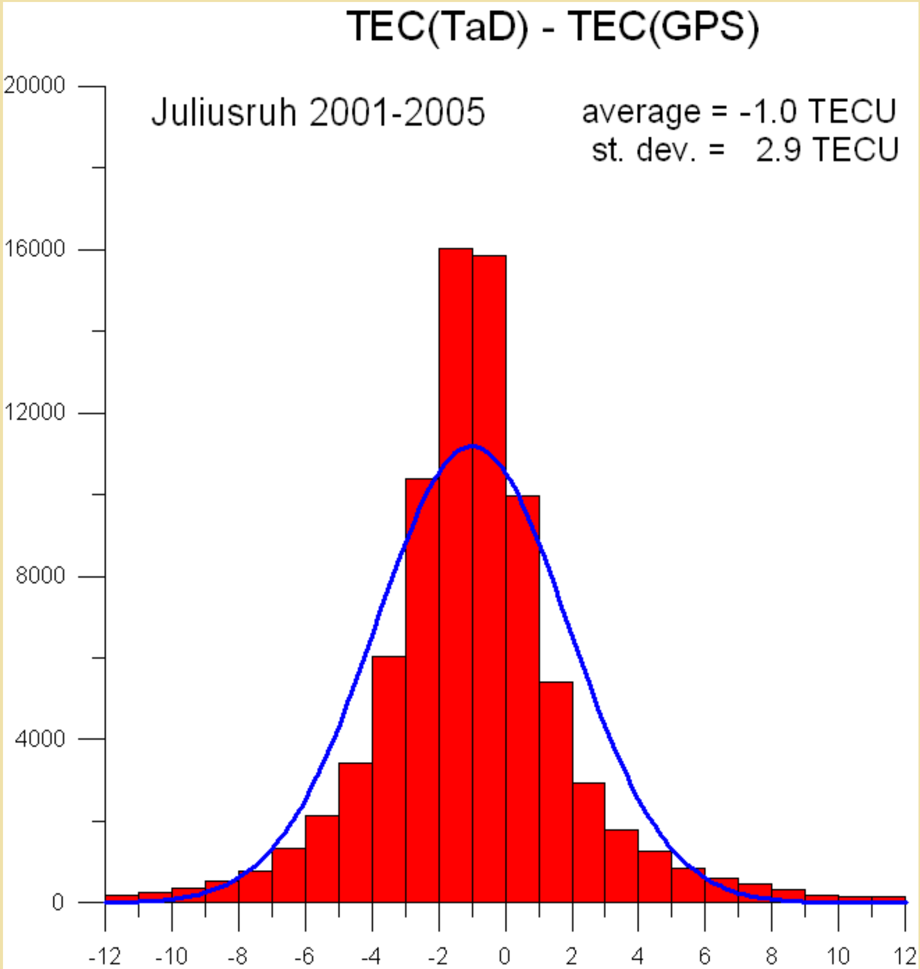


Internal consistency check: how well the model can reproduce ISIS-2 derived TEC

From Belehaki et al., SWSC, 2012

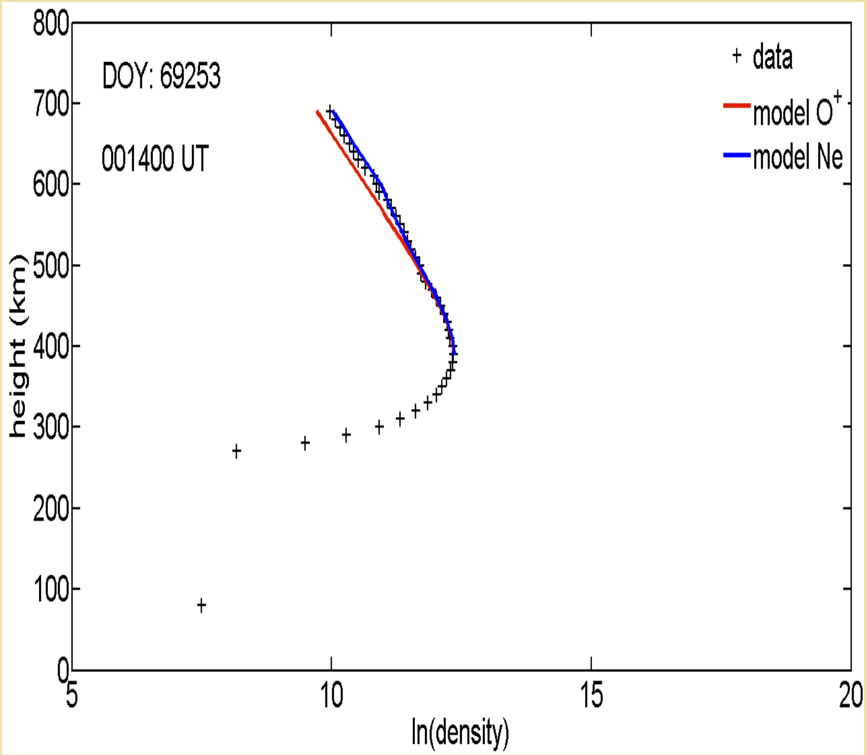
TaD verification results
Comparison with TEC-GNSS ground based receivers



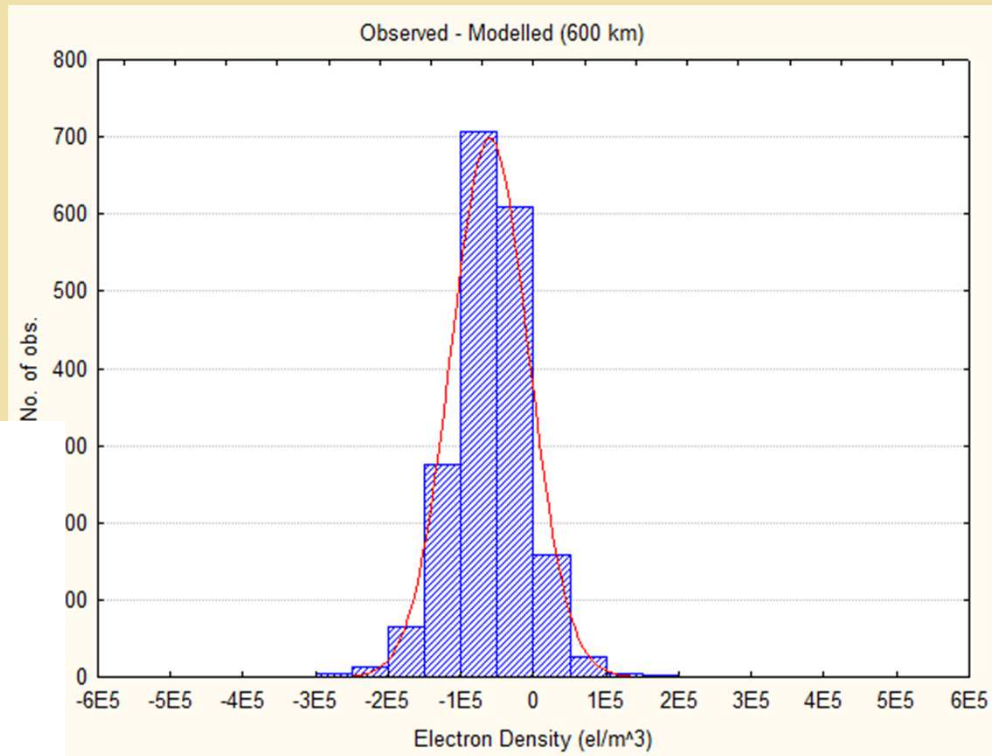


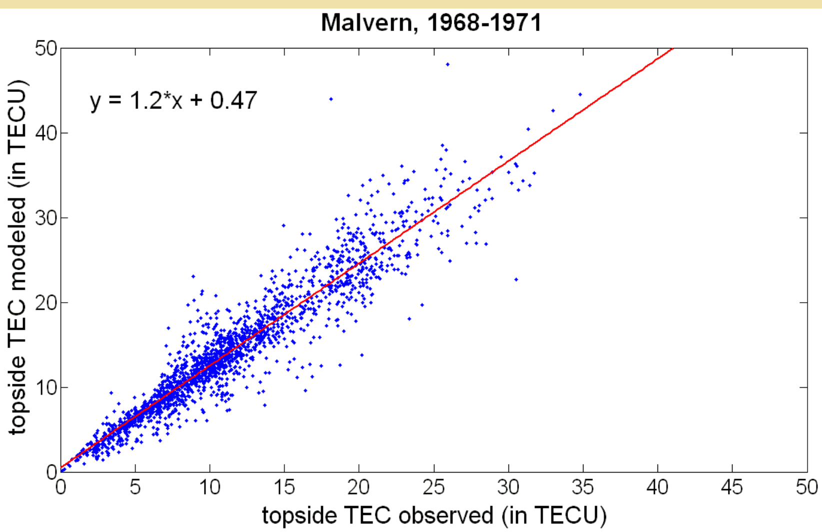
Kutiev et al.,
Acta Geo., 2009

TaD verification results
Topside ED: comparison with Malvern ISR



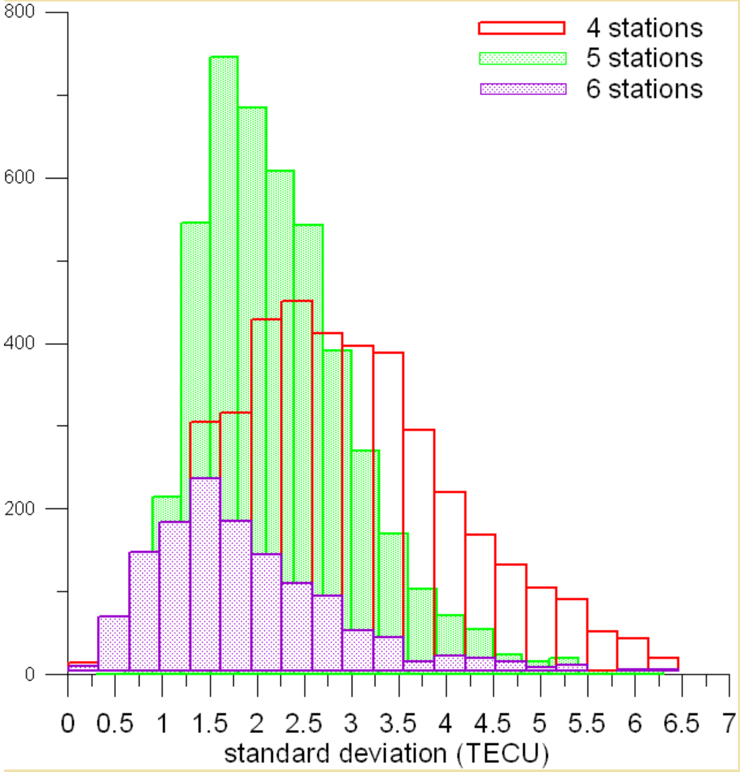
Example for TaD derived profiles based at Malvern site



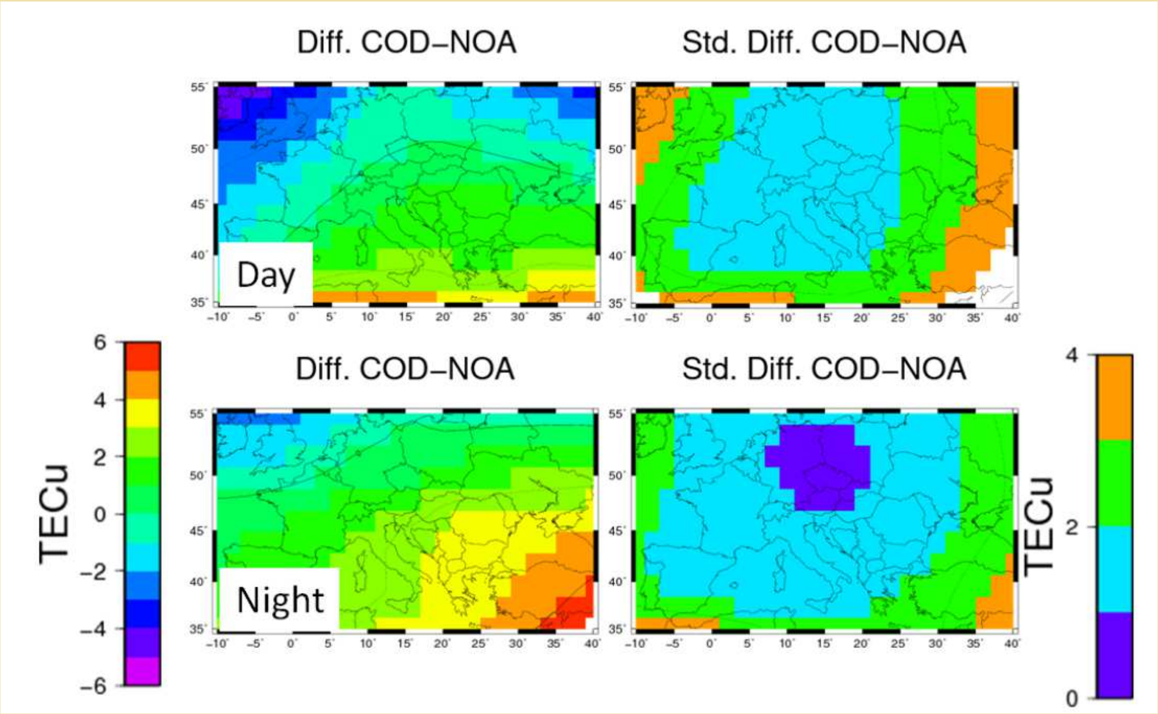


The distribution of the simple difference between the observed ISR and the modeled electron densities at 600 km

Validation of TaD maps

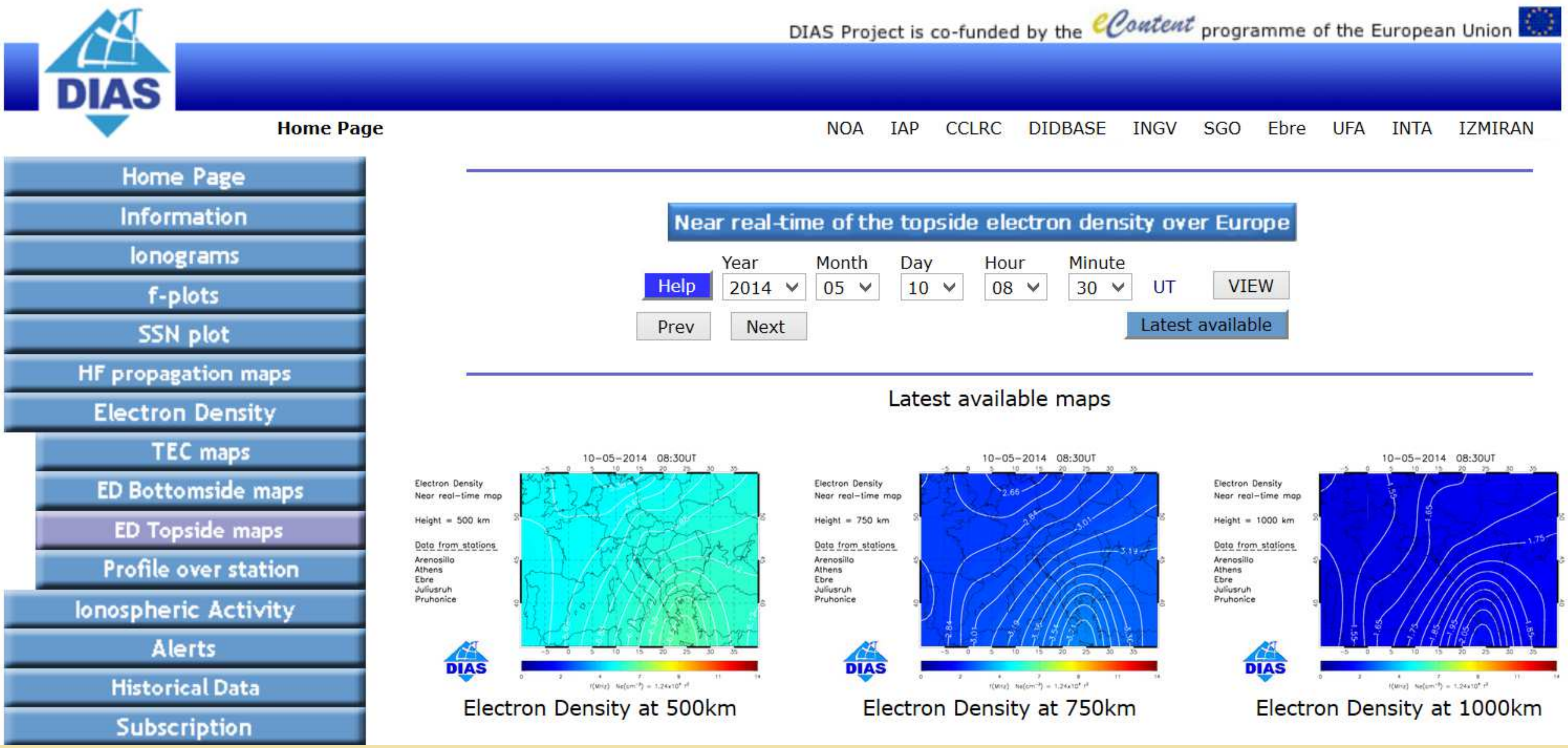


Comparison of TaD-TEC maps with EUREF-ROB and CODE maps for a period of 12 months (November 2012 – October 2013).
Reasonable agreement with a maximum discrepancy of 3 TECU for the 96% of the cases, depending on the latitude of the geographic location under consideration.



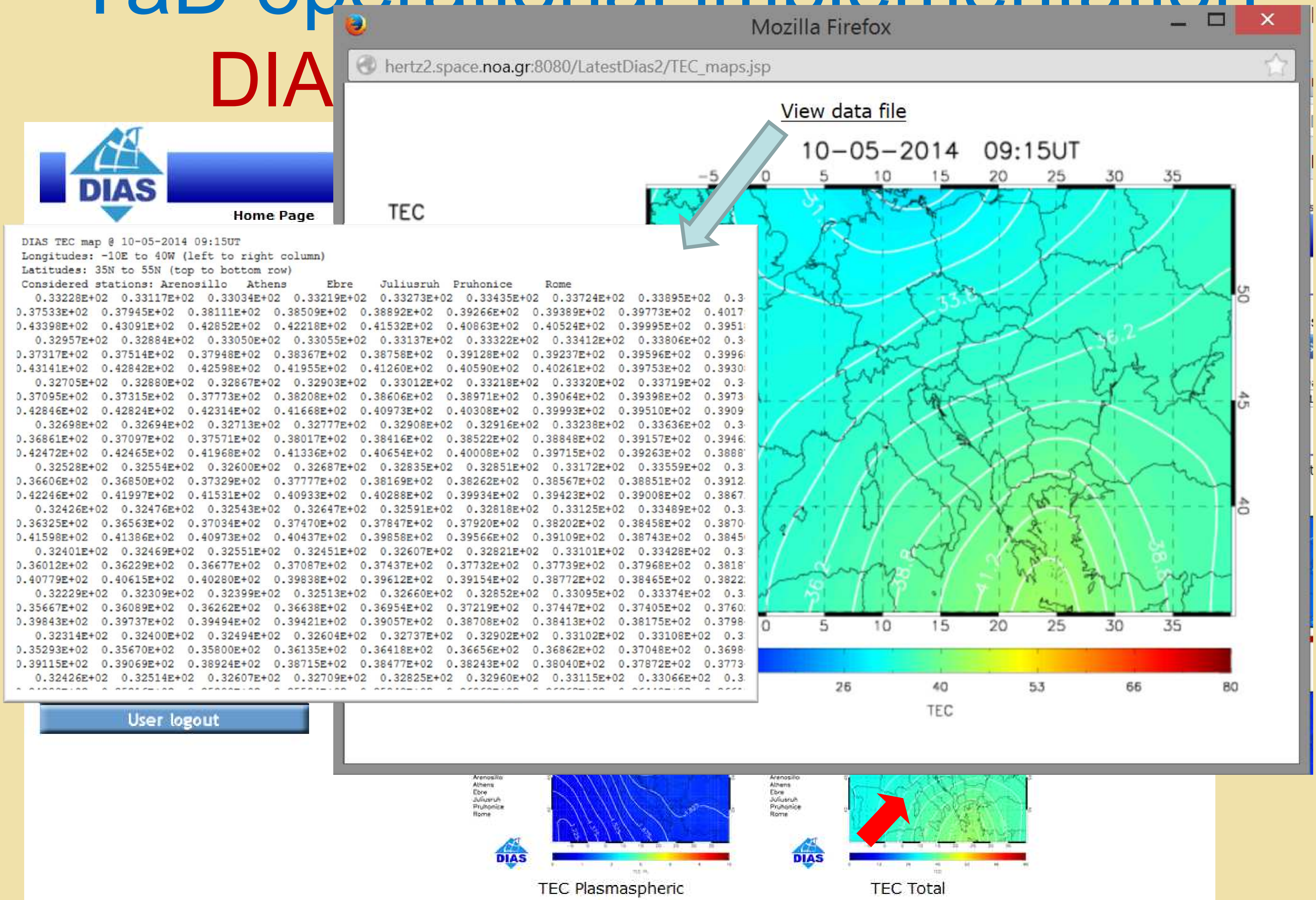
TaD operational implementation

DIAS: EDD at predefined heights

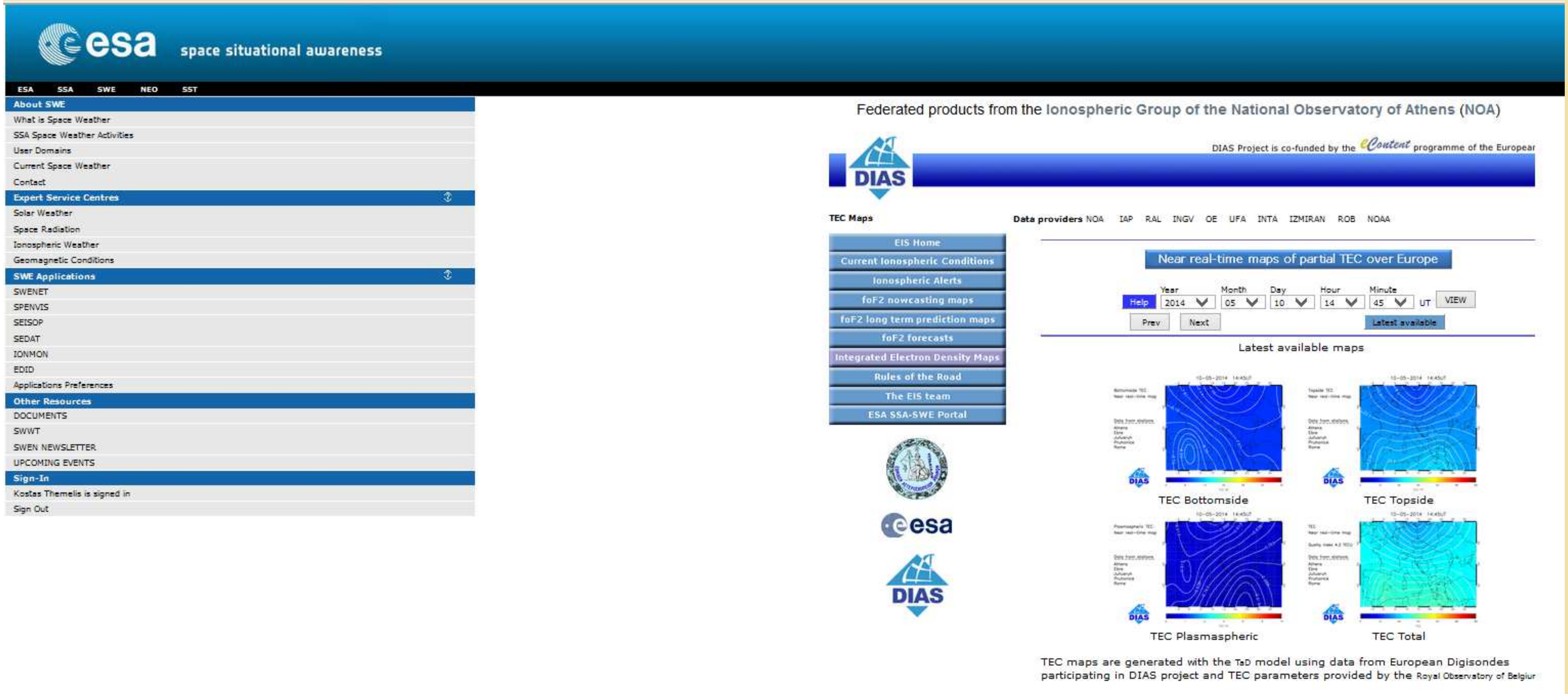


TaD operational implementation

DIA



TaD operational implementation
ESA-SSA SWE: TEC and partial TEC



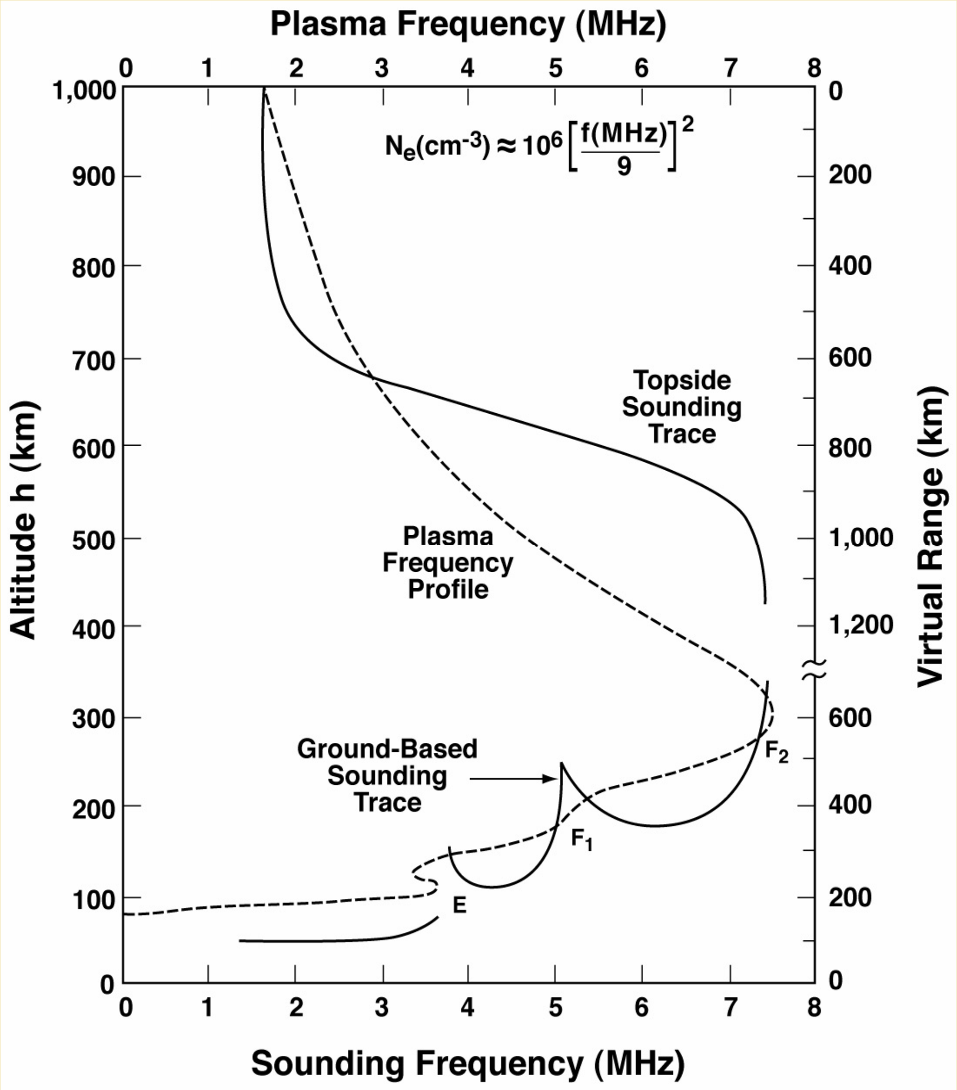
Conclusions

- TSMP provides the electron density profile in the topside ionosphere and plasmasphere, based on the modeling of Alouette, ISIS-1 and ISIS-2 data
- TSMP depends on TSM parameters H_T and h_T and on the independent parameters month, LT, glat, Kp and F10.7
- TSMP offers the basic empirical functions based on which TaD calculates 3D electron density profiles and TEC maps over the area of the DIAS network. The service is running for more than a year, demonstrating operational reliability even with autoscaled F2 parameters.
- Through IRI-2012, TSMP can be provided as an additional option, to allow further validation by the community of IRI users

Backup slides

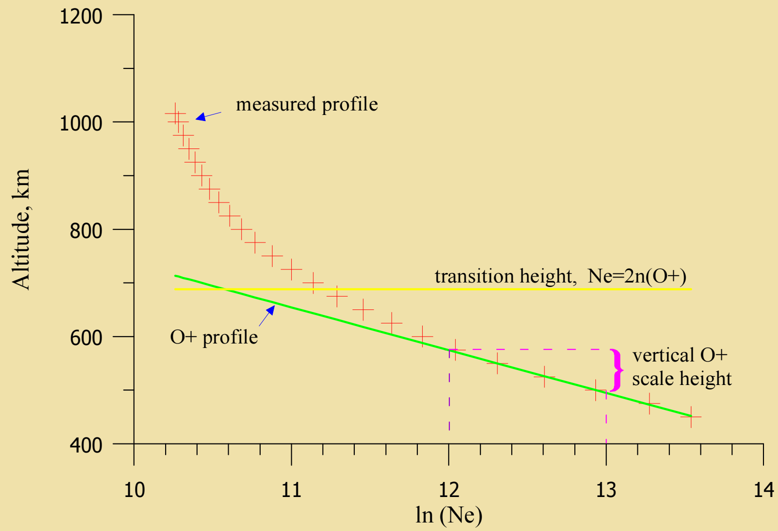
Alouette 1 over flight of Wallops Island Ionosonde Alouette-
1651 UT, 10 June 1968

Adapted from *Jackson et al.* [1980]



Definition of H_T and h_T

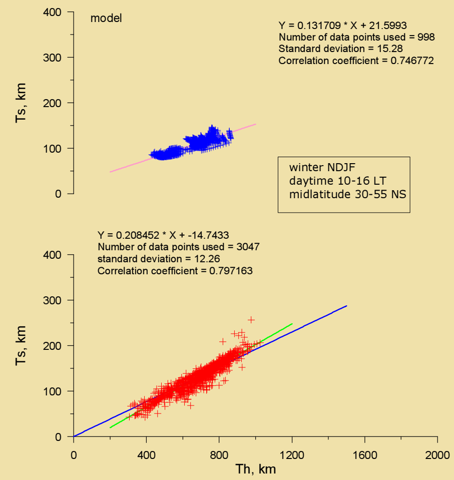
The database, archived at the National Space Science Data Center (NSSDC), Greenbelt, MA, includes 176,622 topside electron density (Ne) profiles from the Alouette-1a, -1b, -1c and -2 and ISIS-1 and -2 topside sounders, covering the period 1962-1979. A detailed description of the database is given by *Bilitza (2001)*.



Two parameters are extracted from each individual Ne profile: the vertical O^+ scale height (H_T) and the O^+-H^+ transition height (h_T). H_T is defined as the lowest gradient of the measured Ne profiles. The h_T is defined as the height at which the extrapolated to higher altitudes lowest Ne gradient yields a density which is one half of the measured Ne.

H_T/h_T ratio

- It was found that the scale height and transition O^+-H^+ height, extracted from each individual measured Ne profile, highly correlate, with a correlation coefficient exceeding 0.8 at midlatitudes. The upper panel shows the model prediction, while the lower panel shows individual values in a H_T/h_T plot, taken from ±(30, 50) geomagnetic latitude in daytime winter.



- The ratio $R_T=H_T/h_T$ obtained from the individual profiles is modelled as a function of same input parameters as H_T and h_T.

The Topside Sounder Model (TSM)

The scale height H_T, transition height h_T and their ratio R_T are modeled separately by the same type of base functions.

month:	$c_0 + c_1 \sin(x) + c_2 \cos(x) + c_3 \sin(2x) + c_4 \cos(2x)$
local time:	$c_0 + c_1 \sin(x) + c_2 \cos(x) + c_3 \sin(2x) + c_4 \cos(2x)$
glat:	$c_0 + c_1 x + c_2 x^2 + c_3 x^3 + c_4 x^4 + c_5 x^5 + c_6 x^6$
sf:	$c_0 + c_1 x + c_2 x^2$
Kp:	$c_0 + c_1 x + c_2 x^2$

The new Topside Sounder Model (TSM) provides H_T, h_T and R_T for any set of above shown parameters in their defined ranges.

TSMP – the topside sounder-based Ne profiler

We consider α-Chapman shape for N_{O+} and exponential for N_{H+}

N_m is N_{O+} density at the maximum F layer height *hm*.

α-Chapman for O^+: $$N_{O^+} = N_m \exp\left[1 - \frac{h-hm}{H_{O^+}} - \exp\left(-\frac{h-hm}{H_{O^+}}\right)\right]$$

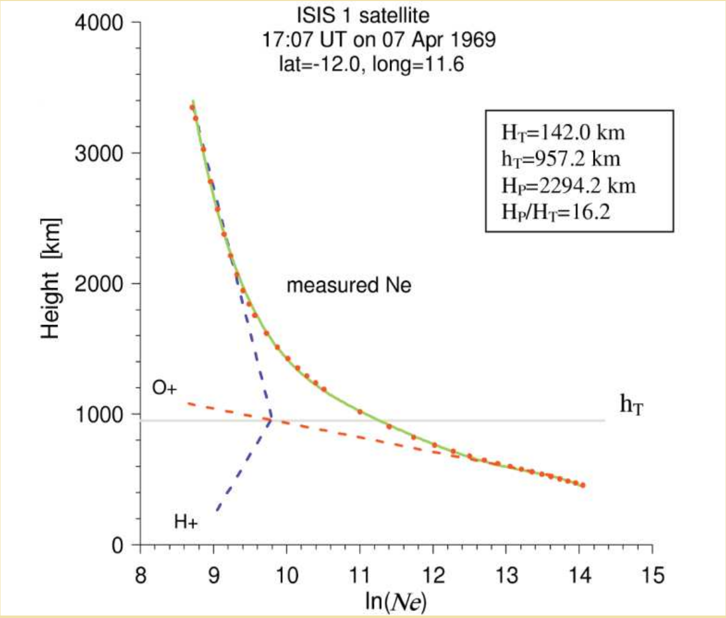
exponential for H^+: $$N_{H^+} = N_{O^+}(h_T)\exp\left(-\frac{|h-h_T|}{H_{H^+}}\right)$$

h_T is the transition height

Plasmasphere extension of TSMP

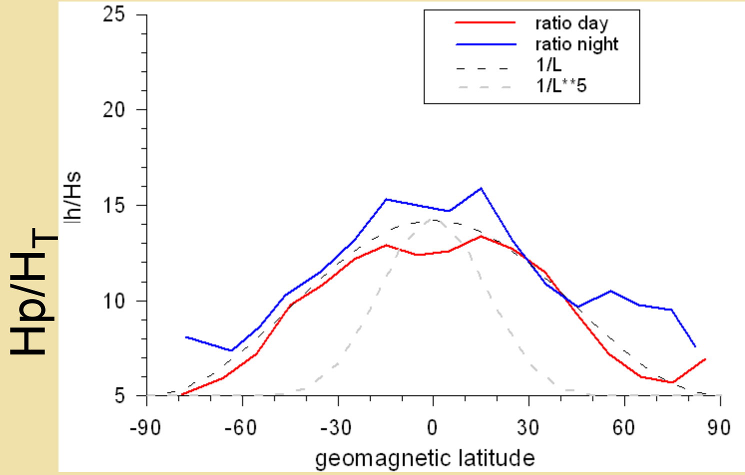
ISIS-1 topside sounder data were used to extract H^+ scale height, further denoted as Hp.

$$H_T \equiv H_{O+}\ ,\ \ Hp \equiv H_{H+}$$

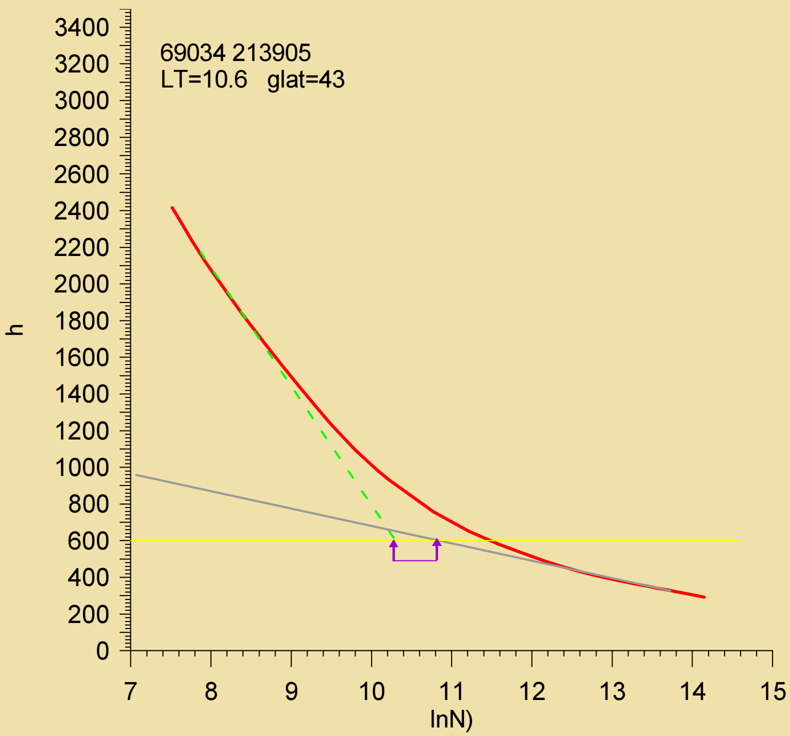


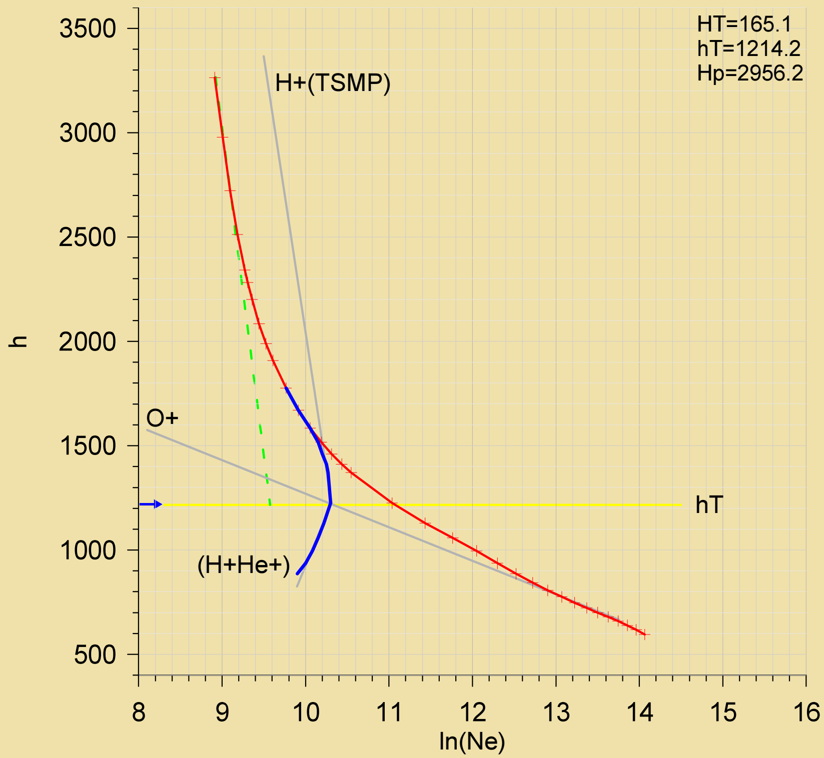
Ratio Hp/H_T is plotted as function of geomagnetic latitude. It is well approximated by 1/L. The expression set up is:

$$Hp = [9\cos^2(glat)+4]H_T$$



Introducing He^+ into TSMP





Topside Sounder Model Profiler (TSMP)

$$Ne = N_{O^+}(h) + gN_{O^+}(h_T)\exp\left(-\frac{|h-h_T|}{Hp}\right) + (1-g)N_{O^+}(h_T)\exp\left(-\frac{|h-h_T|}{4H_T}\right)$$

where $N_{O+}(h)$ is expressed by α-Chapman function:

$$N_{O^+}(h) = Nm\exp\left\{-\frac{1}{2}\left[\frac{h-hm}{Hm} + 1 - \exp\left(\frac{h-hm}{Hm}\right)\right]\right\}$$

Nm is the F layer peak density NmF2,
Hm is the neutral scale height;
g is the ratio N_{H^+} / N_{O^+} at h_T
h_T is the upper transition height;
H_T is O^+ (topside) scale height

Linking TSMP to Digisonde profiler

In the topside: TSM provides scale height H_T, transition height h_T, and their ratio $R_T = H_T / h_T$

At the F layer peak: Digisonde provides NmF2, hmF2, and the topside scale height Hm

Key idea:

In TSMP: Digisonde scale height Hm replaces H_T and new transition height is obtained multiplying Hm by $1/R_T$.

caution:

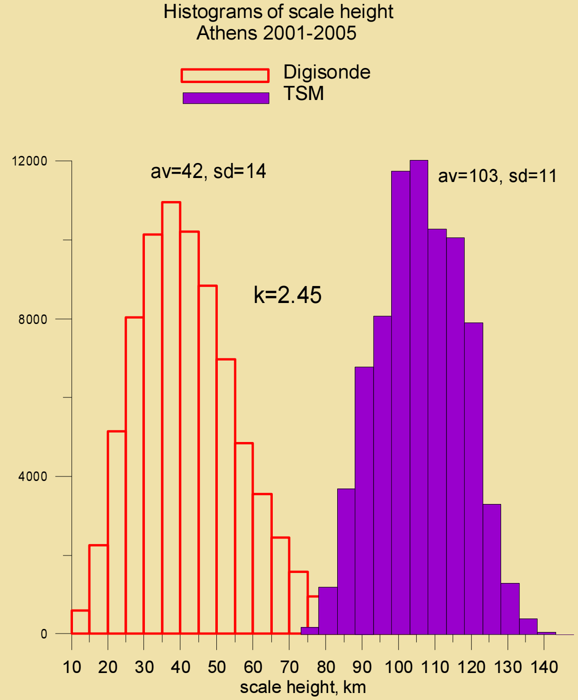
Hm is a neutral scale height; it has to be modified to comply with H_T

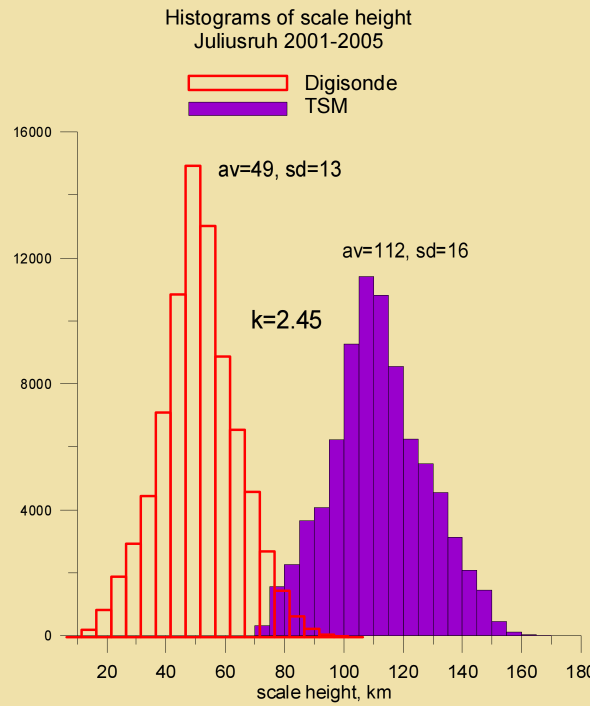
TSMP-assisted Digisonde profiler (TaD)

We couple TSMP with Digisonde by substituting H_T in TSMP with Hm and specifying hmF2 and NmF2 at the F layer peak. The new hybrid profiler is named TSMP-assisted Digisonde (TaD) profiler.

TaD now provides electron density profiles in topside ionosphere and plasmasphere in time of Digisonde sounding, e.g. in real time.

Modifying Digisonde scale height Hm

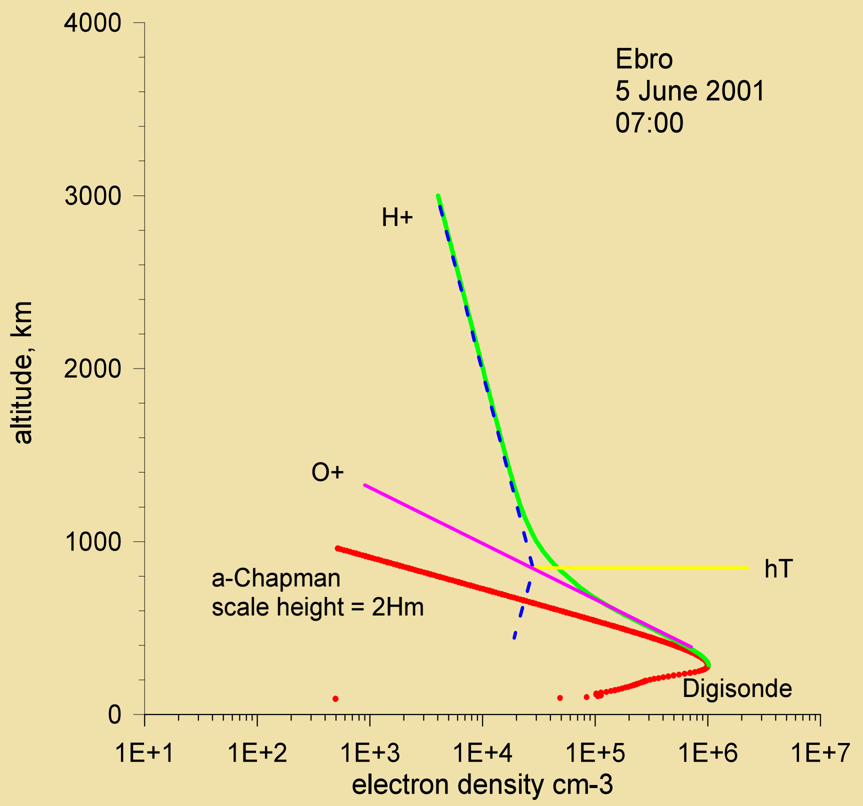




Although average values of Hm and H_T for Athens and Juliusruh differ, their ratio H_T/Hm remains steady. In TaD the topside scale height H_T is taken now as 2.5 Hm, and the transition height $h_T = H_T / R_T$.

α-Chapman and TaD profiles

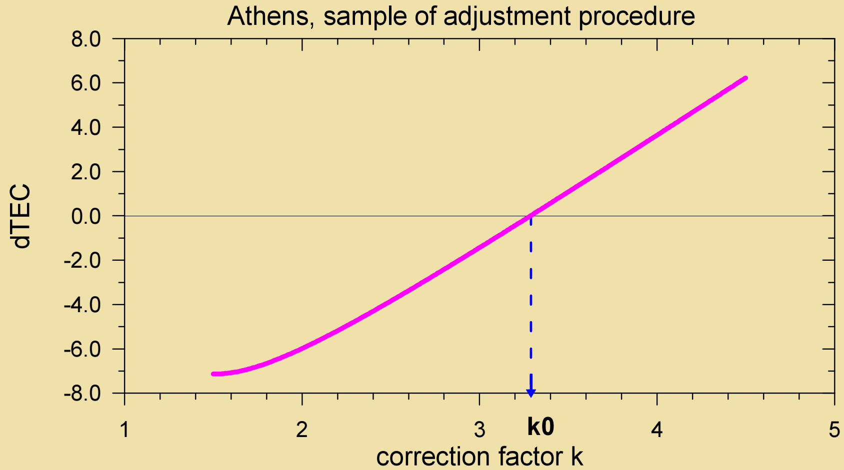
Digisonde topside profile is expressed by the α-Chapman formula. At higher altitudes the profile decreases with a scale height 2Hm, which represent a plasma scale height with plasma temperature Tp=2Tn (Tn=Ti=Te). The O^+ scale height, produced by TaD, is 1.25 times the α-Chapman plasma scale height. This is because the topside plasma temperature is larger than 2Tn.

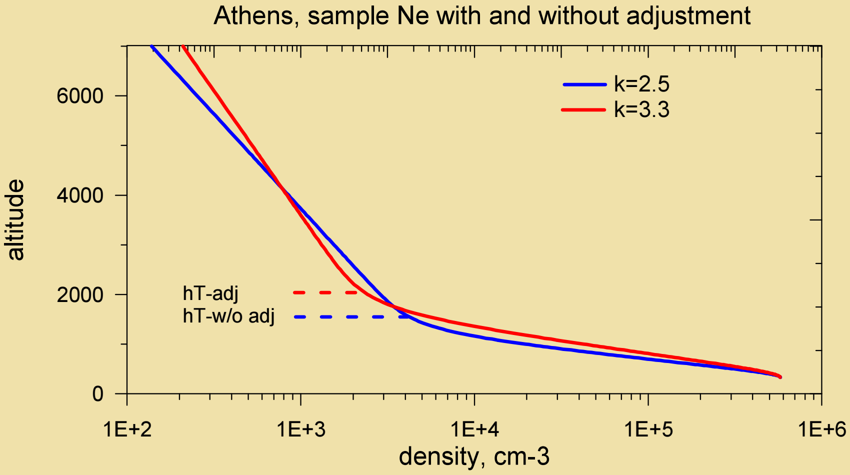


Adjustment procedure

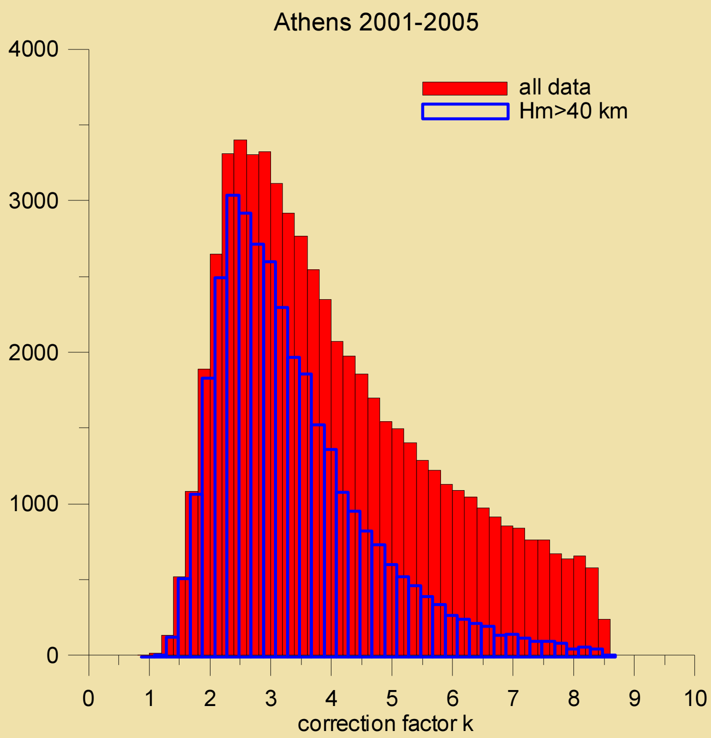
Correction factor k varies between 1.5 and 5 with a step 0.01. The zero value k_0 marks the correction factor to Hm, at which the integral of TaD profile plus the bottomside TEC equal the measured GPS_TEC (dTEC=0).

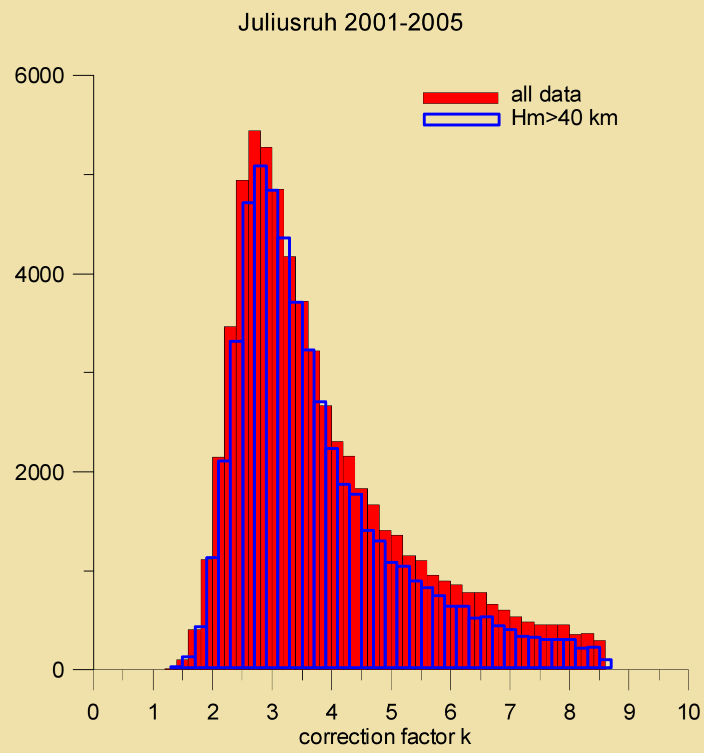
In this sample k_0 =3.3 and corresponding Ne profile is shown by the red line.





Scale height correction





Hm<40 km are 42% of the cases for Athens and 16% for Juliusruh

Error assessment - 1

Transition height h_T and plasmasphere scale height Hp are obtained by statistically defined dependences with Hm:

$$h_T = kHm/R_T \quad \text{and} \quad Hp = kHm(9\cos^2(glat)+4)$$

They introduce errors (uncertainties) even TaD_TEC is adjusted to GPS_TEC with a good accuracy. To estimate the errors coming from all parameters in the TaD profile when varying k, we consider the total change of the integral T as:

$$\Delta T = \frac{\partial T}{\partial k}\Delta k + \frac{\partial T}{\partial Hm}\Delta Hm + \frac{\partial T}{\partial h_T}\Delta h_T + \frac{\partial T}{\partial Hp}\Delta Hp$$

The total differential ΔT is a sum of partial derivatives of T on the parameters at the zero value k_0 (dTEC=0), multiplied by their respective shifts.

Error assessment - 2

At 10% shift of parameter values taken around k_0, the partial contributions in percent to the total change of T, obtained over the whole Athens data set, are:

$$0.1k\frac{\partial T}{\partial k} = (91 \pm 6)\% \qquad 0.1Hm\frac{\partial T}{\partial Hm} = (9 \pm 6)\%$$

$$0.1h_T\frac{\partial T}{\partial h_T} = (4\times10^{-5})\% \qquad 0.1Hp\frac{\partial T}{\partial Hp} = (2\times10^{-9})\%$$

Similar results are obtained for Juliusruh data.

important clue:

With acceptable accuracy the TaD profile can be adjusted to the measured GPS_TEC by varying solely the correction parameter k

Summary of the results

- The Topside Sounder Model (TSM) provides topside scale height HT, upper transition height hT, and their ratio RT depending on geomagnetic latitude, DoY, local time, solar flux and Kp.
- TSM-based profiler (TSMP) provides the shape of topside ionosphere and plasmasphere vertical ion distribution.
- TSMP-assisted Digisonde (TaD) provides in real time electron density profiles up to GPS heights at Digisonde locations.
- TaD was extensively tested and verified by all available independent source of data. The average error compared with measured TEC does not exceed 3 TECU.
- TaD profiling accuracy is significantly increased when the profiles are adjusted with GPS-derived TEC from co-located receiver.