ABSTRACT

We present statistical analysis of recalibrated TPMU - PROBA II microsatellite long-term measurement of the floating potential FP and the electron temperature Te in comparison with the Te and the FP measured data with Swarm Langmuir Probes and IRI model computed data. The analysis is performed for all seasons from year 2010 until now. **Thermal Plasma Measurement Unit (TPMU)** scientific instrument was developed for PROBA II microsatellite and launched in November 2009. The device is working with limitations of scientific measurements caused very probably by installed on-board software. This cause a specific distortion in electron temperature Te data. This behaviour of the instrument is stable and lasting since begin of the mission. Measured floating potential FP and the electron temperature Te data are completed with orbital parameters.

We implemented the stochastic method of polynomial regressions via **Vandermonde matrix**. In order to evaluate the resulting model at specific data points, Te data measured by the Swarm Langmuir Probes in similar space-time coordinates and the IRI (International Reference Ionosphere) model computed Te data in identical space-time coordinates with TPMU - PROBA II instrument we used.

The recalibrated Te data react physically in presented intervals. Use this procedure we improved physical characteristics of data and we significantly reduced their systematic distortion. This recalibration opens opportunities to scientific interpretation of measured data.

METODOLOGY

General description

Let $X = x_1, \ldots, x_n$, $Y = y_1, \ldots, y_m$ be two sequences of nondecreasing numbers, where $n \leq m$.

To each x_i we assign corrensponding y_j, where

$$p(i) := \lfloor i \cdot \frac{m}{n} \rfloor$$

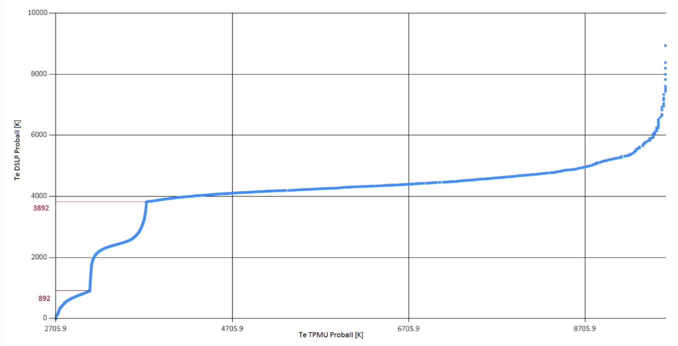
We can partially define conversion function from X to Y:

$$\forall i \in \{1, \ldots, n\} : f(x_i) = y_{p(i)}$$

By using fitting methods we can fit missing points in f.

Our case

X is original data from TPMU Proba II instrument (altered by bug),
Y is correct data from another satellite measurement.
By using method on this data we get following function f:



- Data can be splitted into 3 parts continuous function.
- Onto these parts fitting method can be successfully applied.
- Recalibration using space-time identical IRI model data is in progression

A ***Vandermonde matrix*** is a type of matrix that arises in the polynomial least squares fitting, Lagrange interpolating polynomials (Hoffman and Kunze p. 114), and the reconstruction of a statistical distribution from the distribution's moments (von Mises 1964; Press et al. 1992, p. 83).

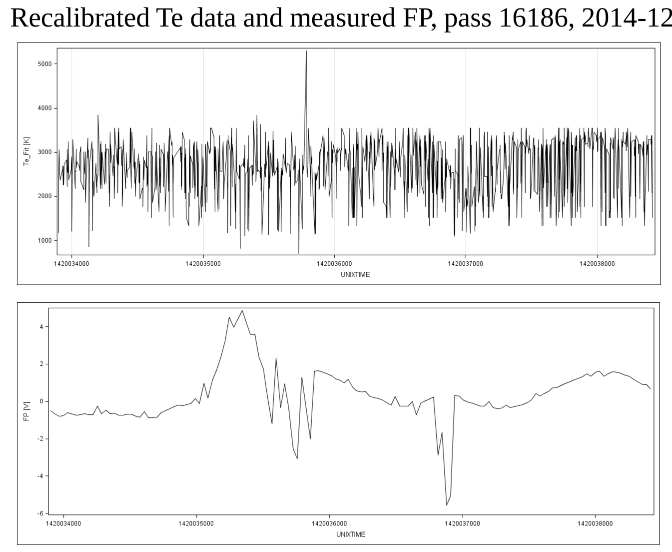
The solution of an $n \times n$ Vandermonde matrix equation requires $O(n^2)$ operations.

A Vandermonde matrix of order n is of the form:

$$\begin{bmatrix} 1 & x_1 & x_1^2 & \cdots & x_1^{n-1} \\ 1 & x_2 & x_2^2 & \cdots & x_2^{n-1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_n & x_n^2 & \cdots & x_n^{n-1} \end{bmatrix}.$$

Example of TPMU recalibrated data

Recalibrated Te data and measured FP, pass 16186, 2014-12-31



The Thermal Plasma Measurement Unit *(TPMU) was designed and manufactured as a part of scientific payload of the PROBA II satellite.*
It is intended for research of the cold plasma parameters like electron temperature, ion density, ion temperature and floating potential of the satellite. The main TPMU goal is the validation and testing of new design of the instrument which is necessary for possible applications of TPMU design for future scientific missions. The device was designed and developed at the Institute of Atmospheric Physics ASCR.
The TPMU is placed in a box containing the electronics block and block of sensors with the retarding potential analyzer (RPA) and two RF sensors.

TPMU measurement range of densities and temperatures:
10 - 1 million ions per cubic centimetre, resp. 800 -10 000 K.
The floating potential measured range: *± 12 volts.*
PROBA II satellite : Orbit *Sun-sychronous,* ***Altitude*** *720 km,* ***Inclination*** *98.298 degrees,*
Size *0.65 x 0.7 x 0.85 m,* ***Mass*** *130 kg,*
Current status: *Active.*

Fig.1: TPMU - PROBA II Microsatellite Instrument.
PROBA II satellite *with the TPMU on board was launched on 2 November 2009. Source: IAP ASCR,*
http://www.esa.int/Our_Activities/Technology/Proba_Missions/About_Proba-2

SWARM *is an European Space Agency (ESA) mission to study the Earth's magnetic field. Two satellites orbit side-by-side decaying naturally from an initial altitude of 460 km to 300 km, while the third orbits at about 530 km.* ***Orbit:*** *Polar.* ***Current status:*** *Active.*
Apogee *SWARM A: ≤460 km, SWARM C: ≤460 km, SWARM B: ≤530 km*
Inclination *SWARM A: 87.4°, SWARM C: 87.4°, SWARM B: 88°*
Attitude control: *Sun-pointing with automatic manoeuvring.*
Size *9.1 m × 1.5 m × 0.85 m,* ***Mass*** *369 kg.*

SWARM satellite constellation *consists of three satellites (Alpha, Bravo & Charlie)*
http://swarm-wiki.spacecenter.dk/mediawiki-1.21.1/index.php/File:Swarm3.png

TPMU - PROBA II microsatellite measurement data recalibration using polynomial regressions via Vandermonde matrix

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Fitted Normal Distribution for TPMU - ProbaII, Measured Te[K]

Parameter	Symbol	Estimate
Mean	Mu	3467.1
Std Dev	Sigma	296.6599

Goodness-of-Fit Tests for Normal Distribution

Test	----Statistic-----		------p Value------	
Kolmogorov-Smirnov	D	0.168	Pr > D	<0.010
Cramer-von Mises	W-Sq	28001.996	Pr > W-Sq	<0.005
Anderson-Darling	A-Sq	171303.675	Pr > A-Sq	<0.005

Quantiles for Normal Distribution

Percent	Observed	Estimated
1.0	3001.70	2776.97
5.0	3094.60	2979.14
10.0	3103.20	3086.91
25.0	3152.80	3267.01
50.0	3583.50	3467.10
75.0	3696.40	3667.19
90.0	3722.60	3847.28
95.0	3730.20	3955.06
99.0	4122.80	4157.23

Fitted Normal Distribution for TPMU - ProbaII, SWARM-A Fitted Te[K]

Parameter	Symbol	Estimate
Mean	Mu	2692.747
Std Dev	Sigma	603.5887

Goodness-of-Fit Tests for Normal Distribution

Test	----Statistic-----		------p Value------	
Kolmogorov-Smirnov	D	0.0748	Pr > D	<0.010
Cramer-von Mises	W-Sq	4294.3003	Pr > W-Sq	<0.005
Anderson-Darling	A-Sq	27216.9631	Pr > A-Sq	<0.005

Quantiles for Normal Distribution

Percent	Observed	Estimated
1.0	1194.00	1288.59
5.0	1515.25	1699.93
10.0	1860.25	1919.22
25.0	2292.50	2285.63
50.0	2797.50	2692.75
75.0	3125.75	3099.86
90.0	3366.25	3466.28
95.0	3566.90	3685.56
99.0	3784.80	4096.90

Fitted Normal Distribution for TPMU - ProbaII, IRI model Fitted Te[K]

Parameters for Normal Distribution

Parameter	Symbol	Estimate
Mean	Mu	2802.846
Std Dev	Sigma	440.5399

Goodness-of-Fit Tests for Normal Distribution

Test	----Statistic-----		------p Value------	
Kolmogorov-Smirnov	D	0.0799	Pr > D	<0.010
Cramer-von Mises	W-Sq	7575.9668	Pr > W-Sq	<0.005
Anderson-Darling	A-Sq	49802.9801	Pr > A-Sq	<0.005

Quantiles for Normal Distribution

Percent	Observed	Estimated
1.0	1740.94	1778.00
5.0	1881.50	2078.22
10.0	2098.00	2238.27
25.0	2557.75	2505.71
50.0	2888.75	2802.85
75.0	3138.00	3099.99
90.0	3316.50	3367.42
95.0	3387.82	3527.47
99.0	3487.90	3827.69

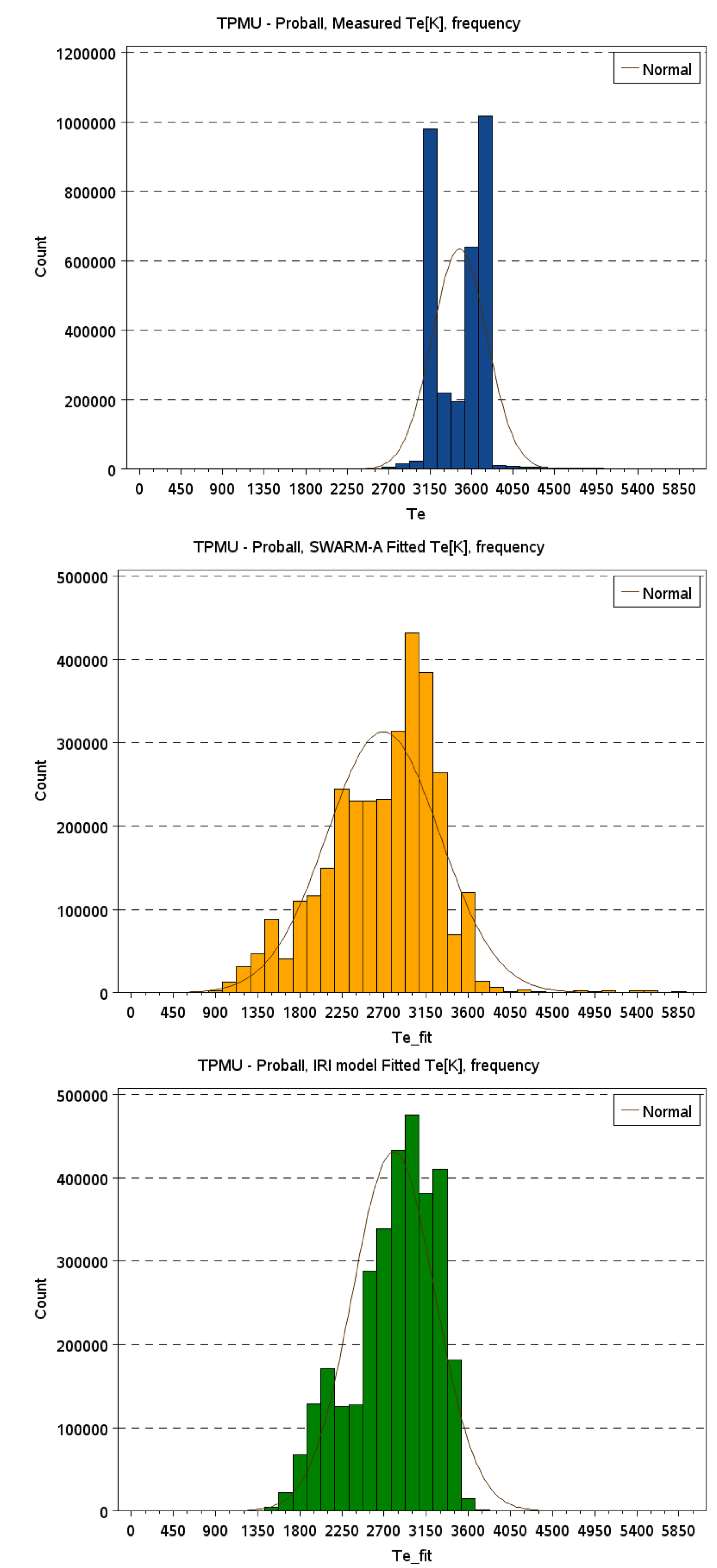

Fig.2: Comparison of Te[K] measurement by TPMU PROBA II and recalibrated TPMU Te data using SWARM Langmuir Probes measured data and IRI model computed Te. *Plots are organized in panels by recalibration data pattern (PROBAII, SWARM A and IRI model) in right panels are the density histograms of Te. In left part are statistical comparison of TPMU Te measurement and recalibrated data. The analysis was perform for 50 516 585 records of SWARM A measurement, 55 850 642. Number of TPMU PROBA II measurement was 3 173 502.*

IRI-2016 model

IRI-2016 was also used for recalibration of the PROBA II data. The International Reference Ionosphere (IRI) is an empirical standard model of the ionosphere and the topside ionosphere based on available and reliable data sources specifying climatology of electron density, ion composition, electron temperature, and ion temperature in the altitude range from 50 km to 2000 km (e.g., Bilitza et al., 2017).
For the electron temperature a model developed by Truhlik et al., (2012) which is included in IRI as the recommended option since IRI-2012 was employed (TBT-2012). This newer model takes advantage of better global coverage provided by satellite measurements (20 satellites), includes solar activity variation of the electron temperature and uses the invdip latitude coordinate that is close to the magnetic inclination (dip) near the magnetic equator and closer to invariant latitude at higher latitudes and thus correlates well with the observed variation patterns of the topside electron temperature (Truhlik et al., 2001).
For each PROBA II measurement IRI electron temperature was calculated. For the period from 2010 to 2015 it represents more than 3 million data points.

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TPMU THERMAL PLASMA MEASUREMENT UNIT

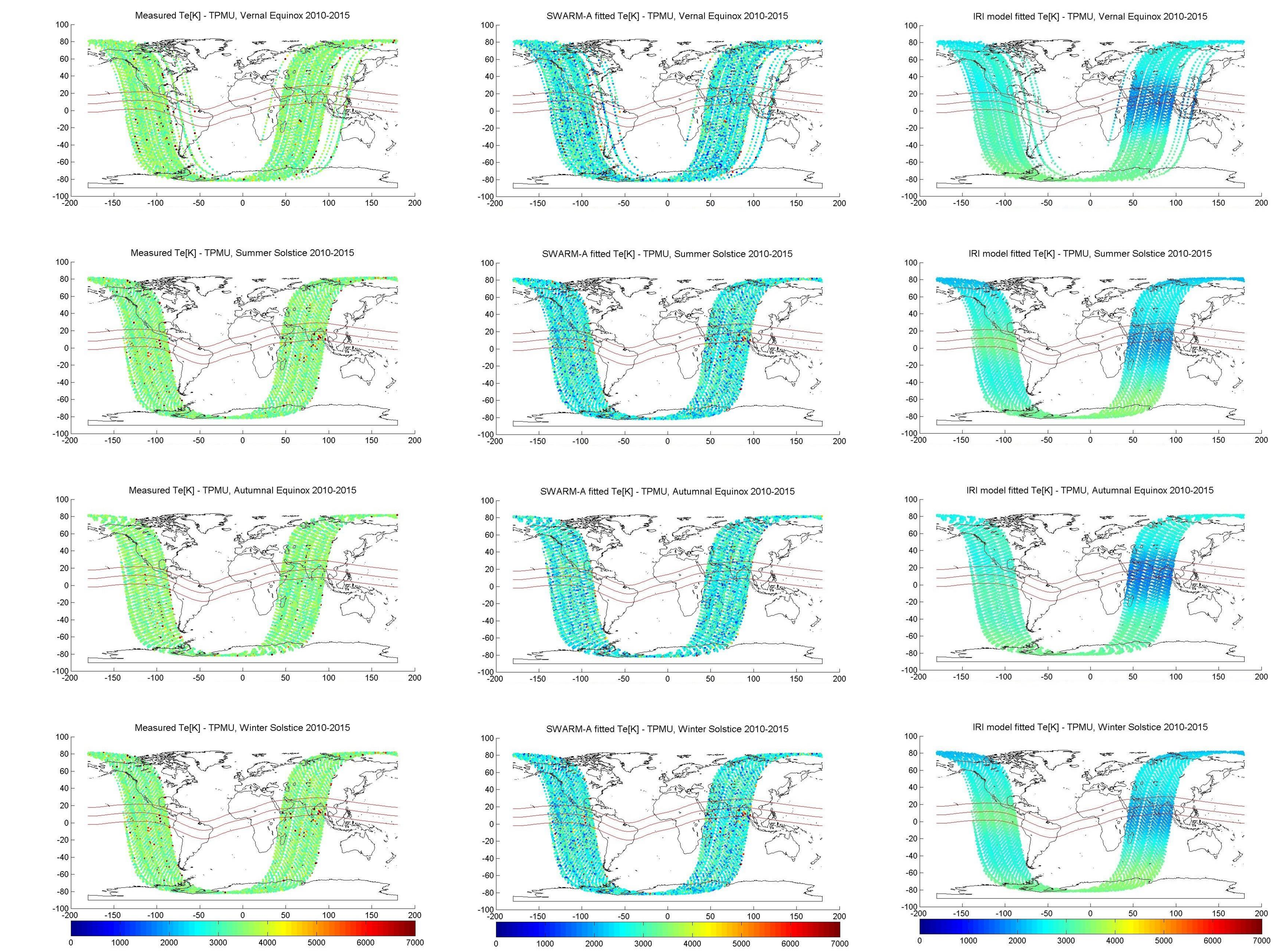

Fig.3: Te measurement by TPMU PROBA II and recalibrated TPMU Te data using SWARM Langmuir Probes measured data and IRI model computed Te.
The left panel presents Te TPMU measured data, in the middle, we can observe recalibrated Te data using SWARM Langmuir Probes measured data, and on the right are recalibrated IRI model computed Te data.. The PROBAII satellite is synchronized to the Sun, so measuring is in the same geographical coordinates, ie there is no global coverage. Geomagnetic equator and the 10th parallels North and South are drawn with red line.

CONCLUSIONS

This proves that systematically biased measurement of electron temperatures for period of years 2010 – 2015 might be recalibrated using this method. The recalibrated Te data react physically in presented intervals. Use this procedure we improved physical characteristics of data and we significantly reduced their systematic distortion. The Te data recalibrated using IRI model pattern are by far more physically realistic than those recalibrated using SWARM A pattern. We will continue to assemble and analyse TPMU Te data in the next period.

DATA SOURCES

The satellite Proba2 telemetry data, the TPMU unit onboard measurement.
The geographical coordinates computed from Tle parametres by ORBL algorithm.
World Data Center for Geomagnetism, Kyoto University, Japan, Space Physics Interactive Data Resource (SPIDR), National Geophysical Data Center, Boulder, USA.
SWARM Langmuir Probes *data provided by the European Space Agency.*

REFERENCES

Box, G. E. P., Jenkins, G. M., and Reinsel, G. C. (1994), Time Series Analysis: Forecasting and Control, 3rd Edition, Englewood Cliffs, NJ: Prentice-Hall.

Sokal, R. R., and Michener, C. D., *A statistical method for evaluating systematic relationships*, Univ. Kansas Sci. BulL, 1958, 38, 1409-1438. [1.2.4, 1.2.5, 5.1, 5.4.1, 5.5.1].

Berghmans, D. et al, The PROBA2 Mission: The First Two Years of Solar Observation, Solar Physics, Volume 286, Issue 1, 2013.

Bilitza, D., Altadill, D., Truhlik, V., Shubin, V., Galkin, I., Reinisch, B., Huang, X., 2017. International Reference Ionosphere 2016: From ionospheric climate to real-time weather predictions. Space Weather-the International Journal of Research and Applications 15 (2), 418-429.

Truhlik, V., Bilitza, D., Triskova, L., 2012. A new global empirical model of the electron temperature with the inclusion of the solar activity variations for IRI. Earth Planets and Space 64 (6), 531-543.

Truhlik, V., Triskova, L., Smilauer, J., 2001. Improved electron temperature model, and comparison with satellite data. International Reference Ionosphere - Workshop 1999 27 (1), 101-109.

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