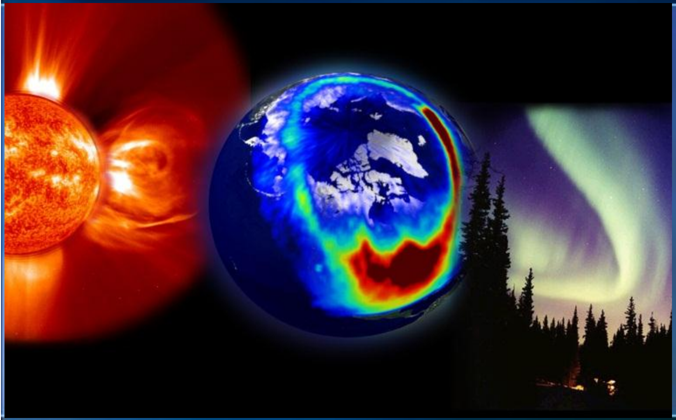

Physics of Sun, Heliosphere and Space Weather – Applications and Simulations - M.Phy. 553/554

The Ionosphere

Volker Bothmer[1]

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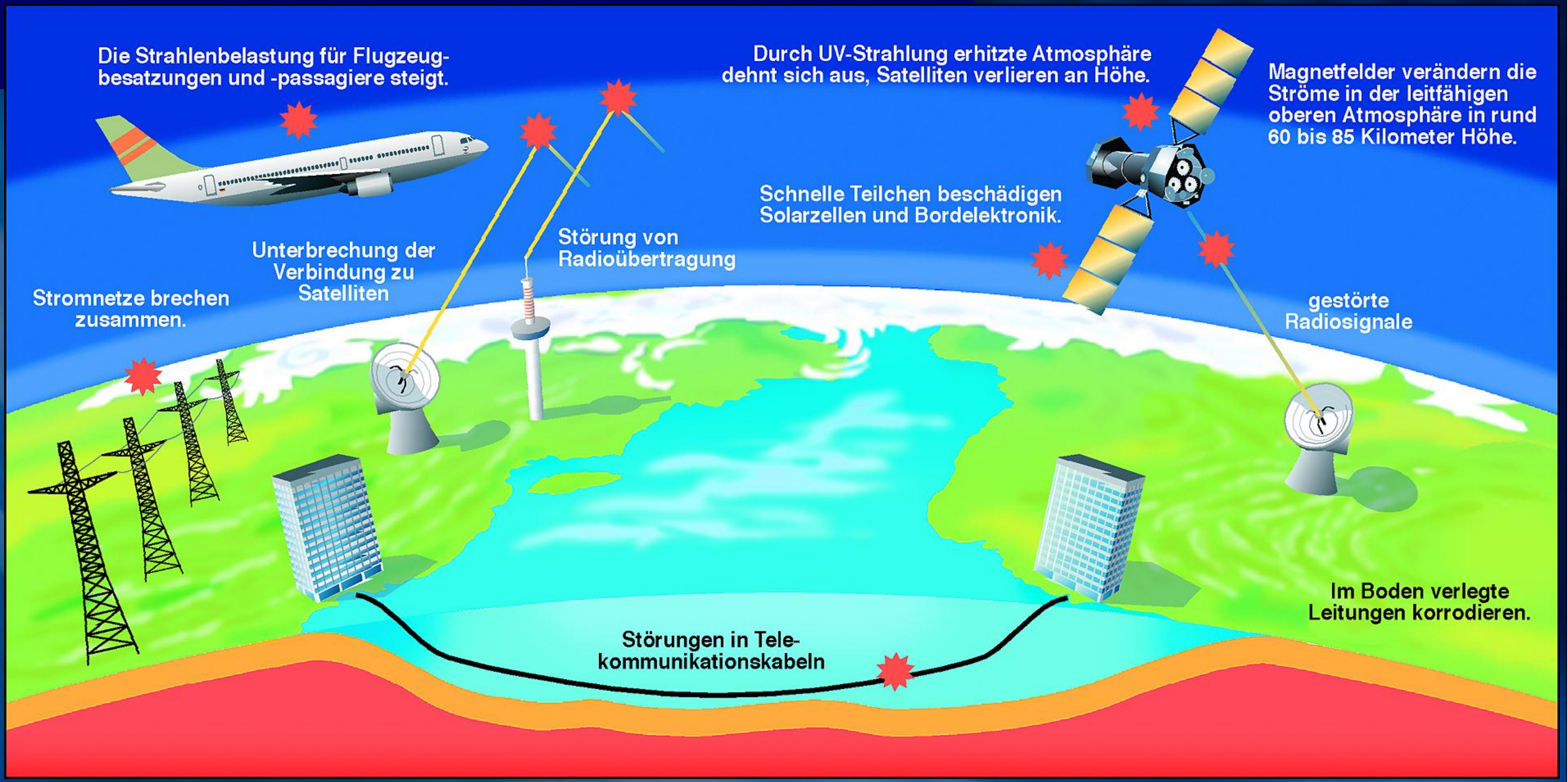
SoSe 2011

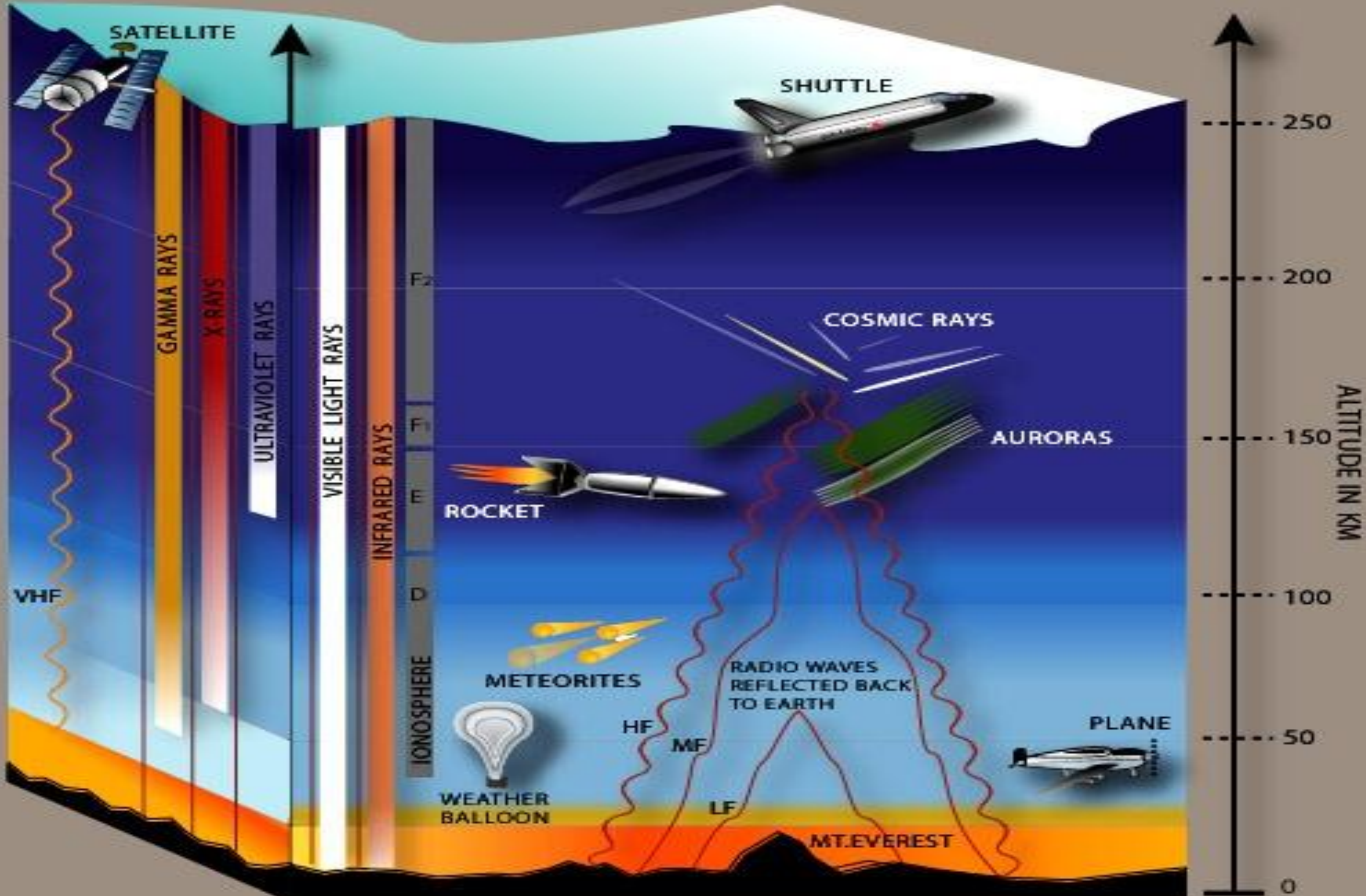
Effekte des Weltraumwetters



Quelle: Rainer Michaelis, Angela Grosse, Volker Bothmer, Hamburger Abendblatt vom 16.4.2007

Entdeckung der Erd-Ionosphäre

- Idee hochatmosphärischer Ströme von Humboldt (1806), Gauß (um 1839), Kelvin (1860) und Stewart (1883) zur Erklärung erdmagnetischer Fluktuationen.
- 1901 wurde das Thema dieser möglichen elektrischen Ströme interessant, als es Marconi gelang Radiowellen über den Atlantik zu senden.
- Heaviside und Lodge (1902) erklärten Reflexion EM-Wellen an freien Ladungsträgern in der Hochatmosphäre, hervorgerufen durch solare UV-Strahlung.
- 1924 erster Nachweis der sogenannten Kennelly-Heaviside-Schicht (E-Schicht) durch Radiowellenexperimente (Appleton (Nobelpreis), Barnett in England, Breit, Tuve in USA).
- Zur Zeit: ca. 100 Ionosondenstationen, Prinzip der Echolotung; Radaranlagen; heute zusätzlich Weltraummessungen (GNSS).



Close-up of a drawing that shows the penetration of different kinds of electromagnetic radiation into the atmosphere. Note also the different layers of the ionosphere (D, E, F).

KEY - RADIO WAVES

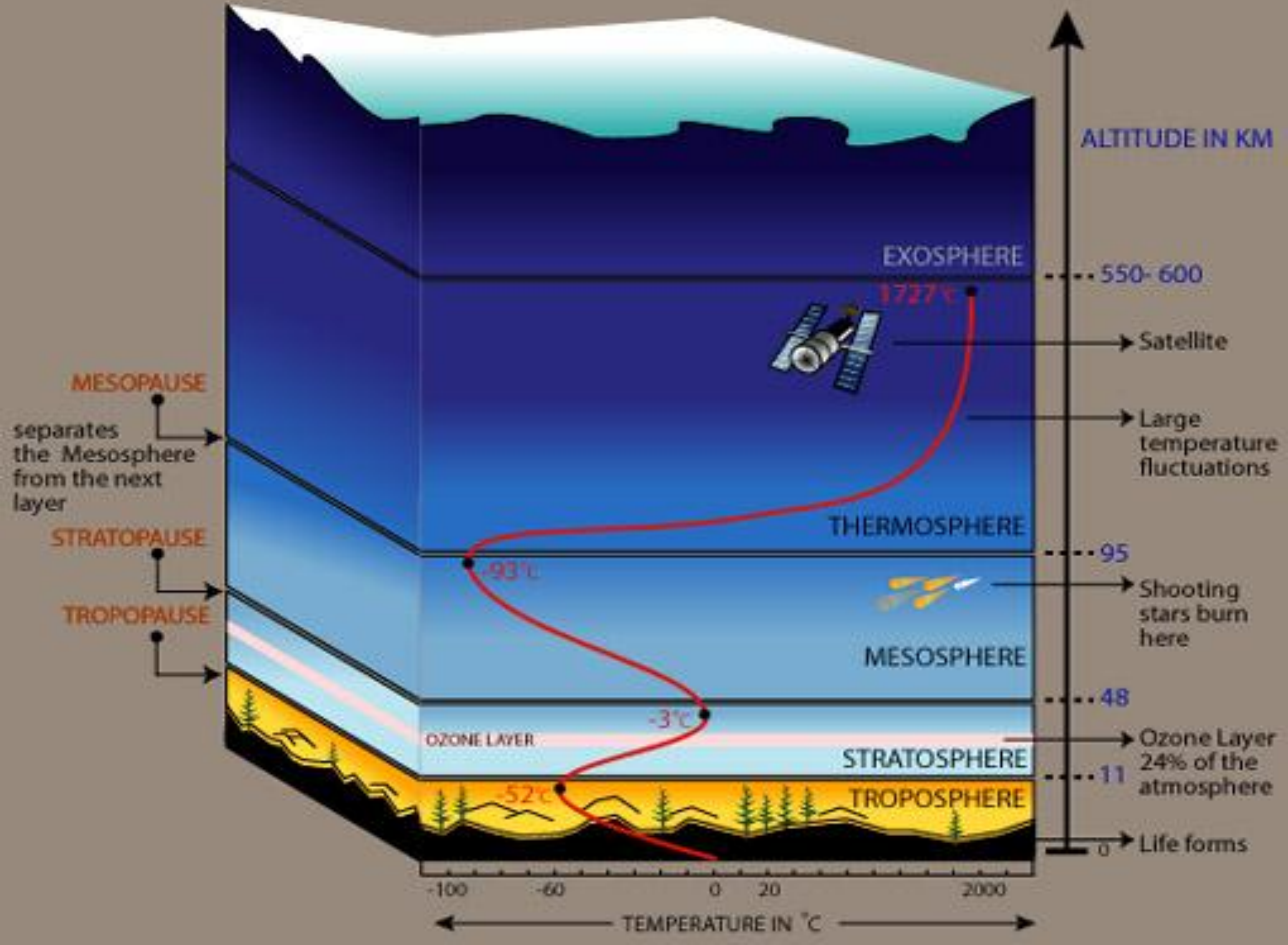
LF - LOW FREQUENCY
MF - MEDIUM FREQUENCY
HF - HIGH FREQUENCY
VHF - VERY HIGH FREQUENCY

Ionosphäre der Erde

- Die Ionosphäre ist die ionisierte Komponente der höheren Atmosphäre.
- Gemisch thermische und gravitativ an die Erde gebundener Ladungsträgergase.
- Ladungsträgergas ist nur Komponente – Spurengas.

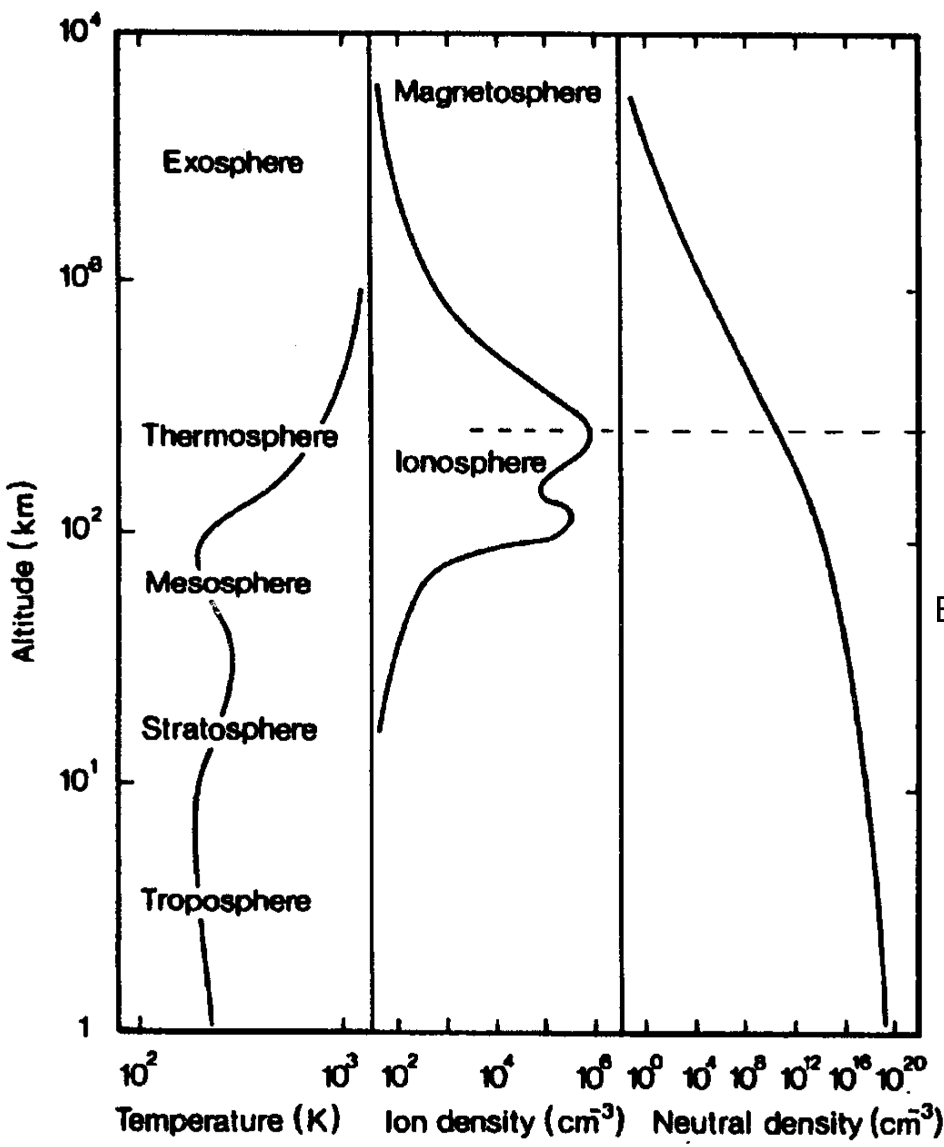
Trotzdem führt dies zu wichtigen Auswirkungen:

- elektrische Ströme
- elektrodynamische Aufheizungen durch Joul'sche Wärme
- Einfluß auf thermosphärische Winde
- Modifikation EM-Wellen (Telekommunikation und Navigation)



ALTITUDE IN KM
EXOSPHERE
550- 600
1727°C
Satellite
Large temperature fluctuations
MESOPAUSE
separates the Mesosphere from the next layer
THERMOSPHERE
STRATOPAUSE
95
-93°C
Shooting stars burn here
TROPOPAUSE
MESOSPHERE
48
-3°C
OZONE LAYER
Ozone Layer 24% of the atmosphere
STRATOSPHERE
11
-52°C
TROPOSPHERE
Life forms
0
-100
-60
0
20
2000
TEMPERATURE IN °C

Grundsätzliche Merkmale der Erdatmosphäre und Ionosphäre



Degree of ionization

$$\frac{n_e}{n_n} \approx 10^{-4} - 10^{-3}$$

Elektronendichte ~ $10^{11}/m^3$

Parameter der Ionosphäre

Maximale Ionisationsdichte: ~ 1 - 30 x 10^{11} m^{-3}

(Chapman-Schicht, hängt von Bilanz aus Strahlungsenergieabgabe, Dichte (mittlere freie Weglängen), Ionisations- und Rekombinationsprozessen ab).

Höhe des Maximums: ~ 220 – 400 km

Schichtdicke: ~ 100 – 400 km

Oberhalb von ca. 90 km Höhe gilt: $n_i \sim n_e$

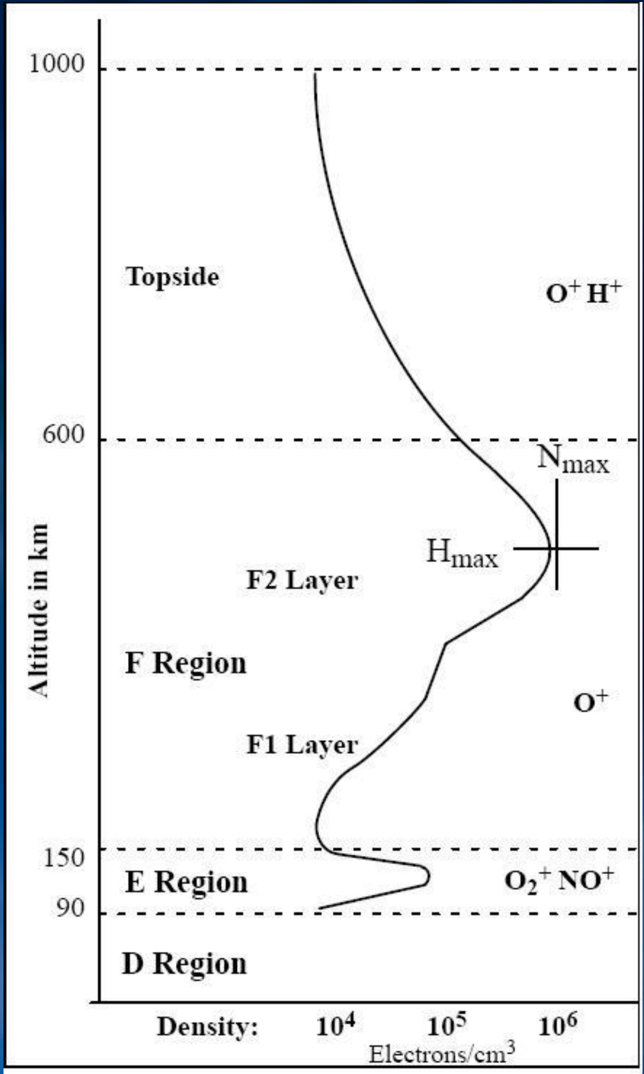
D.h.: Die Gesamtdichte positiver Ionen ist gleich der Dichte der Elektronen.

In unterer Ionosphäre dominieren die molekularen Ionen O^+_2 und NO^+.

Haupt-Ion im Bereich des Schichtmaximums ist O^+ wegen Dominanz thermosph. atomarem Sauerstoffs.

Ionosphere – Regions

- Different Regions of the Ionosphere
  - **D** (70 - 90 kms, ionized by X-rays 0.1-1 nm)
  - **E** (100 - 120 kms, ionized by EUV 80-103 nm and X-rays 1-20 nm)
  - **F** (forms **F1** and **F2** layers during the day) (ionized by EUV 20-80 nm)



http://www.sel.noaa.gov/info/Iono.pdf

Parameter der Ionosphäre

Ionosphäre	D-Region	h < ~ 90 km	$H_3O^+ (H_2O)_n$, NO^-_3
	E-Region	90 <~ h <~ 170 km	O^+_2, NO^+
	F-Region	170 <~ h <~ 1000 km	O^+
Plasmasphäre		h >~ 1000 km	H^+

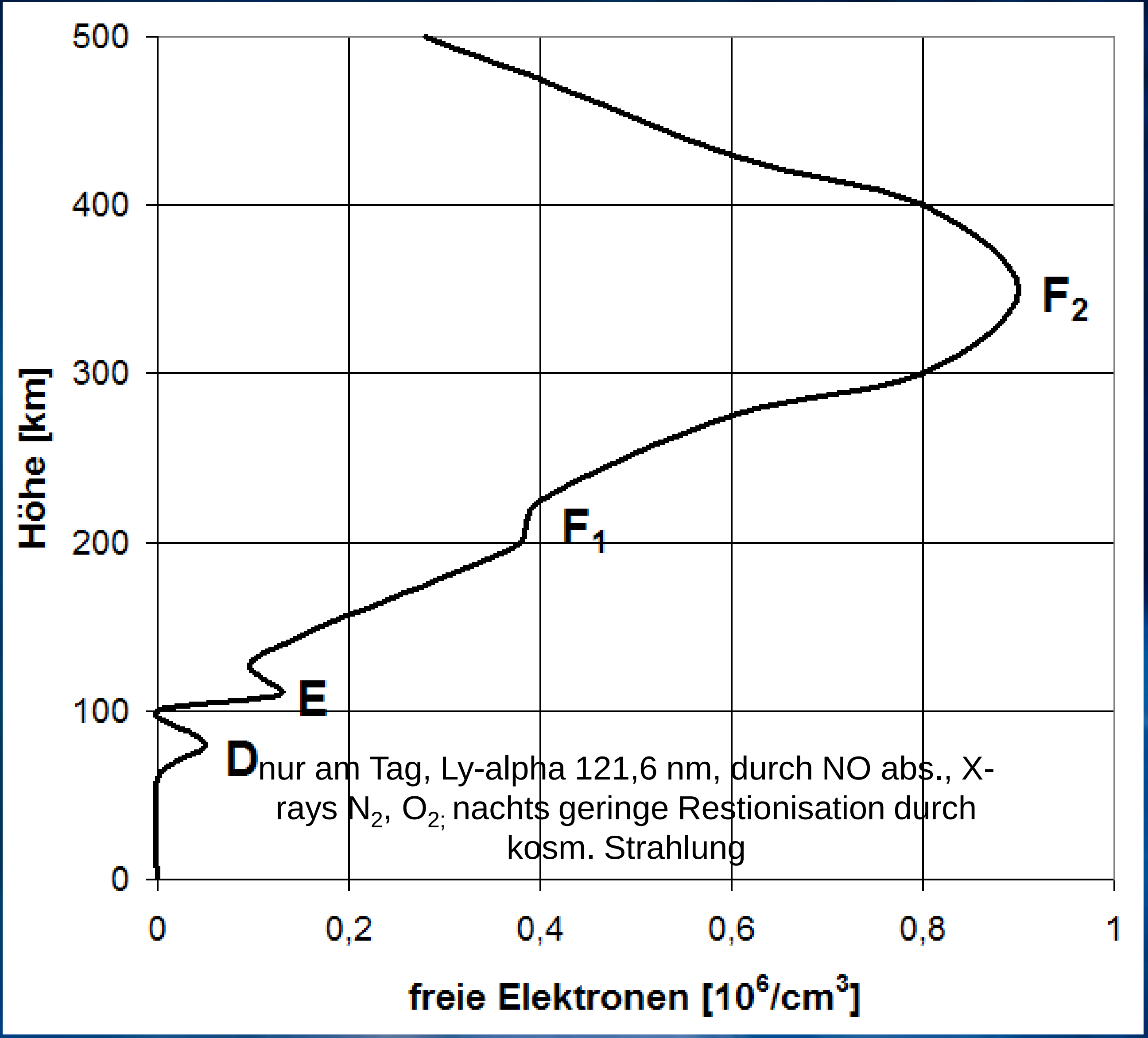
Hochatmosphäre insgesamt nur schwach ionisiert, d.h. $n/n_n << 1$

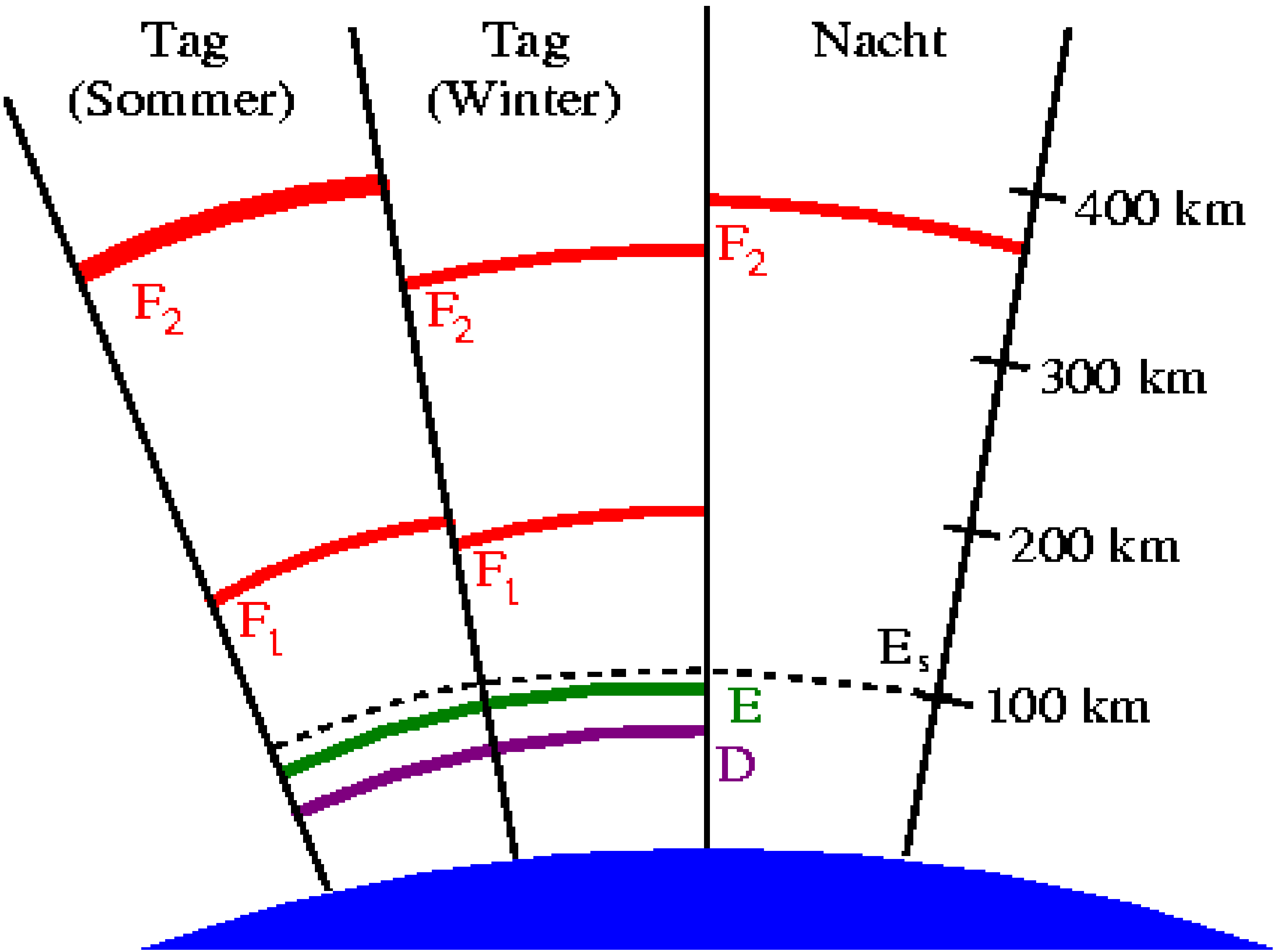
ca. 10^{-2} an Oberkante (1000 km Höhe)

10^{-3} an Schichtunterseite (100 km Höhe)

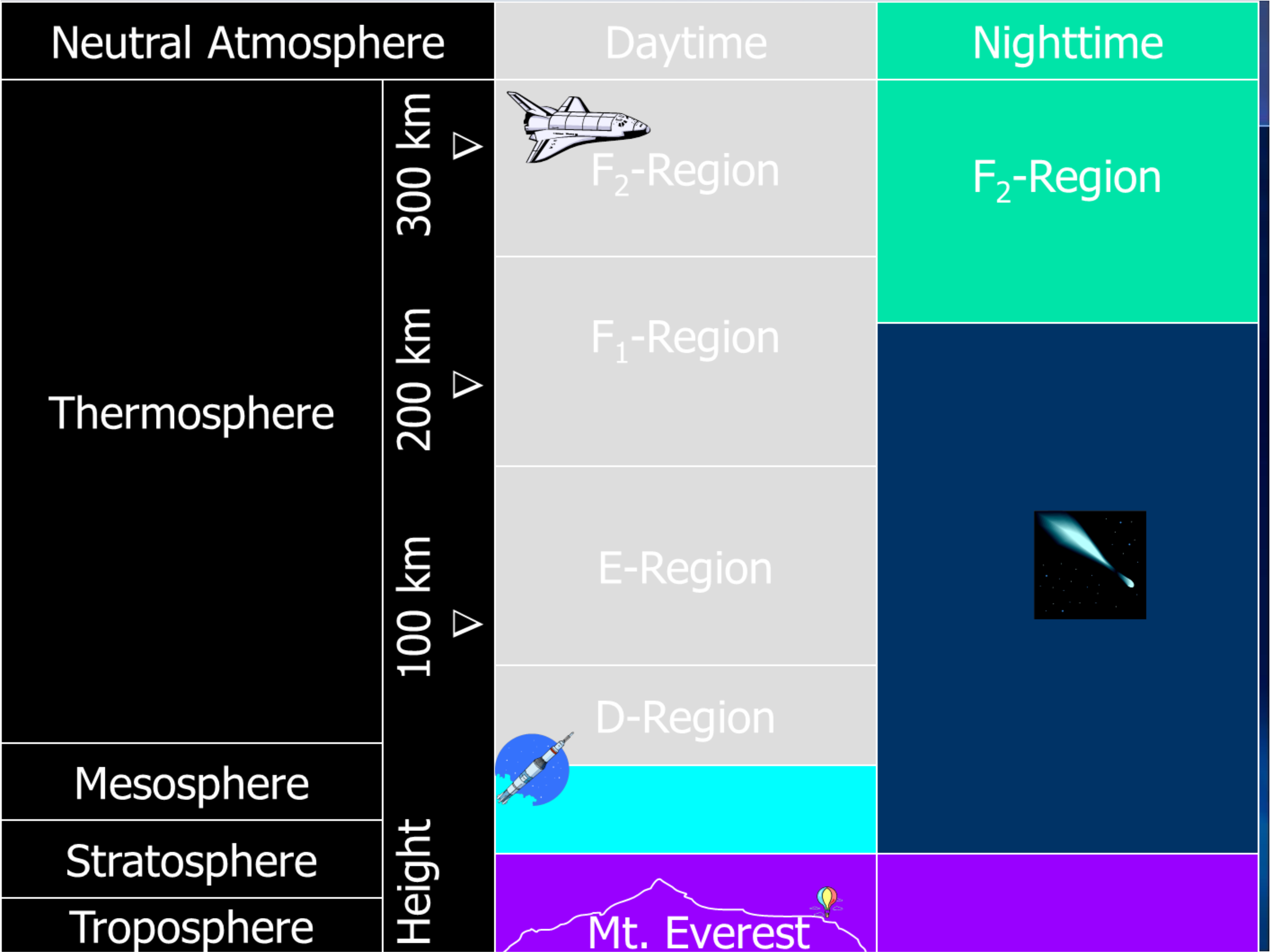
Trotzdem ist Ionosphäre größte Ladungsträgerkonzentration in Erdumgebung

Maxima der Ionisation entstehen durch Energieabsorption an bestimmten Teilchenarten





Tag
(Sommer)
Tag
(Winter)
Nacht
400 km
300 km
200 km
100 km
F_2
F_2
F_2
F_1
F_1
E_s
E
D


Neutral Atmosphere
Daytime
Nighttime
Thermosphere
Mesosphere
Stratosphere
Troposphere
300 km
200 km
100 km
Height
F_2-Region
F_1-Region
E-Region
D-Region
F_2-Region
Mt. Everest

Ionosphere – D Layer Properties

Photo-Chemical Reactions

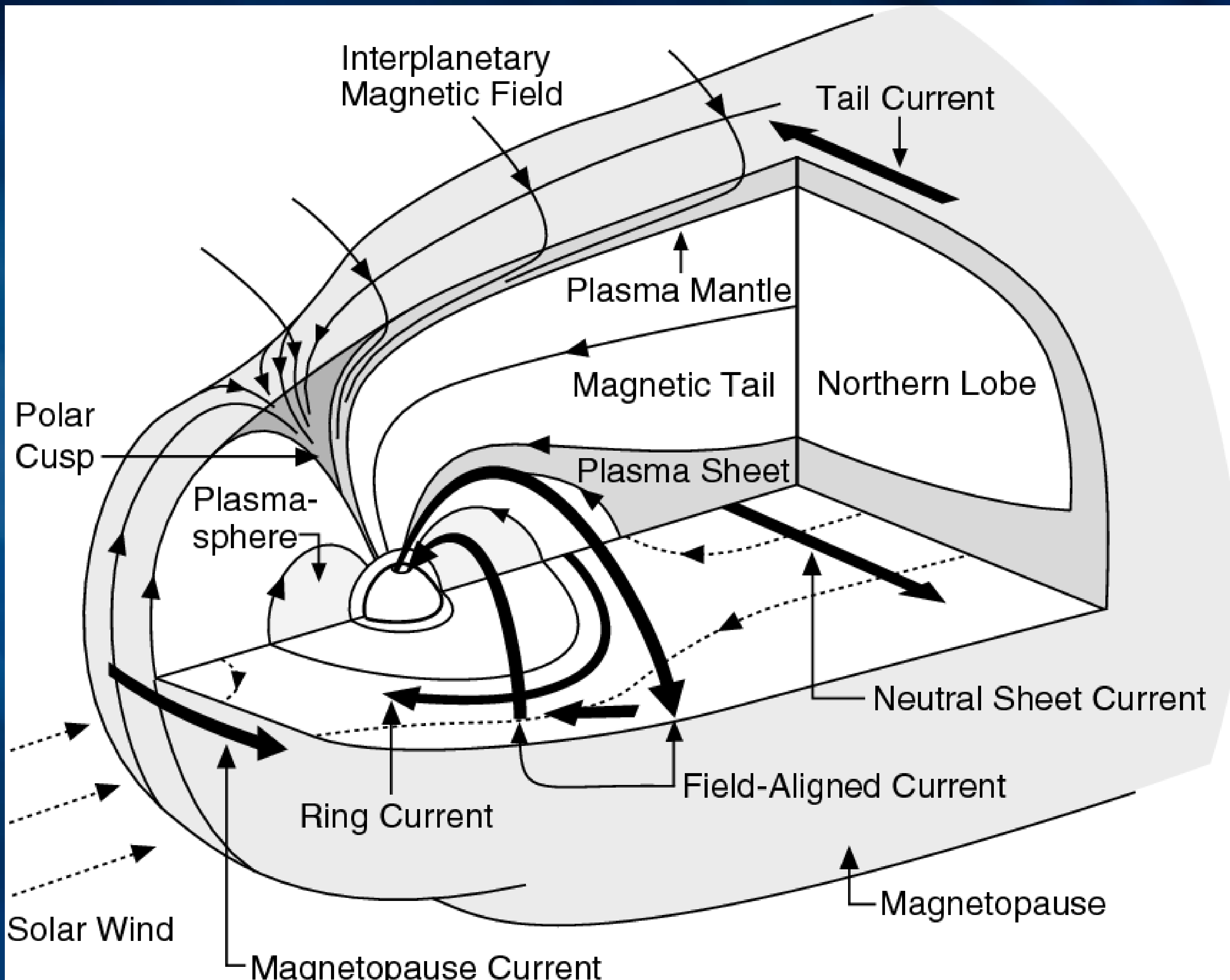
- Photo-Ionization
  - $O + hv \rightarrow O^+ + e^-$ hv = 13.6 eV
  - $N_2 + hv \rightarrow N_2^+ + e^-$ hv = 15.6 eV
  - $O_2 + hv \rightarrow O_2^+ + e^-$ hv = 12.1 eV

- Molecular-Ionization
  - $O^+ + O_2 \rightarrow O_2^+ + O$
  - $O^+ + N_2 \rightarrow NO^+ + N$
  - $N_2^+ + O \rightarrow NO^+ + N$

- Recombination
  - $NO^+ + e^- \rightarrow N + O$
  - $O_2^+ + e^- \rightarrow O + O$
  - $N_2^+ + e^- \rightarrow N + N$

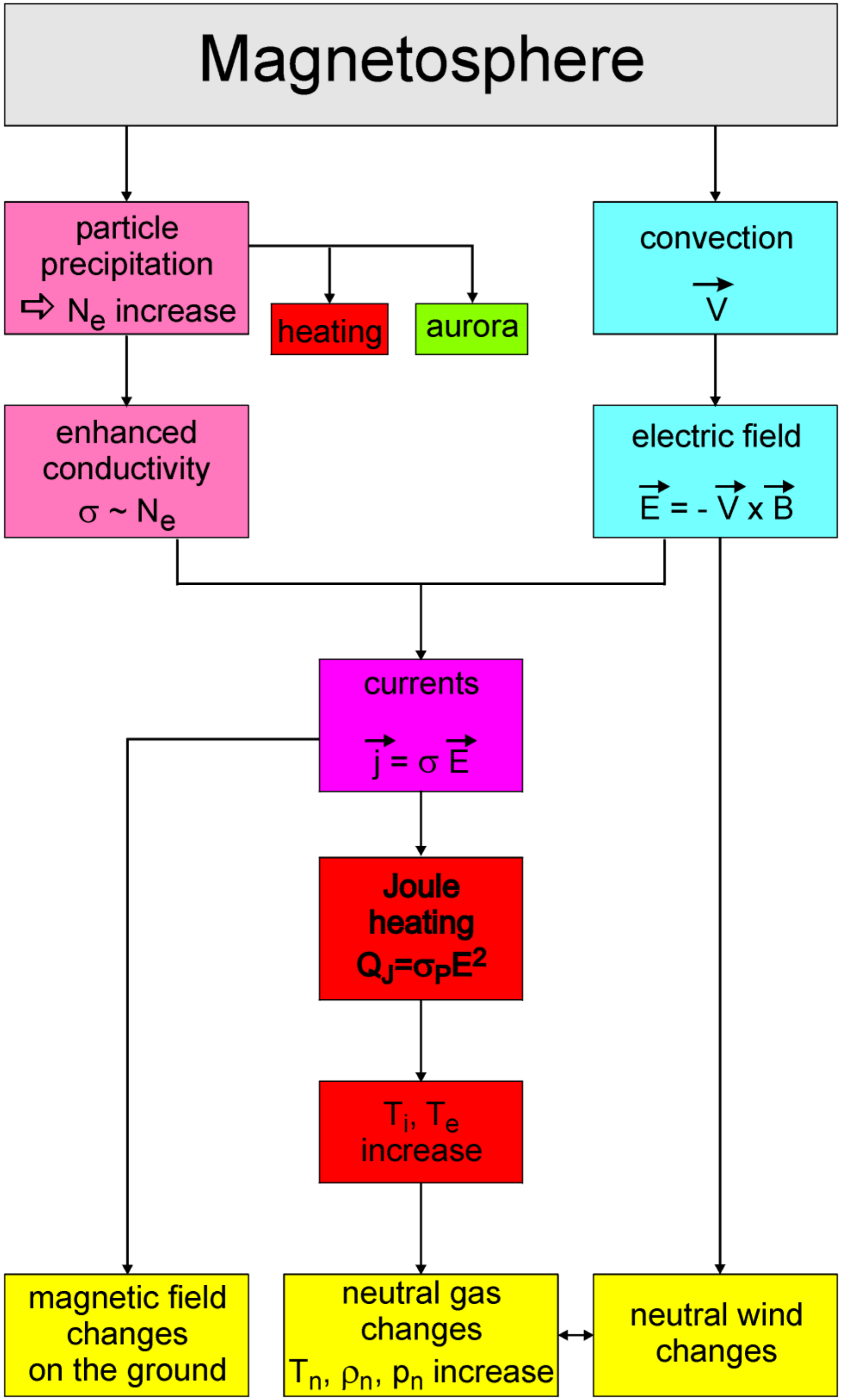
Present during the day – however, very low ionization 1000 e^-/m^3 compared to 100,000 e^-/m^3 in E layer and 1,000,000 e^-/m^3 in the F layers.

Magnetosphärische Stromsysteme



Ionosphären-Magnetosphären Kopplung - Teilcheneinfällung aus der Magnetosphäre

- Hauptsächlich Elektronen mit keV Energien
- Ausbreitung um Feldlinien
- Stoßwechselwirkung mit Neutronen und Ionen
- Ionisation von Neutronen



Die Prozesse in der Magnetosphäre werden durch den Sonnenwind erzeugt

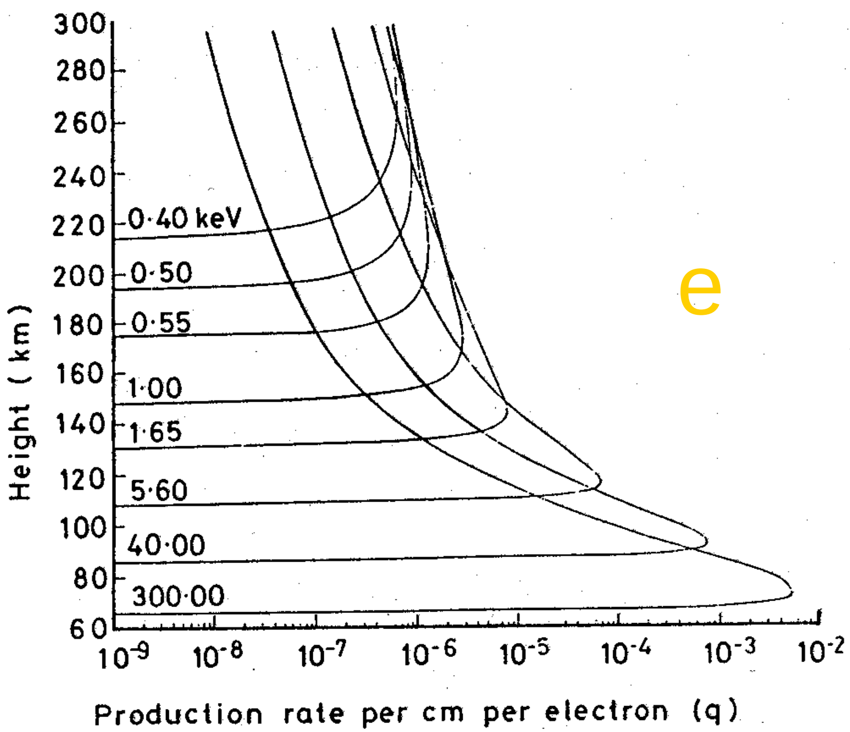
$(\underline{E} = - \underline{v} \times \underline{B})$

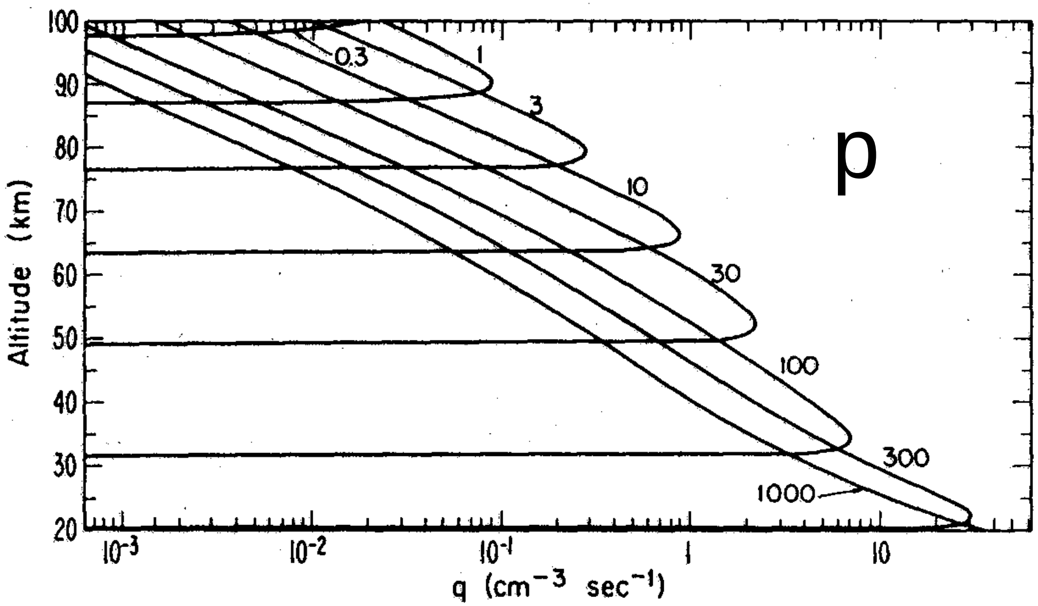
Erhöhte Leitfähigkeit und das el. Feld führen dann zu el. Strömen, hauptsächlich in den Polarlichtzonen in der Dynamo-Region (90-150 km Höhe) gemäß dem Ohm‘schen Gesetz

$\underline{j} = \sigma \underline{E}$

Folgen der elektrischen Ströme in der Ionosphäre

- Heizung des ionosphärischen Plasmas und Transfer zur neutralen Atmosphäre
- Plasma-Instabilitäten
- Erdmagnetische Fluktuationen
- Polarlichter



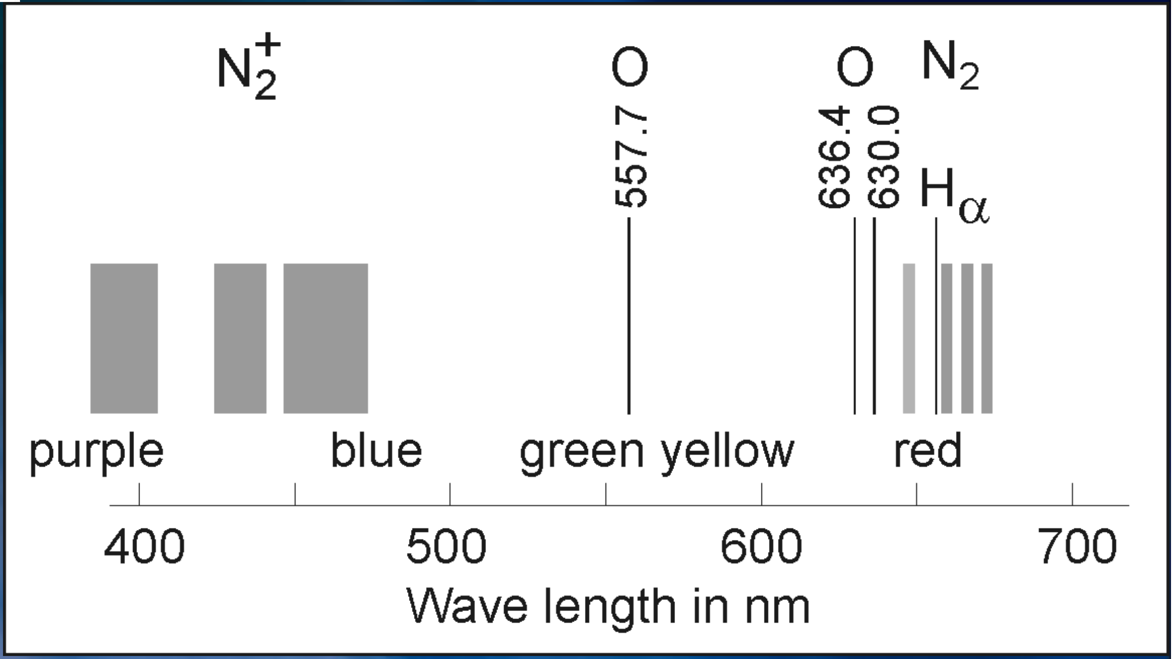


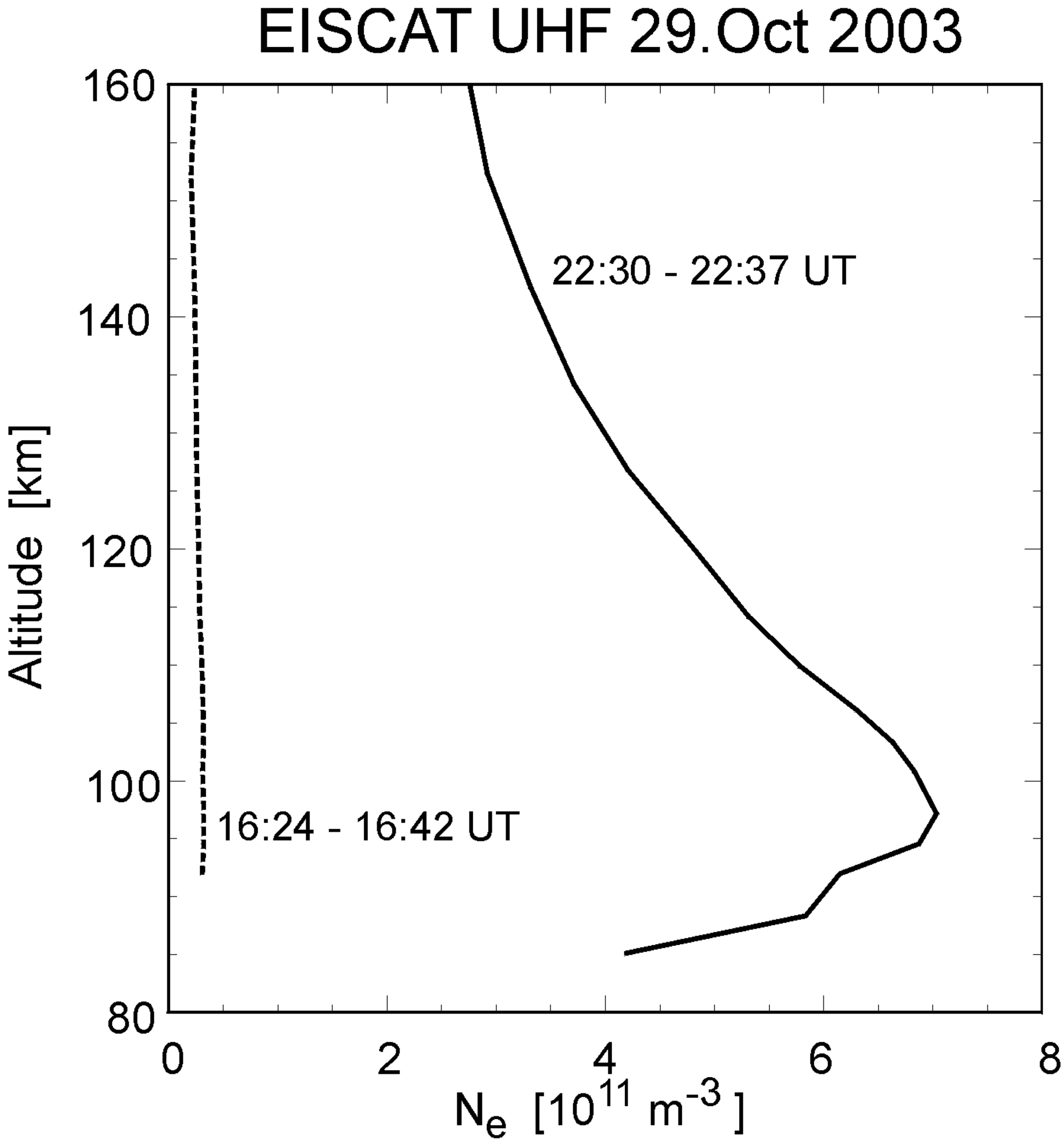
Typische Ionisationsraten

niedrige E-Region, Annahme konst. Elektroneneinfalls mit 10^8 particles/s/m^2/sterad

Stöße

Polarlichter





Beispiel einer Elektronendichte-erhöhung während des geomagnetischen Sturms am 29./30. Oktober 2003

In höheren Breiten kann dann die Elektronendichte durch einfallende Teilchen den durch UV erzeugten Anteil übertreffen

The Ionospheric Response to Violent Solar Storms - Space Weather Effects During the October 2003 Storms

V. Bothmer[1],N. Jakowski[2] and C. Borries[2]

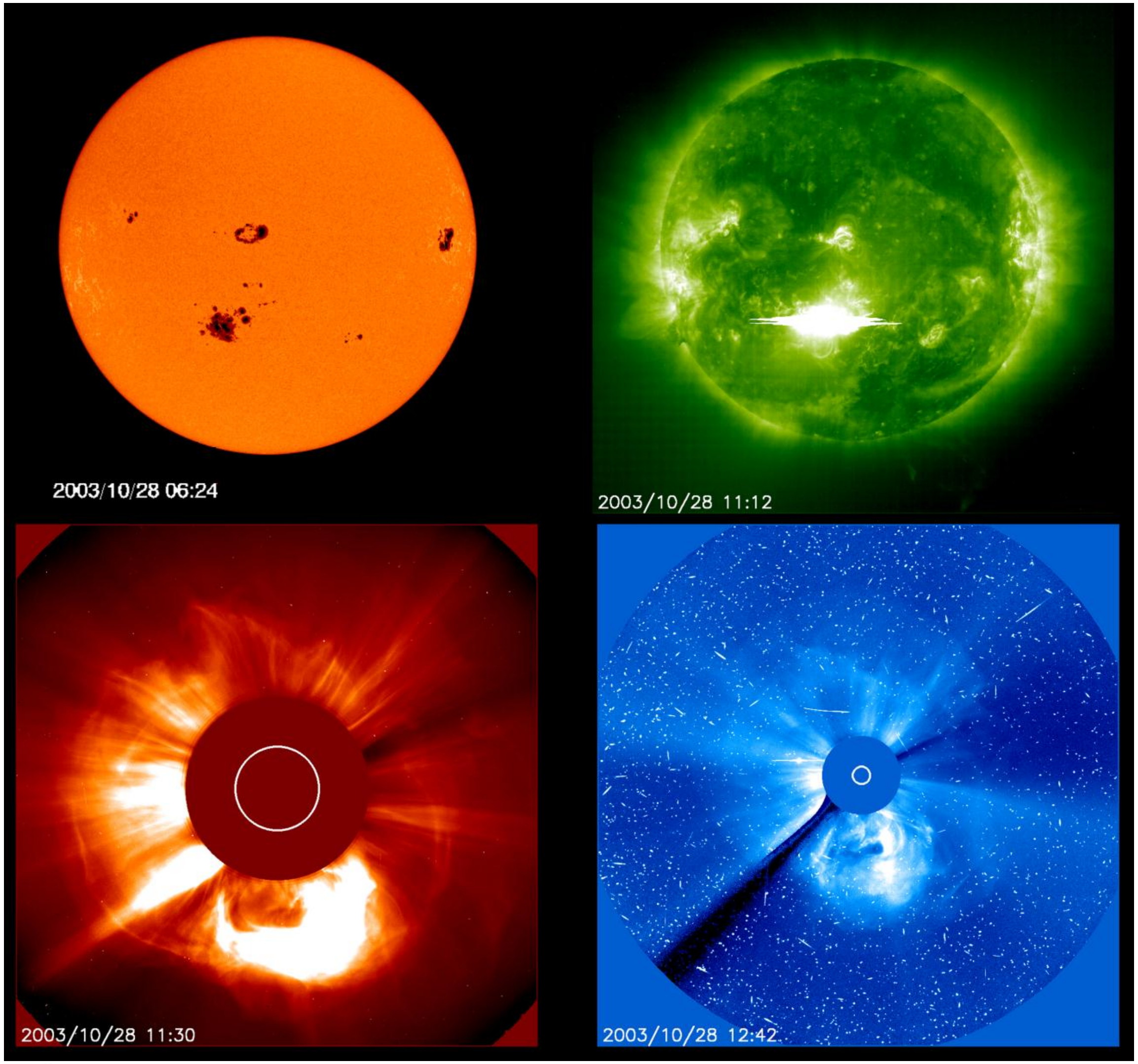
[1]University Göttingen, Institute for Astrophysics, Göttingen, Germany

[2]German Aerospace Center, Institute of Communications and Navigation, Neustrelitz, Germany

Deutsches Zentrum für Luft- und Raumfahrt e.V. in der Helmholtz-Gemeinschaft

Georg-August-Universität Göttingen

Solar Source Region of the Halloween Storms

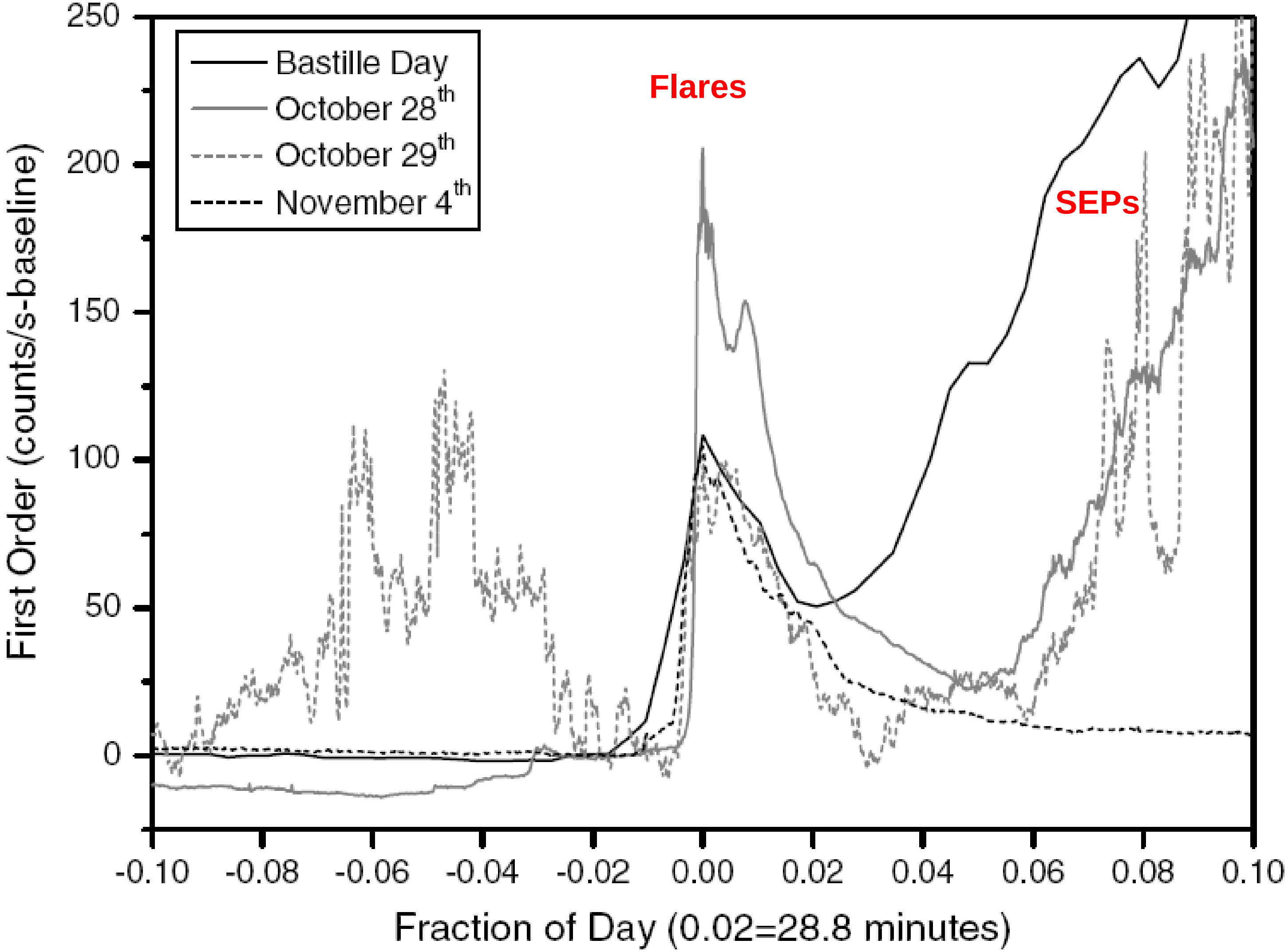


- AR 486 produced several fast CMEs and flares.

Table 2: Top Flares Since 1976

Rank	*Date*	*X-ray*	*Region*
1	**11/04/03**	**X28e**	**486**
2	08/16/89	X20e	5629
3	04/02/01	X20e	9393
4	**10/28/03**	**X17**	**486**
5	07/11/78	X15e	1203
6	03/06/89	X15e	5395
7	04/24/84	X13e	4474
8	10/19/89	X13e	5747
9	06/06/82	X12e	3763
10	06/01/91	X12e	6659
11	12/15/82	X12	4026
12	06/04/91	X12e	6659
13	06/06/91	X12e	6659
14	06/11/91	X12e	6659
15	06/15/91	X12e	6659
16	12/17/82	X10	4025
17	05/20/84	X10	4492
18	01/25/91	X10	6471
19	06/09/91	X10	6659
20	**10/29/03**	**X10**	**486**

SOHO EUV Count Rates

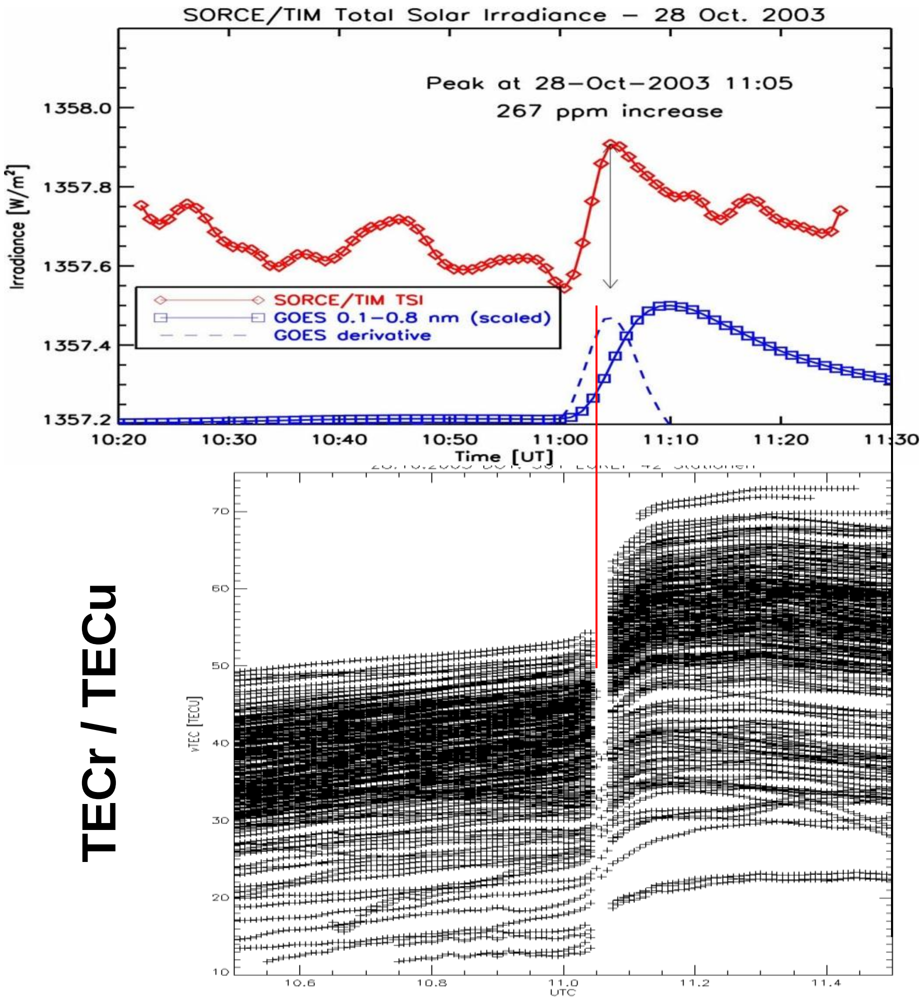


Tsurutani et al. 2006

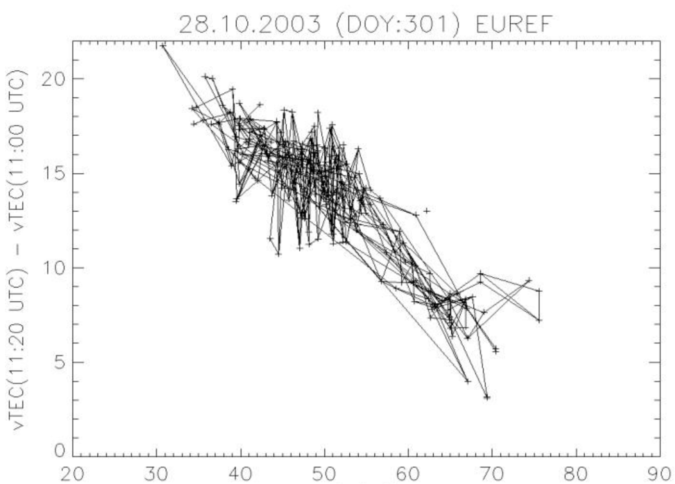
Solar flare induced dTEC on 28 October 2003

- Strong Solar Flare was observed on 28 October 2003 at 11:05 UT
- Total solar irradiation enhances within a few minutes by 267 ppm
- Rapid and strong increase of TEC at all GPS measurements (range error ≤ 3.5 m)
- Number of usable GPS measurements dropped down from 30 to 7

TECr / TECu

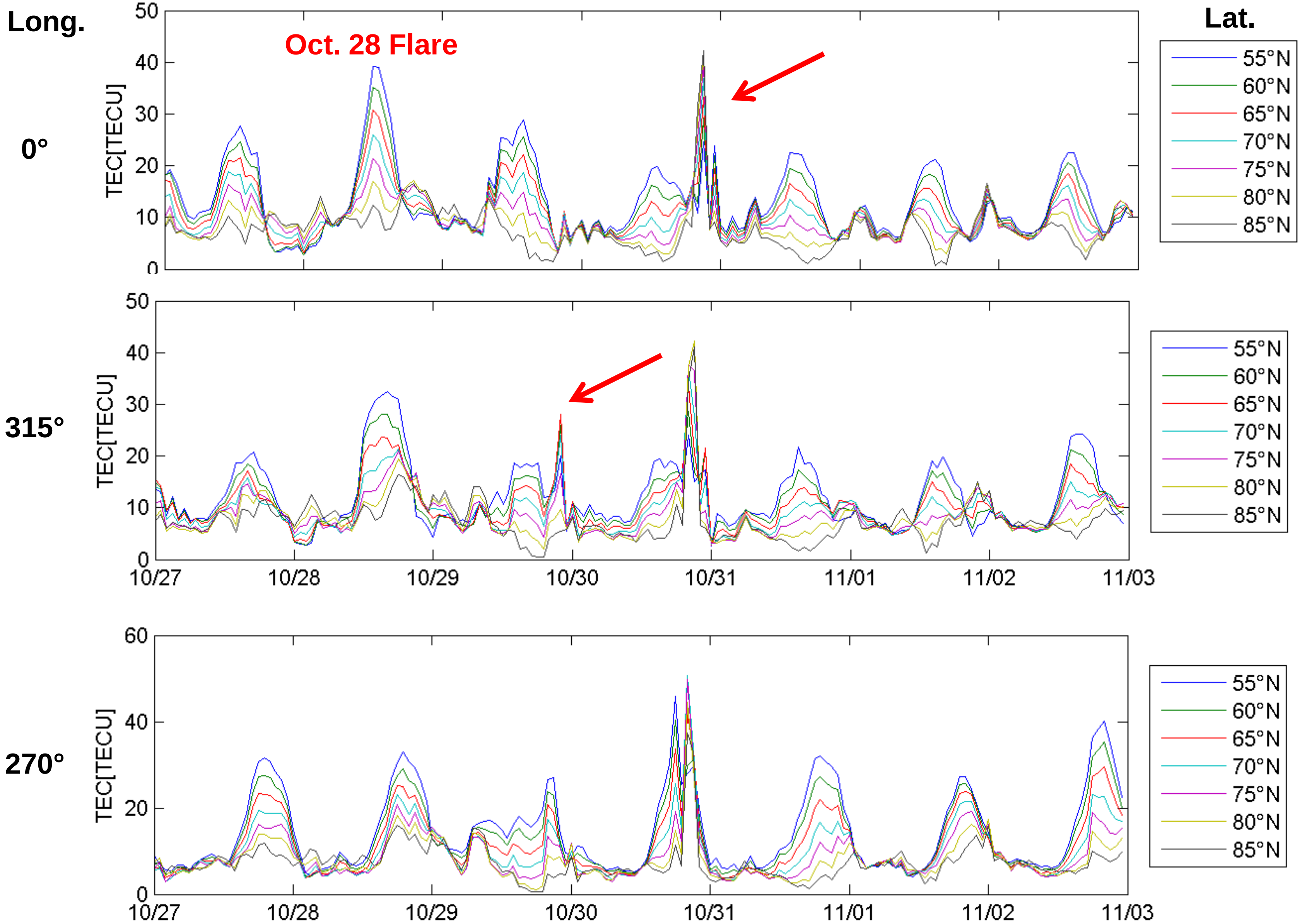


Time UT/ hrs.

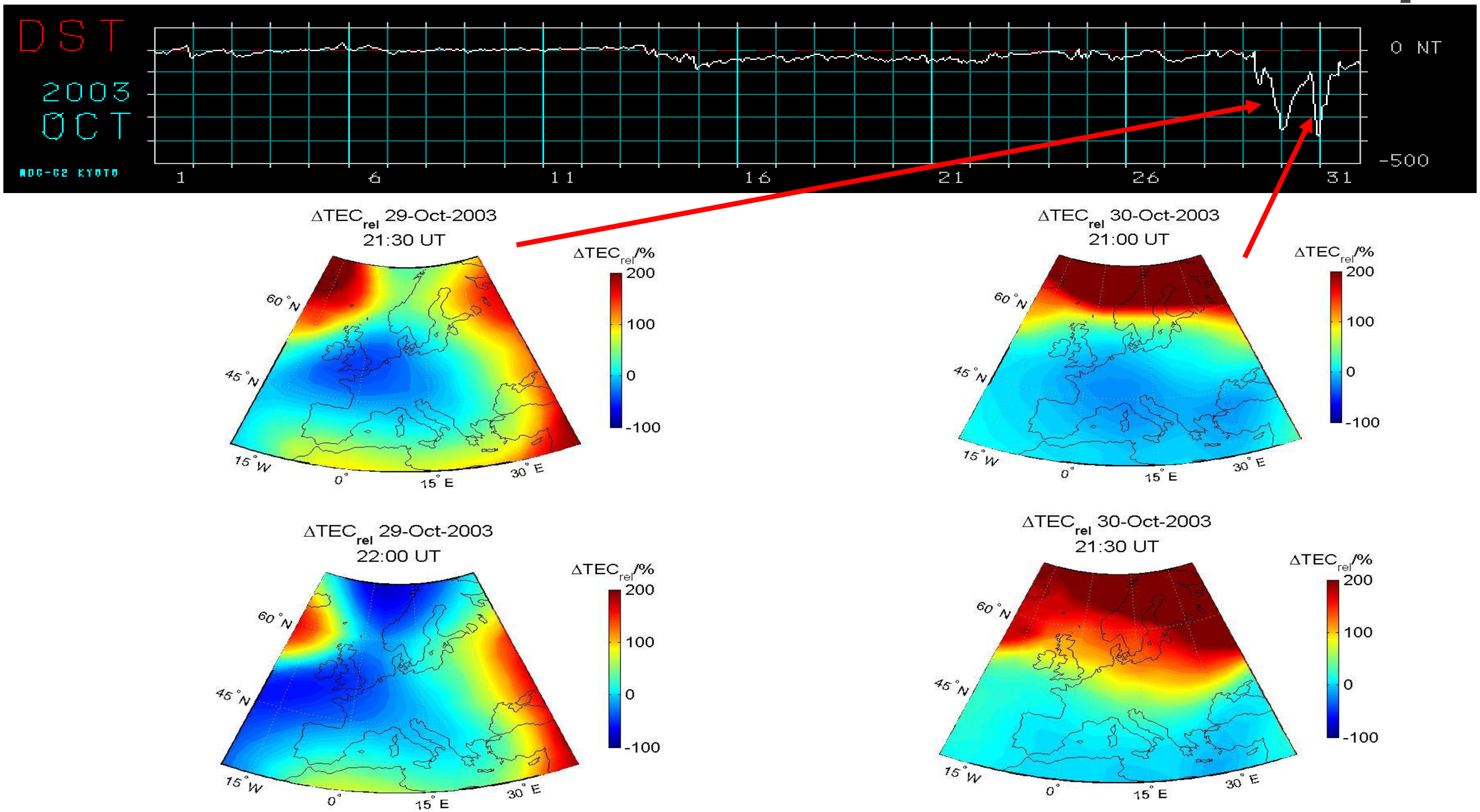


Geographic Latitude / °N

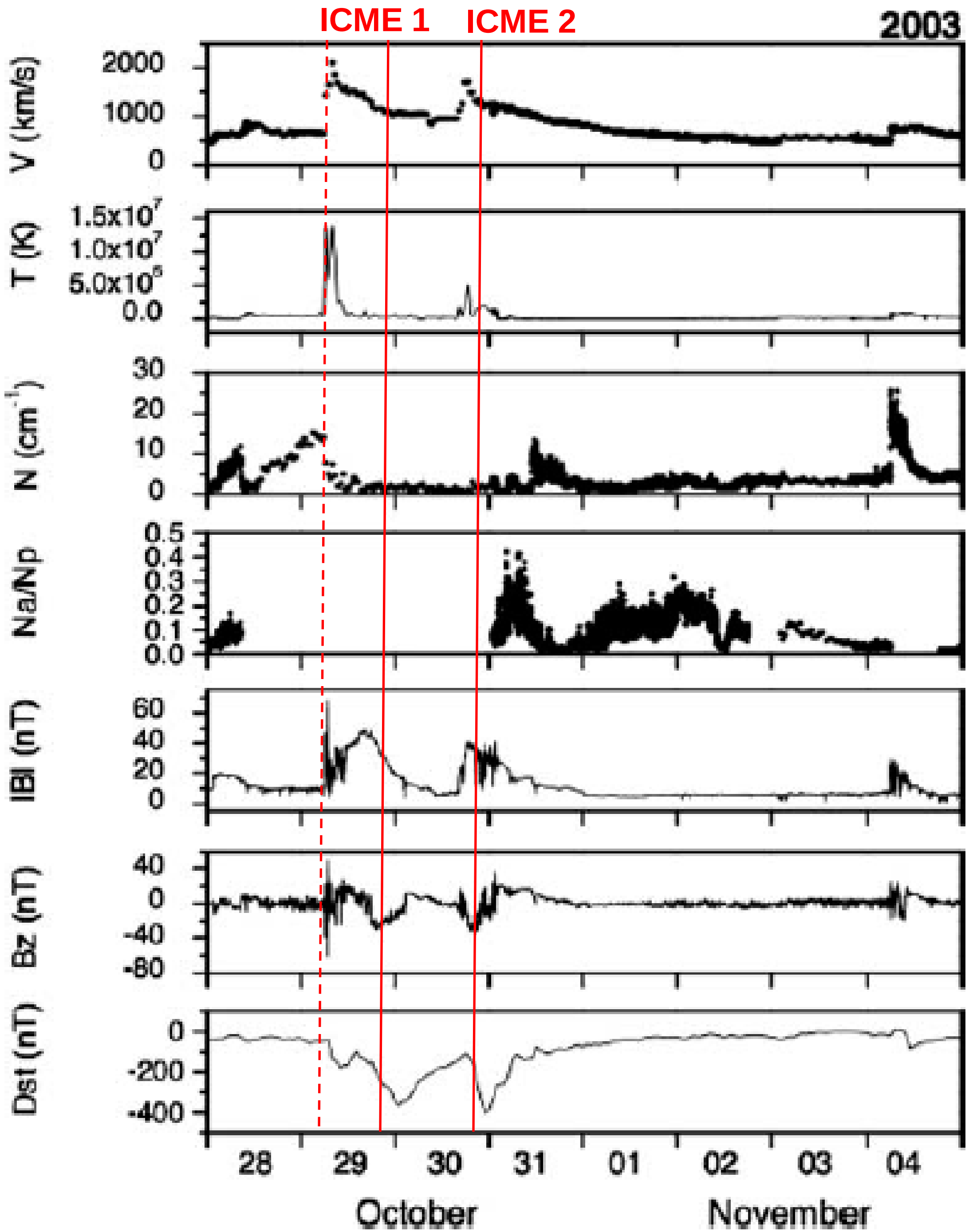
TEC Measurements



Storm on 28 – 31 October 2003 over Europe



- Different perturbation pattern over Europe in the evening hours (21-22 UT)
- Propagation of enhanced density towards lower latitudes on 30 October



Solar Wind and Geomagnetic Response

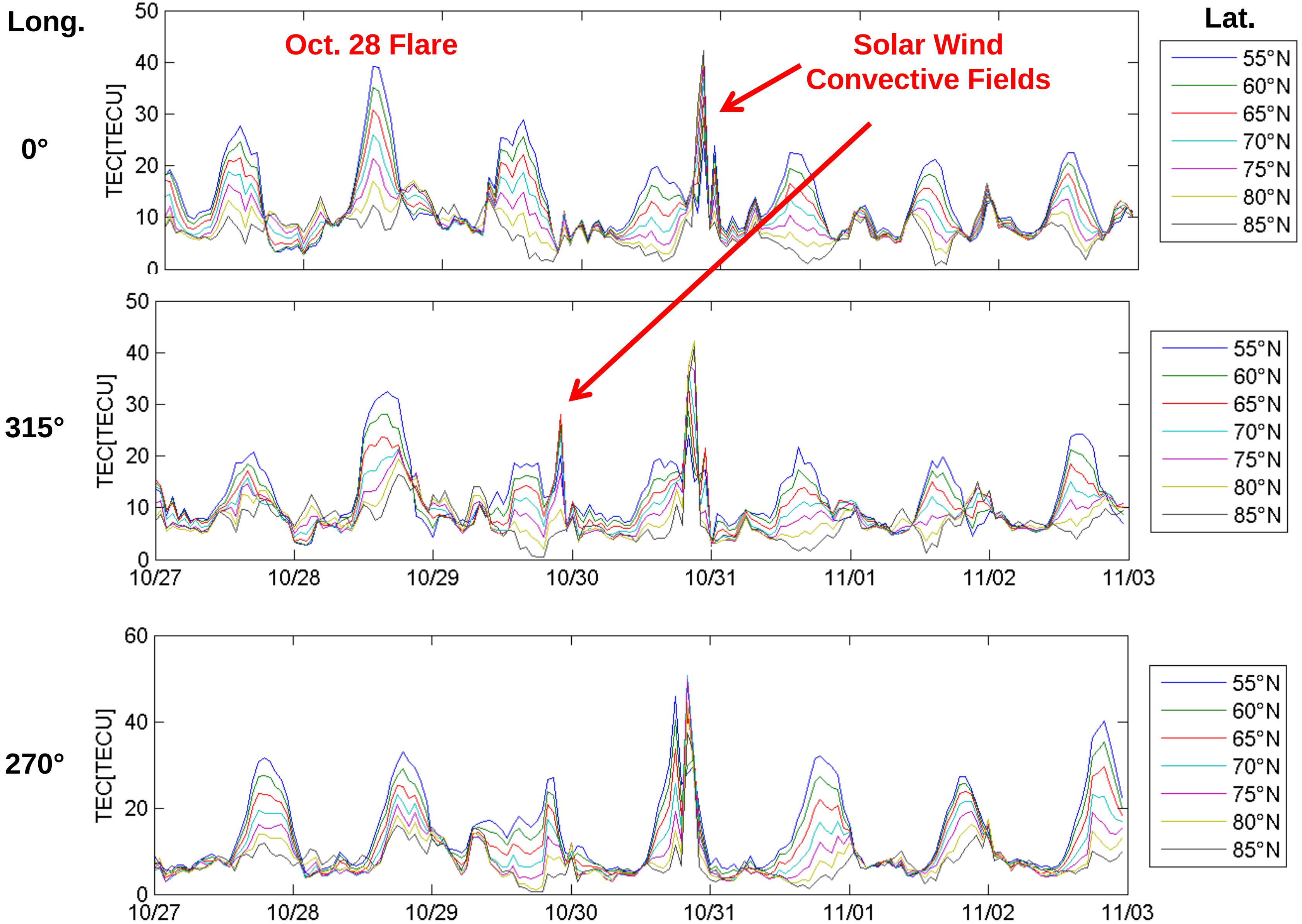
Three important phases:

1. Strong shock driven by ICME 1

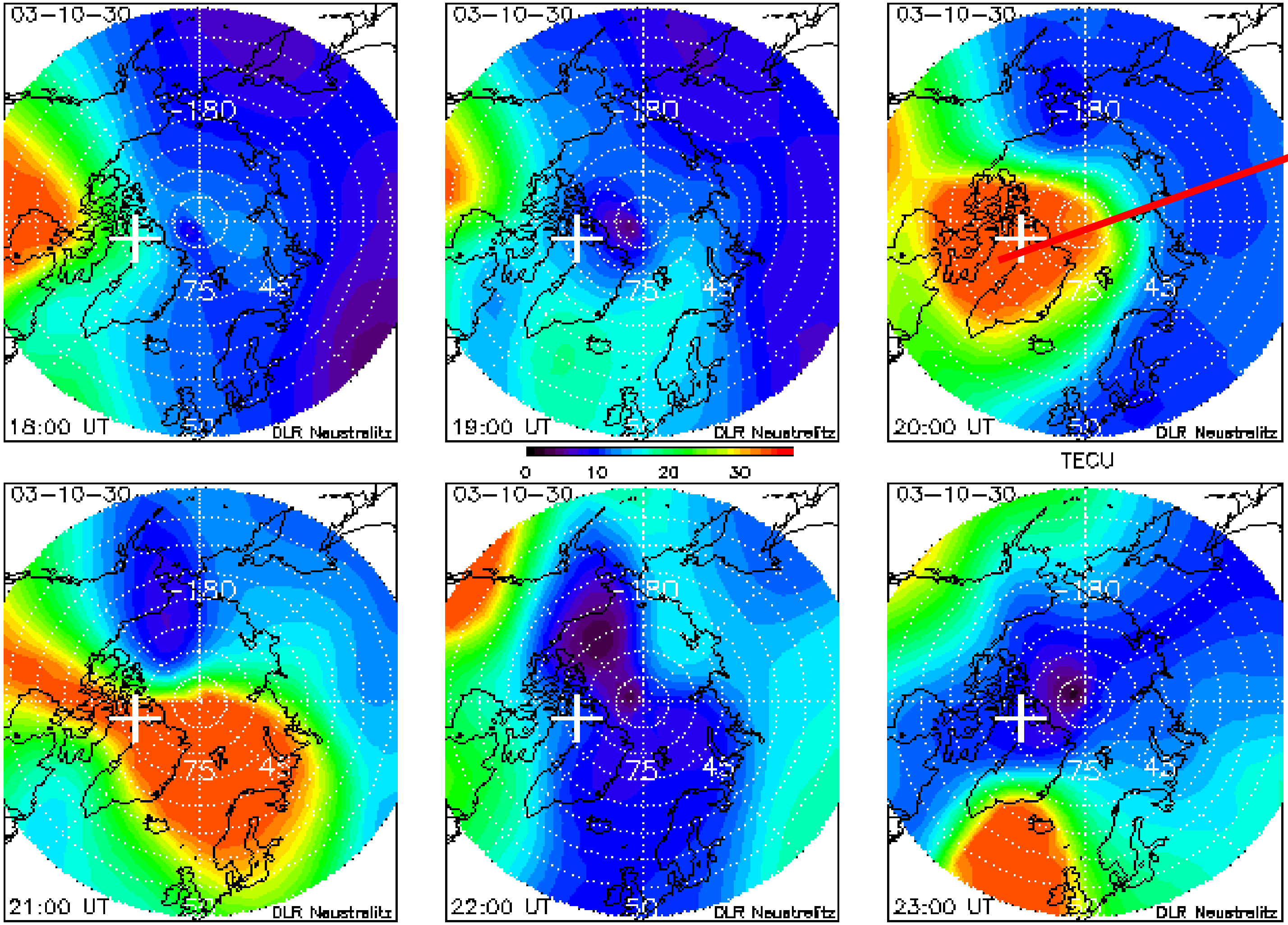
2. -Bz in trailing portion of ICME 1

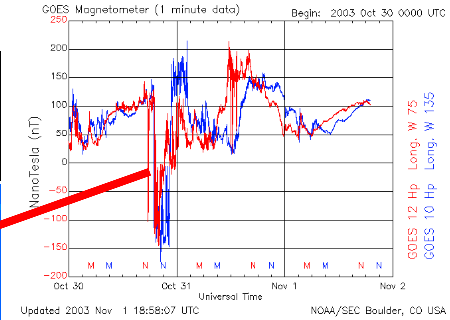
3. -Bz in compressed leading edge of ICME 2

TEC Measurements



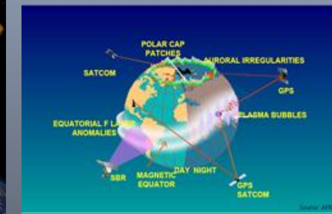
Ionospheric Convection on October 30





IMF / nT

SEVENTH FRAMEWORK PROGRAMME



AFFECTS

Advanced Forecast For Ensuring Communications Through Space

Project Overview

v.120511

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

IKД

Fraunhofer IPM

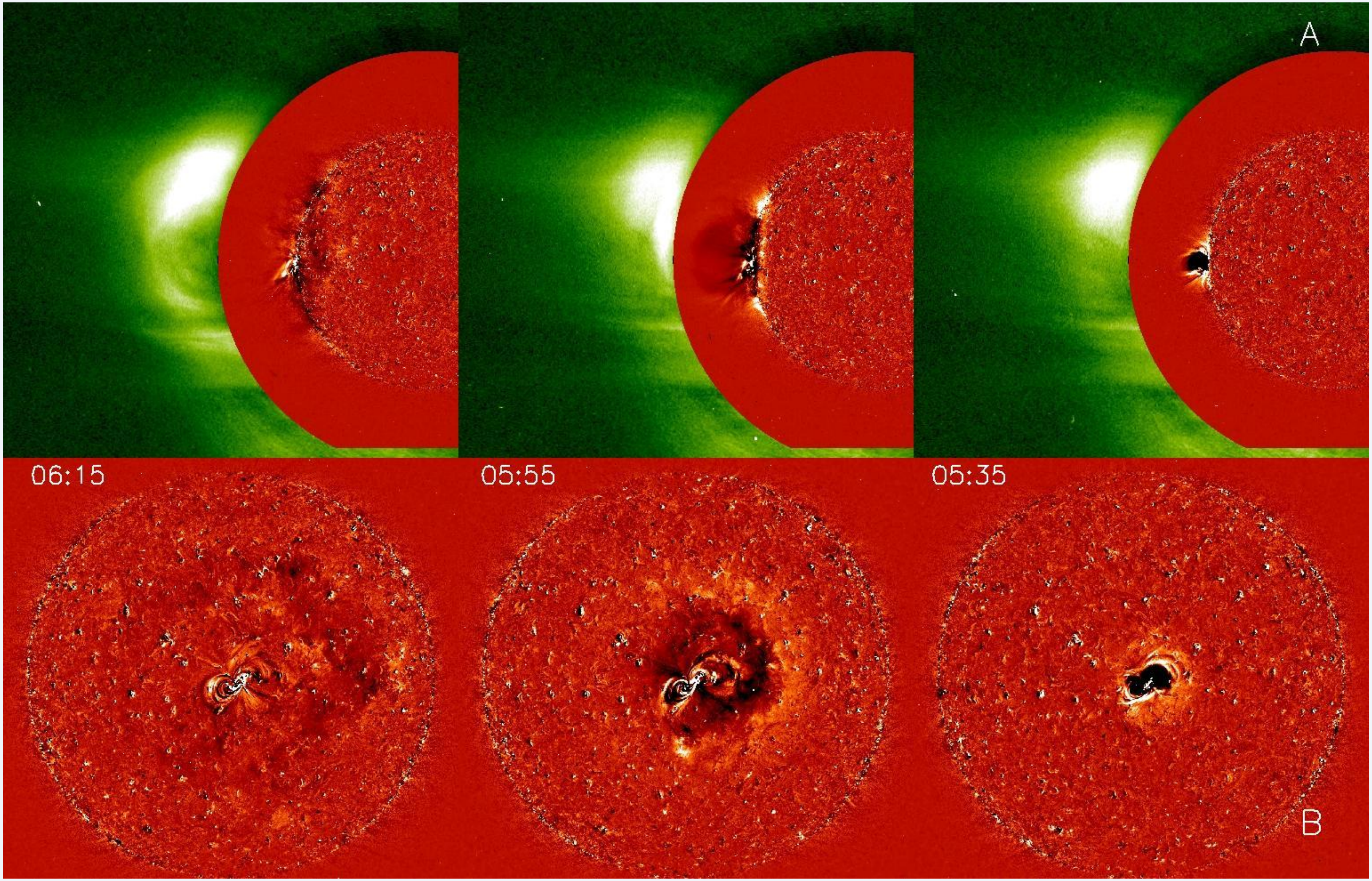
UNIVERSITETET I TROMSØ

DLR

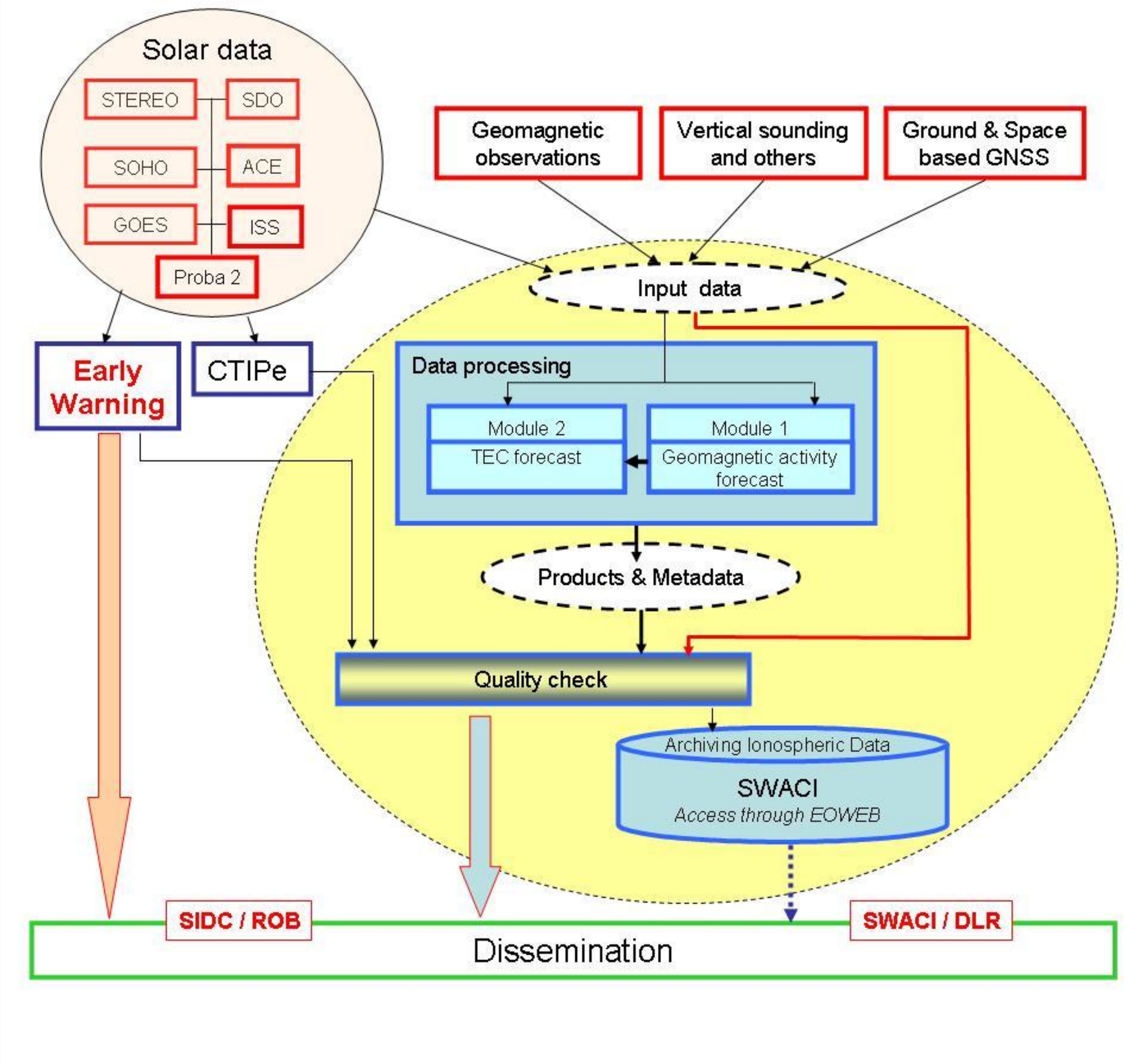
EADS astrium

NOAA

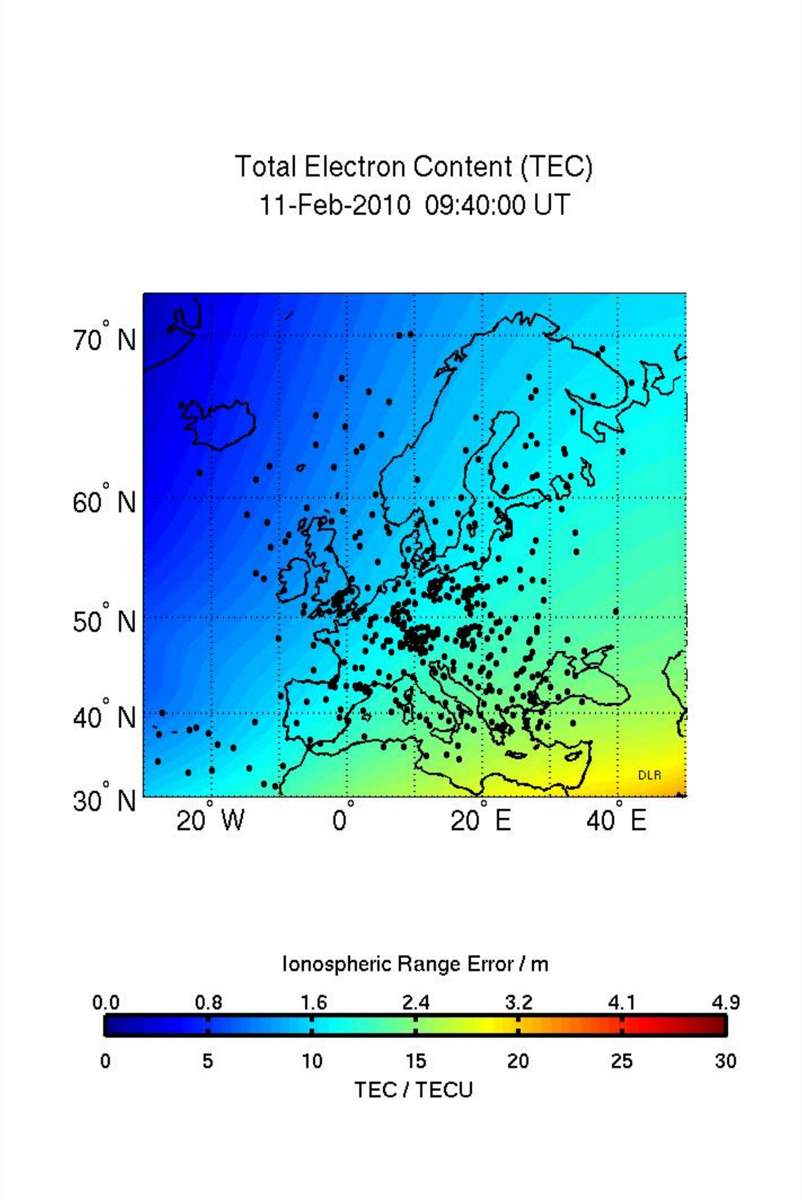
AFFECTS – Early Warnings



AFFECTS – Workflow

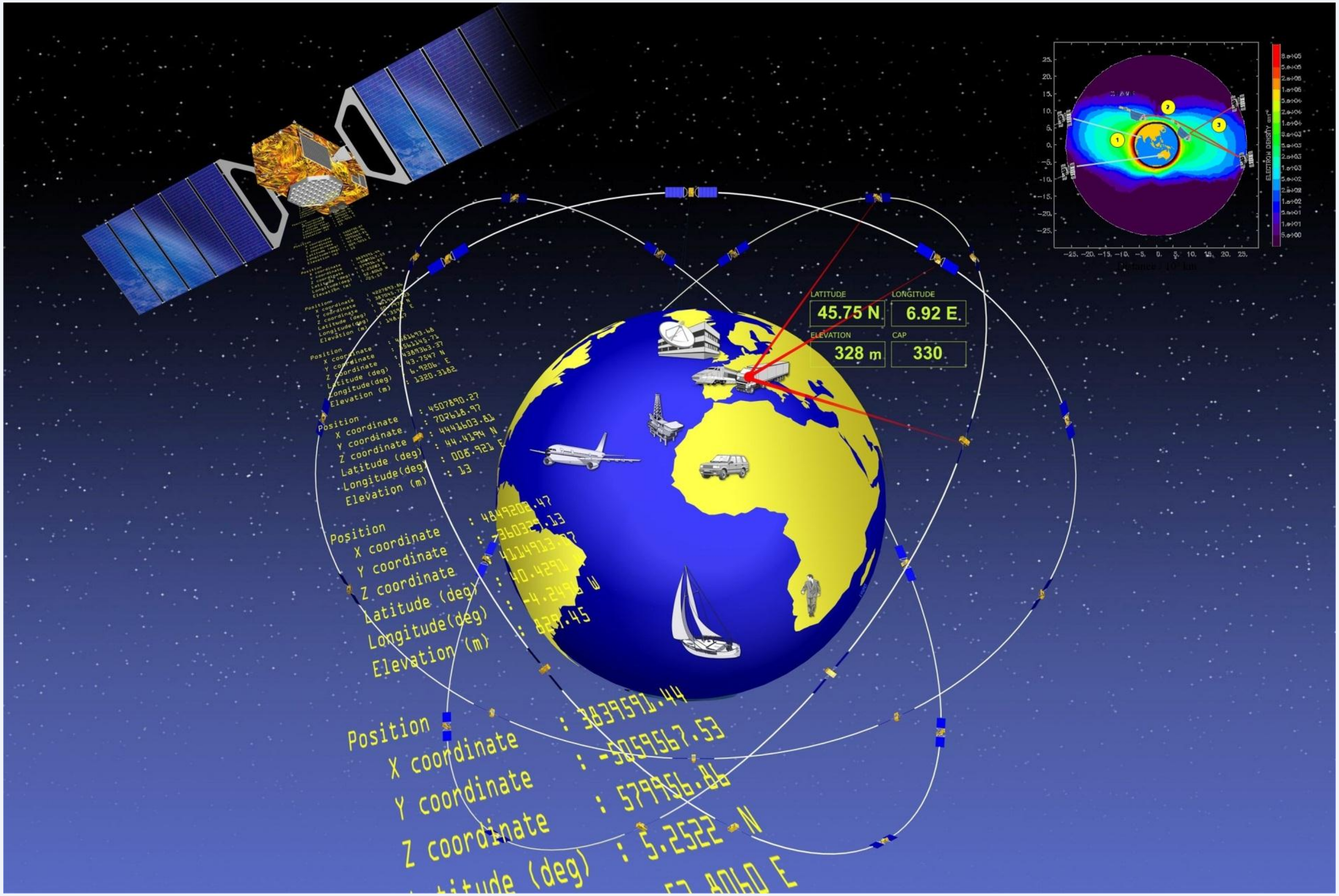


TEC - Maps


Total Electron Content (TEC)
11-Feb-2010 09:40:00 UT
70° N
60° N
50° N
40° N
30° N
20° W
0°
20° E
40° E
DLR
Ionospheric Range Error / m
0.0
0.8
1.6
2.4
3.2
4.1
4.9
0
5
10
15
20
25
30
TEC / TECU

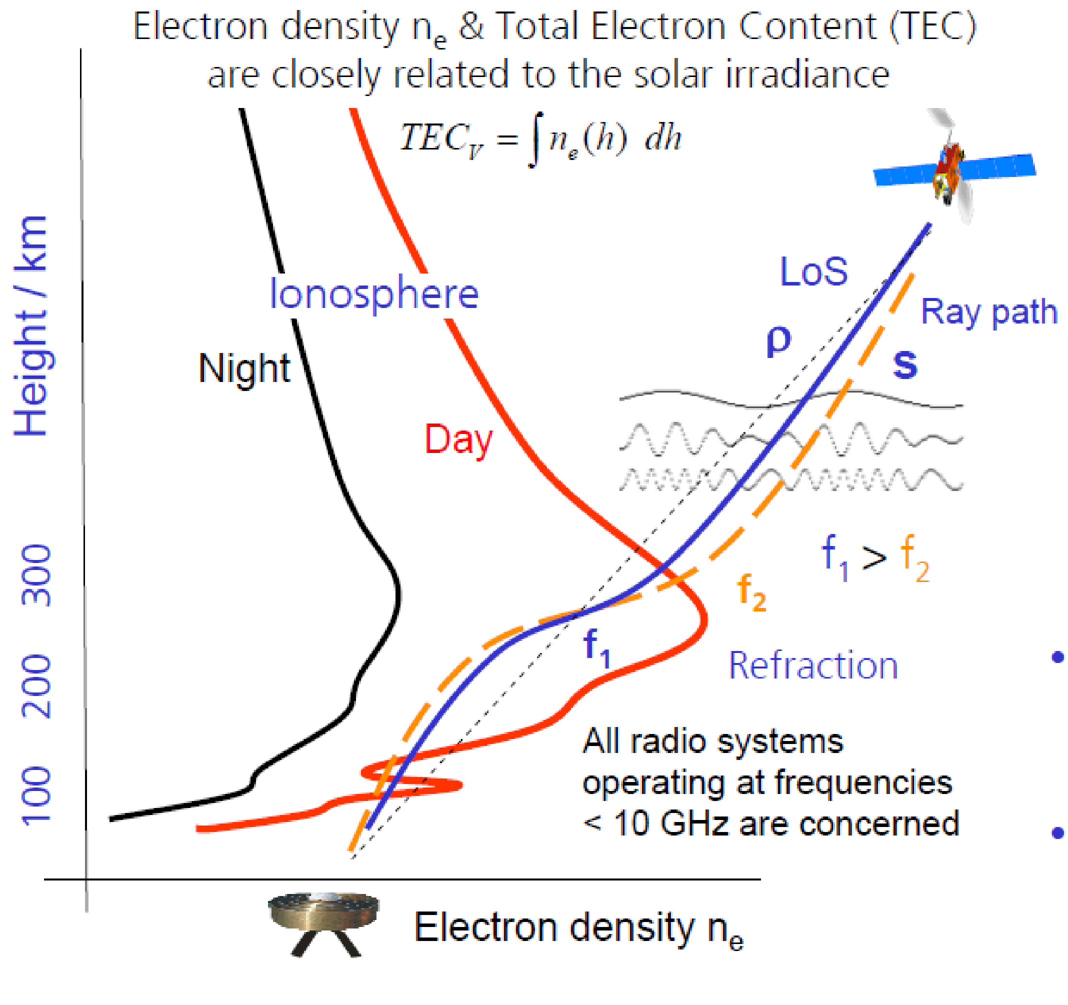
AFFECTS – Logo

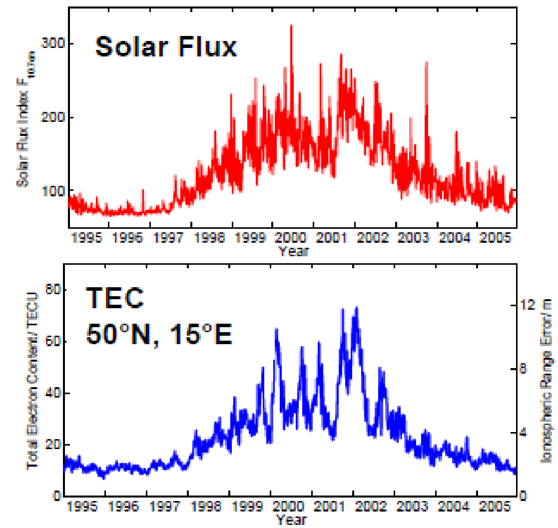
Disturbance of Telecommunication Signals



Erhöhung des ionosphärischen TEC durch solare EUV-Strahlung. Quelle: DLR, N. Jakowski

Radio wave propagation in the ionosphere



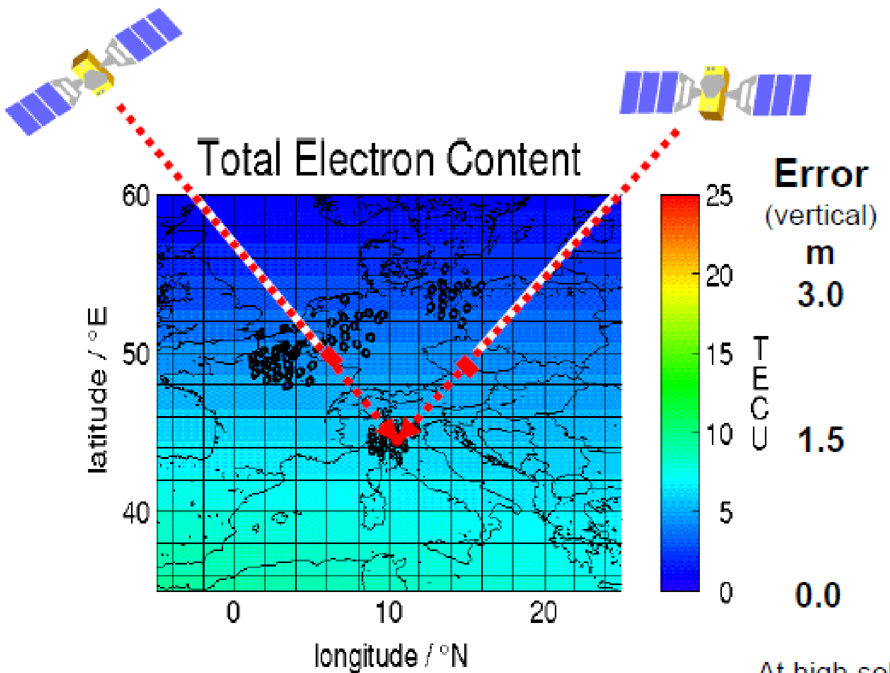


Ionosphere causes

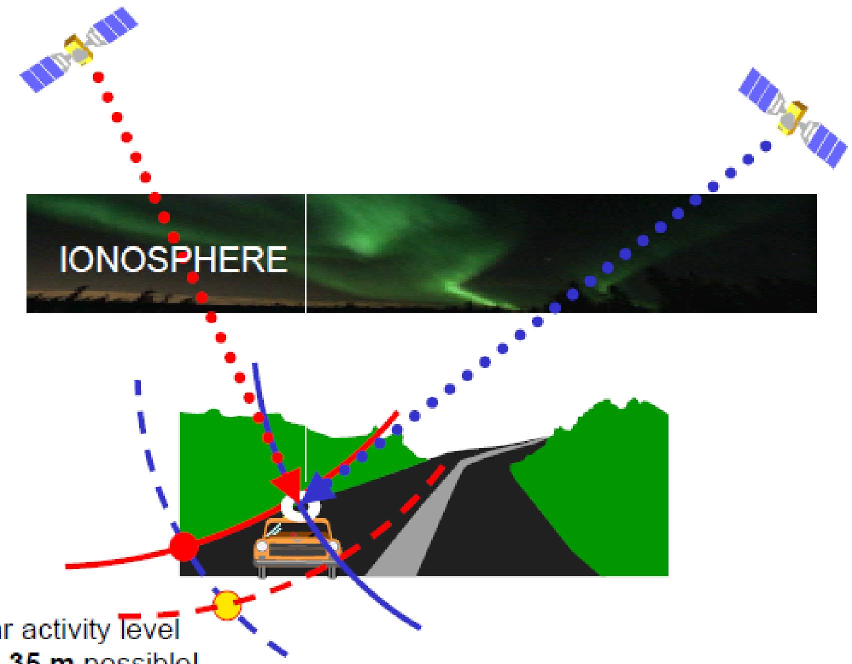
- Regular effects due to the presence of plasma
  - signal delay
  - rotation of polarisation
- Irregular effects due to plasma distortions, turbulences
  - misinterpretation of data due to horizontal gradients (HMI)
  - Radio scintillations

Störung von Telekommunikations-und Navigationssytemen. Quelle: DLR, N. Jakowski

TEC – monitoring - Navigation errors



Sample:16 GPS stations Time: 01:04:00 UT



At high solar activity level errors up to **35 m** possible!

$d_I^{(1)} = \frac{K}{f^2}\int n_e ds = \frac{K}{f^2}\cdot TEC$ Ionospheric first order range errror d_I is proportional to TEC

- GNSS*-Data obtained from geodetic networks for TEC Monitoring in streaming mode (IGS, EUREF)
- Empirical modelling of the ionosphere (in DLR: Europe, polar regions, global)
- Near real time monitoring possible

*GNSS- Global Navigation Satellite System

Propagation of EM-Waves in Ionosphere and GPS errors

$$n^2 = 1 - \frac{{\omega_P}^2}{\omega^2}$$

$$\omega_P = \sqrt{\frac{N_e e^2}{\varepsilon_0 m_e}}$$

$$TEC = \int_P N_e ds$$

Typical TEC Values are:

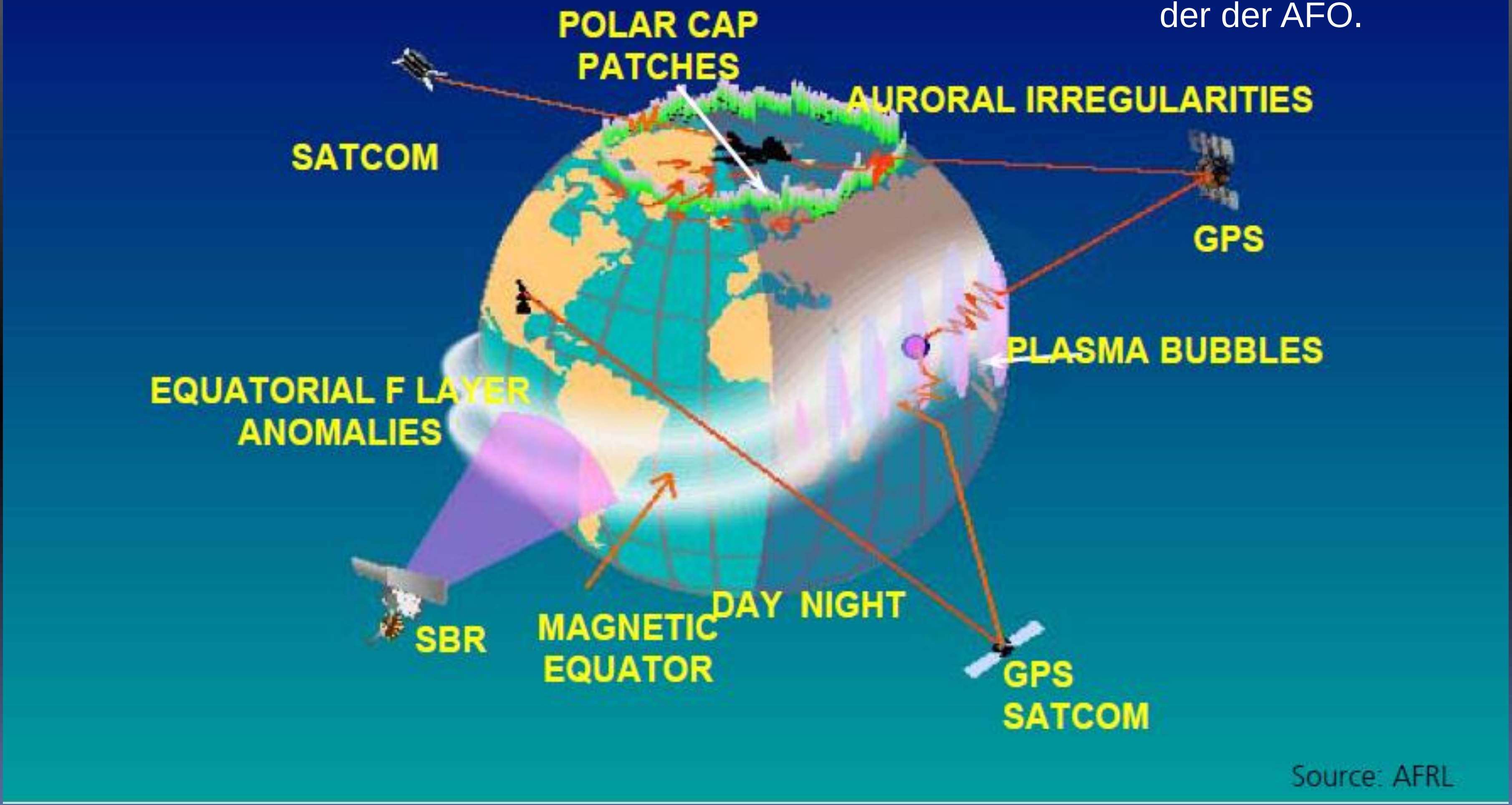
50-60 TECU (TEC-units of 10^{16} electrons/cm^2)

D(mm) = 2.16 TEC (in TECU)

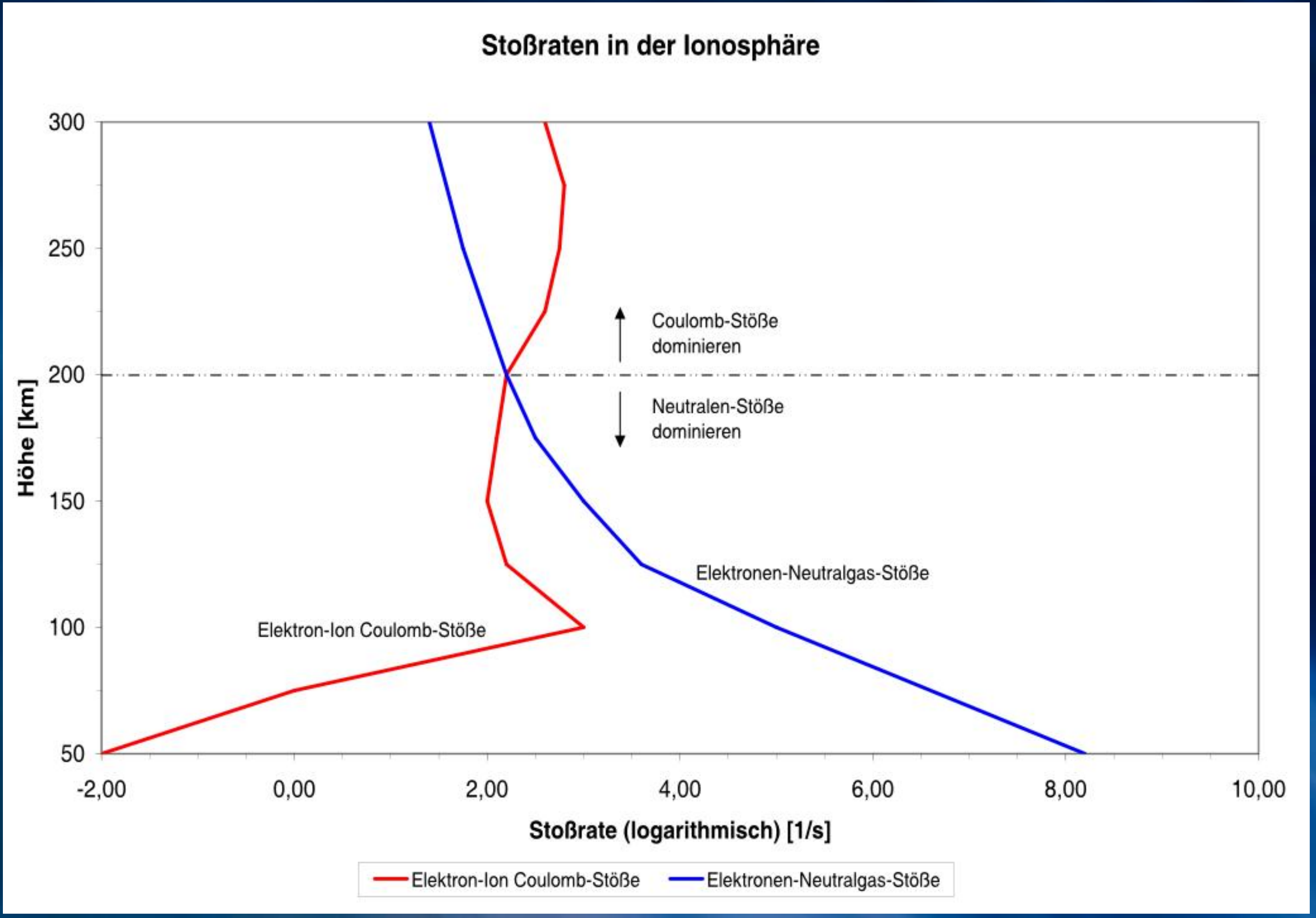
Errors up to 100 m possible

Störung von Telekommunikations-und Navigationssytemen. Quelle: DLR, N. Jakowski

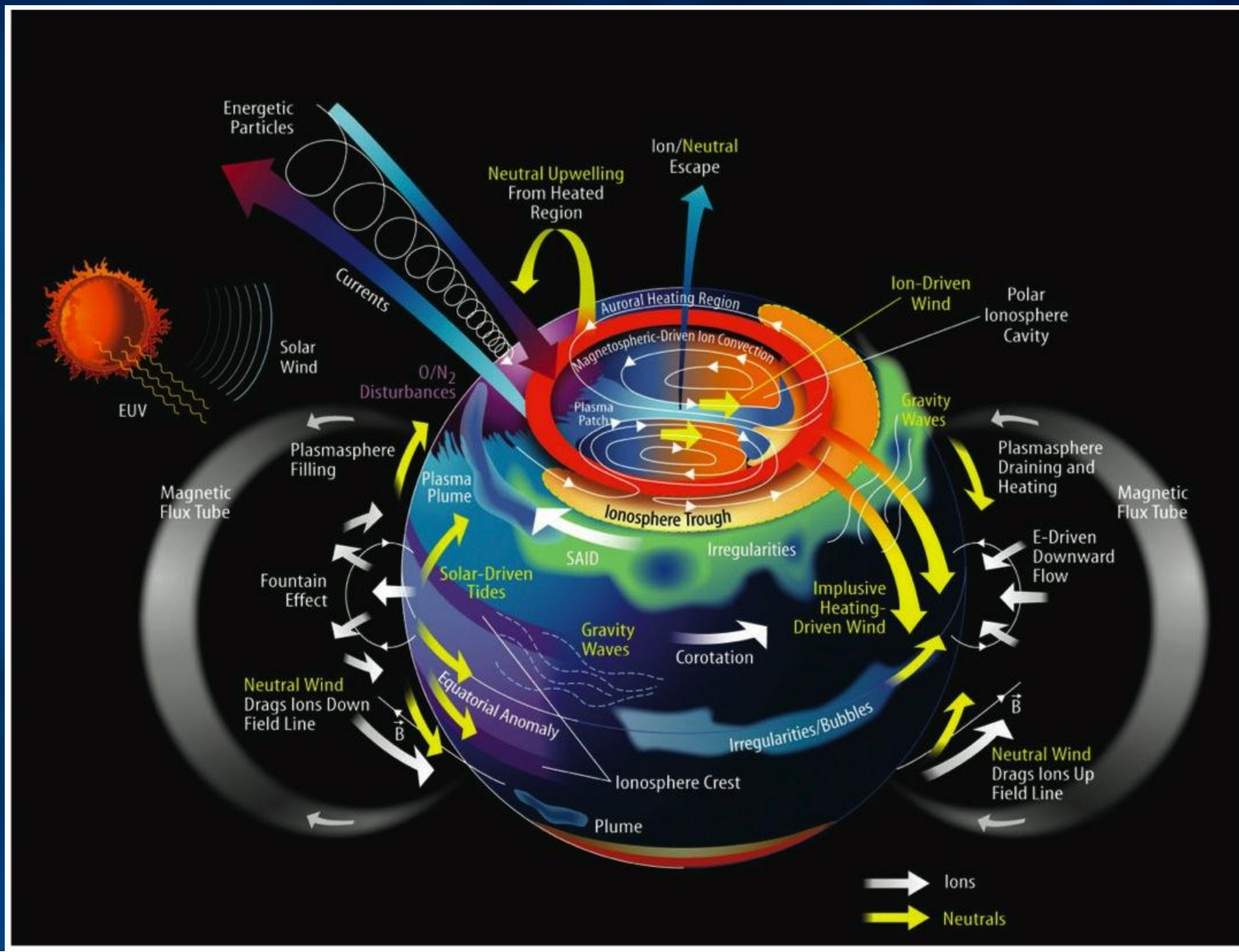
Auch Störung/Ausfall der HF-Kommunikation mit Flugzeugen: s. z.B. Berichte der der AFO.



Magnetosphärische Stromsysteme



Stoßraten in der Ionosphäre
300
250
200
150
100
50
Höhe [km]
-2,00
0,00
2,00
4,00
6,00
8,00
10,00
Stoßrate (logarithmisch) [1/s]
Coulomb-Stöße dominieren
Neutralen-Stöße dominieren
Elektronen-Neutralgas-Stöße
Elektron-Ion Coulomb-Stöße
Elektron-Ion Coulomb-Stöße
Elektronen-Neutralgas-Stöße



Energetic Particles
Ion/Neutral Escape
Neutral Upwelling From Heated Region
Currents
Solar Wind
EUV
O/N_2 Disturbances
Auroral Heating Region
Magnetospheric-Driven Ion Convection
Plasma Patch
Ion-Driven Wind
Polar Ionosphere Cavity
Gravity Waves
Plasmasphere Filling
Plasma Plume
Magnetic Flux Tube
Ionosphere Trough
Plasmasphere Draining and Heating
Magnetic Flux Tube
SAID
Irregularities
E-Driven Downward Flow
Fountain Effect
Solar-Driven Tides
Implusive Heating-Driven Wind
Gravity Waves
Corotation
Neutral Wind Drags Ions Down Field Line
Equatorial Anomaly
Irregularities/Bubbles
Neutral Wind Drags Ions Up Field Line
Ionosphere Crest
Plume
Ions
Neutrals