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Radio Occultation Sounding in Ionosphere and Space Weather Applications: Achievements and Prospects

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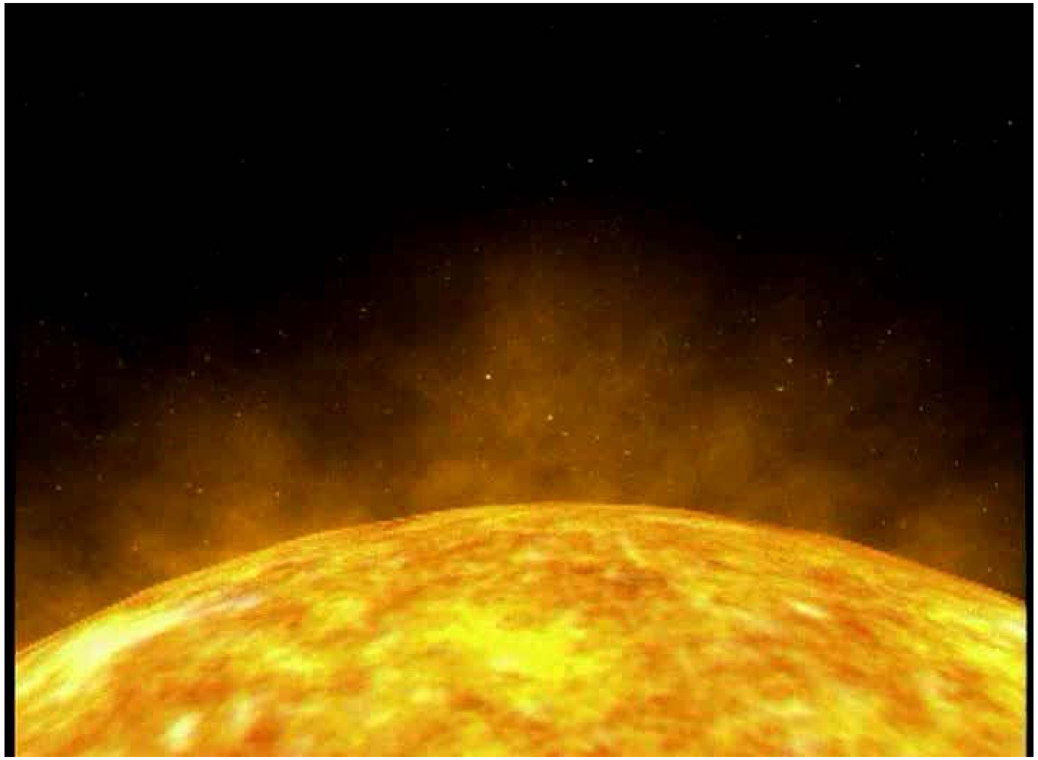
Outline

1. Space Weather
2. Ionospheric RO soundings
3. How did it all start?
4. Achievements
5. Prospects for tomorrow

Space weather

``...conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health"



Ionospheric RO soundings

- RO receiver gives an estimate of the integrated total electron content along the ray path

$$STEC = \int_{Tx}^{Rx} n_e dl$$

- A STEC estimate can be calculated from a least squares fit of

$$STEC_{\varphi} = \frac{1}{d} \frac{f_{L1}^2 f_{L2}^2}{\left(f_{L1}^2 - f_{L2}^2\right)} \left(\varphi_{L1} - \varphi_{L2}\right) + B$$

to

$$STEC_{CP} = \frac{1}{d} \frac{f_{L1}^2 f_{L2}^2}{\left(f_{L1}^2 - f_{L2}^2\right)} \left(P_{L1} - P_{L2}\right)$$

How did it all start…

- Before 1995
  - RO used to study atmospheres and ionospheres of other planets already in the 60's

    => RO technique was rather well known, but not exploited due to lack of infrastructure

    => RO soundings of Earth atmosphere tested from Salyut-7 space station
  - Development of GPS produced the signal source

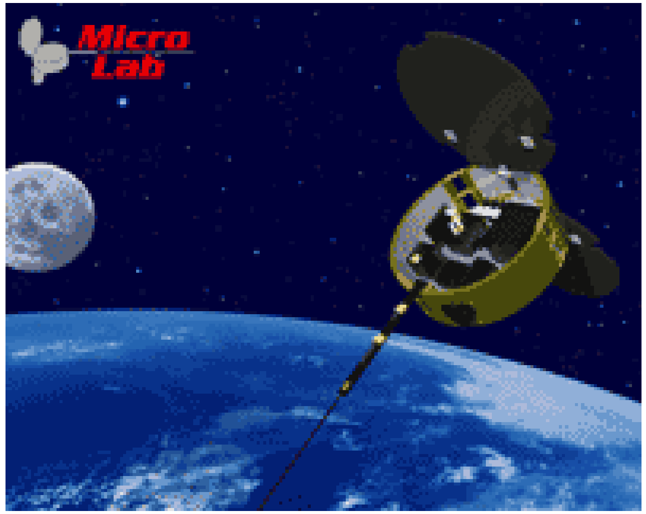
    => first proposal for neutral atmosphere sounding [Lindal, 1988] and ionosphere tomography [Austen et al, 1988] by groups in JPL

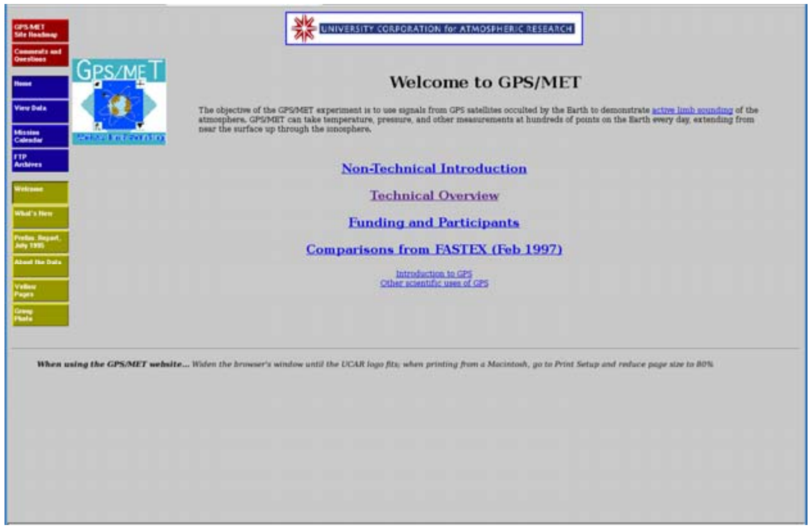
GPS/MET

- The first proof-of-concept mission managed by UCAR (Ware et al., 1995)
- MicroLab 1 satellite launched on April 3, 1995
- Soundings with a space upgraded TurboRogue receiver (Meehan et al., 1992)
- Date freely available to the users

  => huge success for RO community

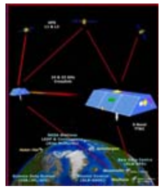
  => more than 90 papers and reports
- Dedicated ionospheric sounding campaigns (e.g. Oct 1996, Jan 1997)
- Data still available via CDAAC

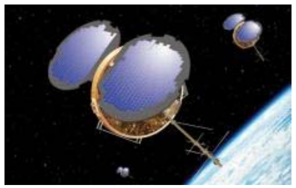




Post-GPS/MET RO missions

- 1999: SUNSAT, Ørsted
- 2000: CHAMP, SAC-C
- 2001: PICOSat (IOX)
- 2002: GRACE
- 2006: COSMIC, Metop-A (GRAS)
- Data archives for most missions:
  - GENESIS
  - CDAAC
- GRAS data has to be accessed from EUMETSAT





Achievements:

- Development of RO science for Earth observations
- Implementation of RO missions (more or less independently)

  => continuation for 10 years

  => continually improving coverage (especially COSMIC)

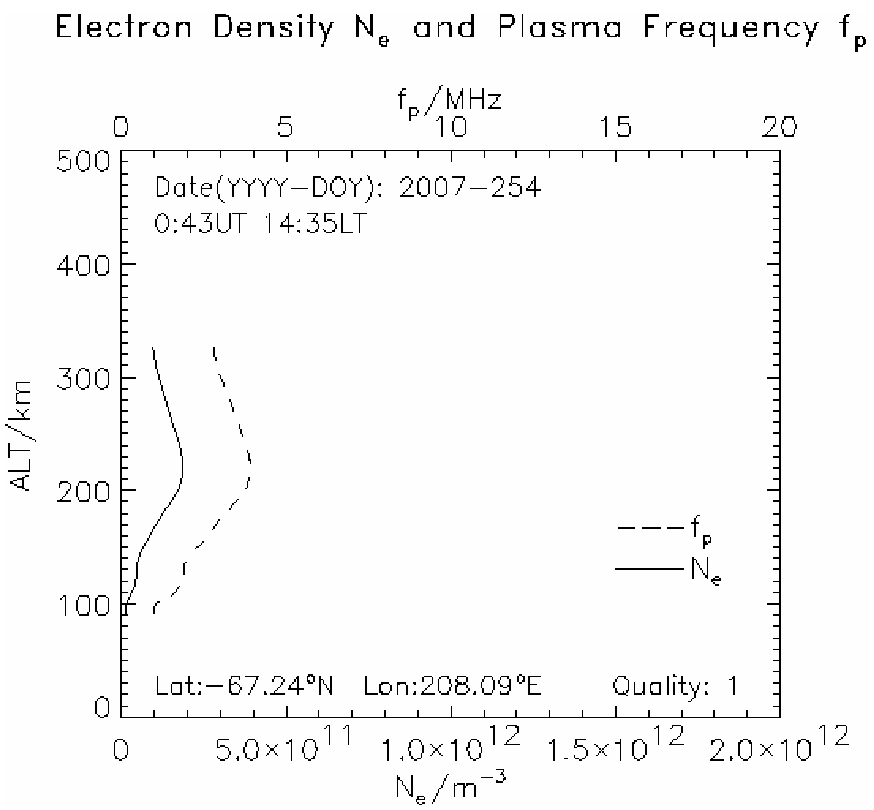
  => RO ionospheric soundings are filling holes in ground based and in-situ observations
- Very open data policy for most missions!!

  => rapid scientific progress

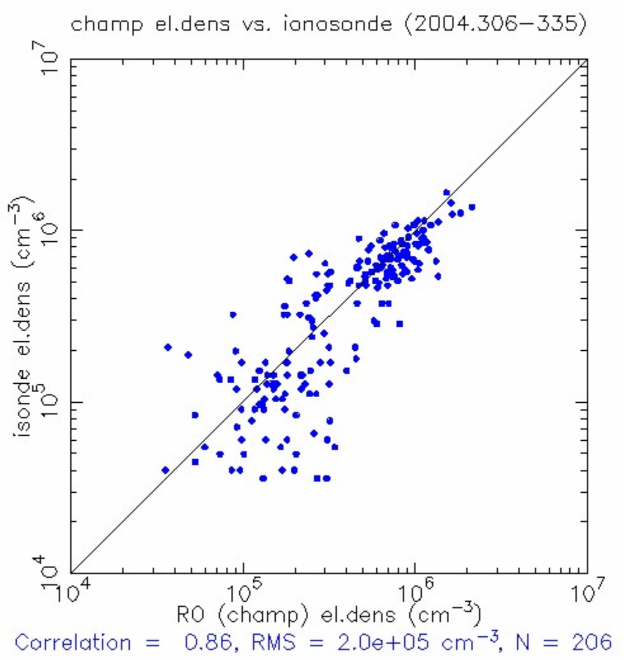
  => identification of new issues

  => generation of new ideas

Scientific achievements: Global TEC soundings



SWACI, DLR



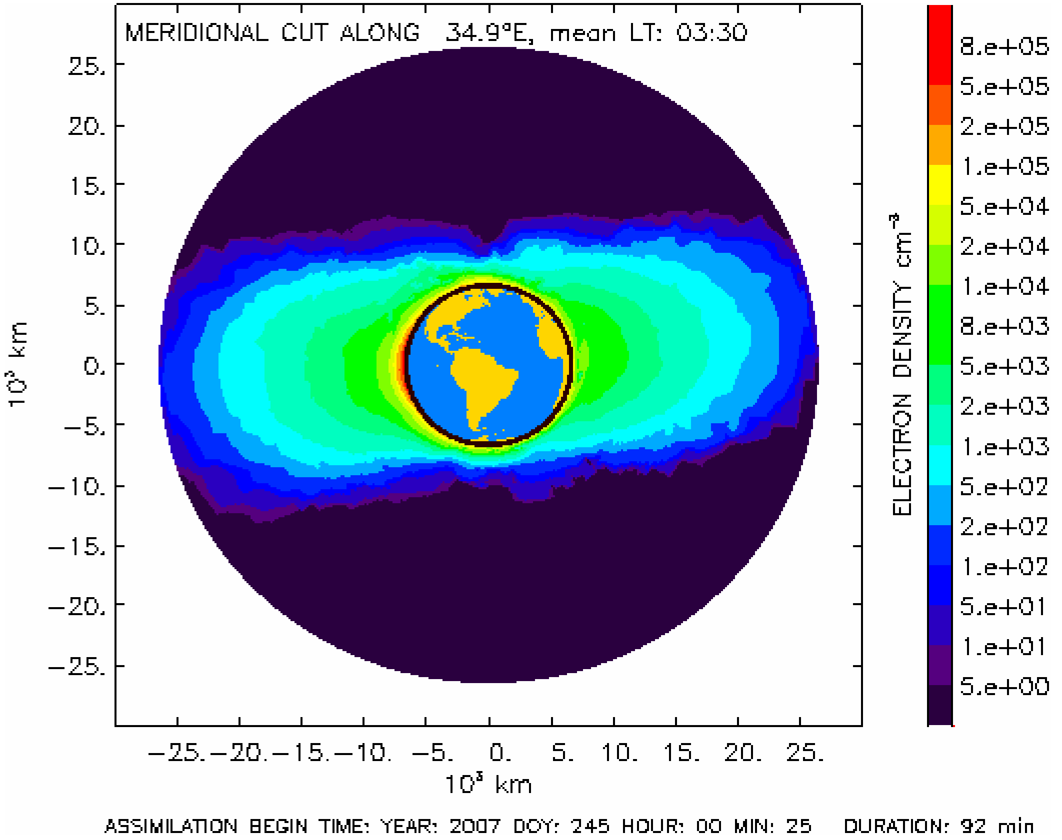
CDAAC

More scientific achievements

New ideas to squeeze new products from RO:

- Detection of sporadic E-layer
- Improved TEC climatology
  - GIM (Global Ionosphere Map)
  - Improved IRI
  - NeQuick enhancements
- Global STECs => improved model validation at different height levels
- Ionospheric tomography

Global ionospheric tomography

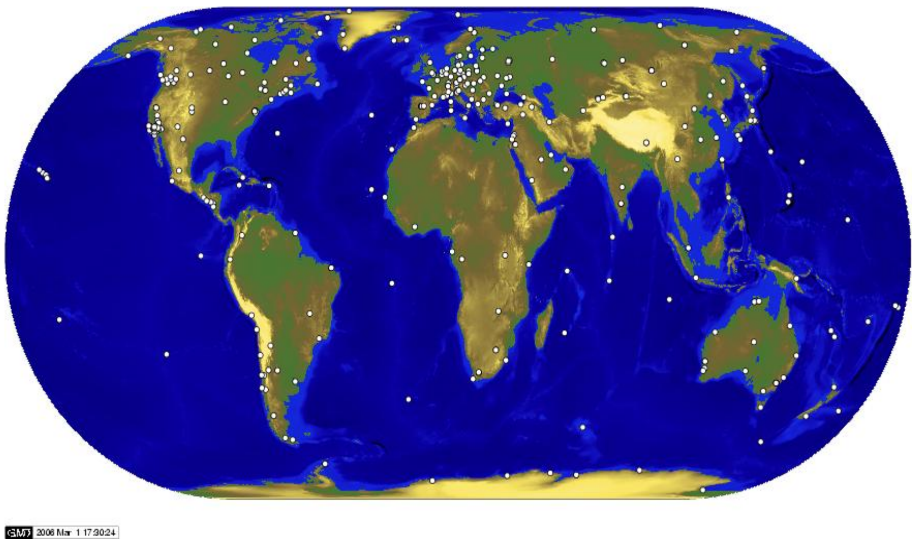


SWACI, DLR

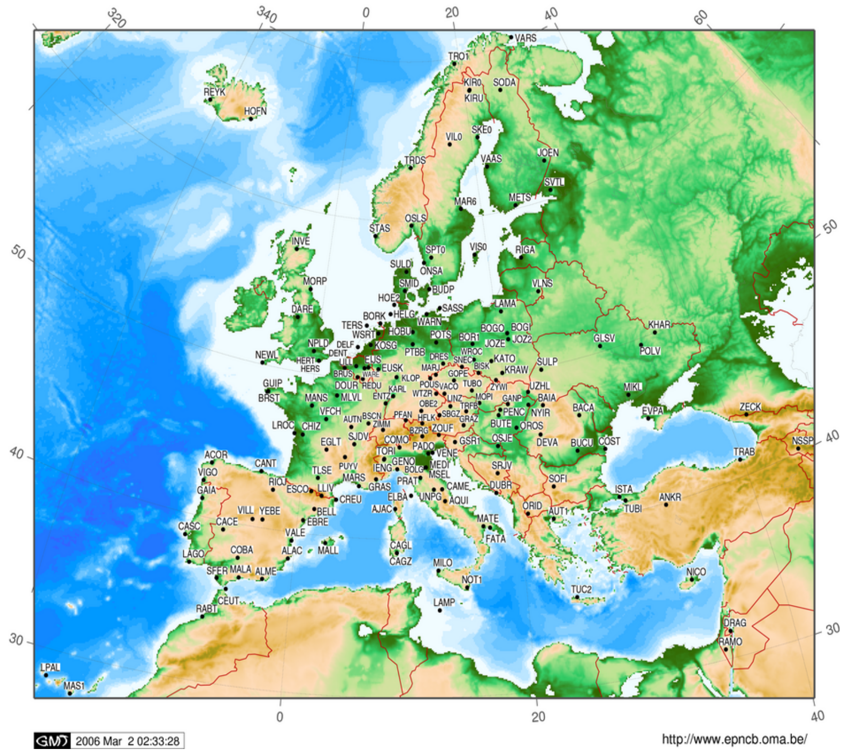
Space weather services and activities

- US
  - SEC (Space Environment Center)
  - University of Michigan
  - NOAA
- Europe:
  - ESA Space Weather Server
  - SWENET: DIFS GIFINT GPS Validation Ionosfera Scintillation Quickmaps SFC SIDC SOARS SPECTRE STIF SWIPPA TSRS
  - SWACI (continuation from SWIPPA pilot project)
  - European Space Weather Portal
  - COST actions: 724, 296

Ground based GNSS networks

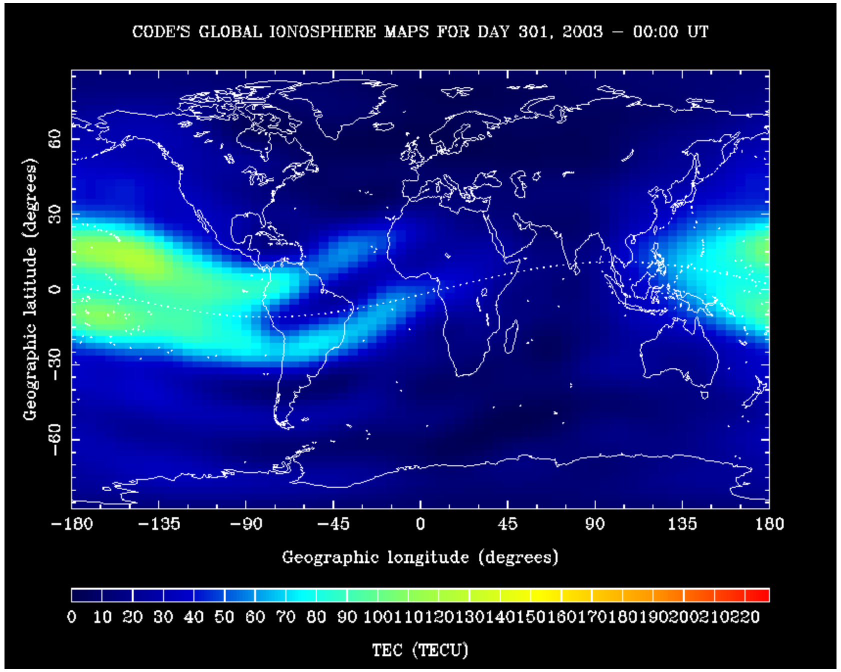


IGS

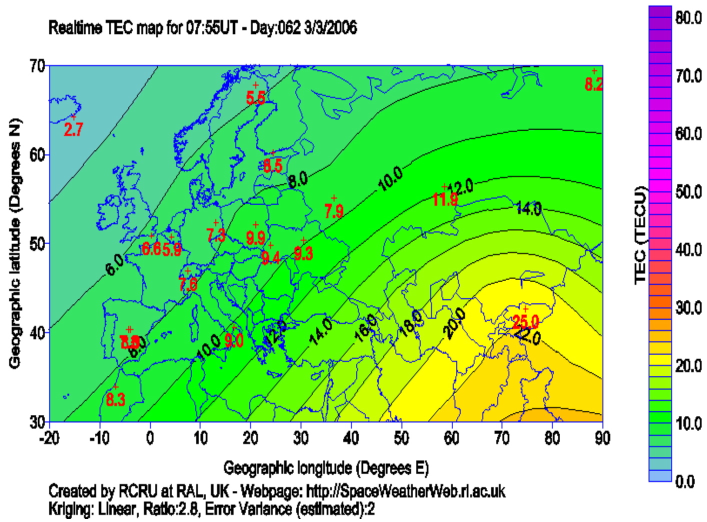


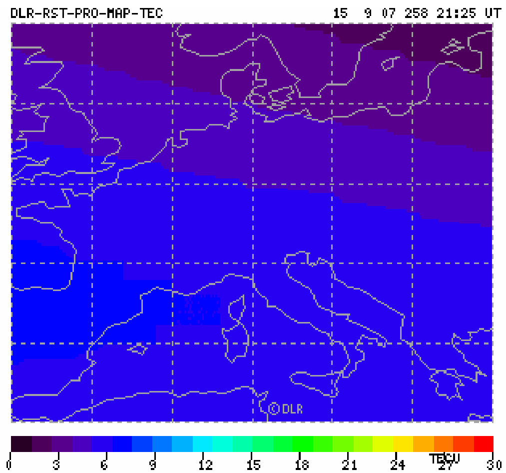
EUREF

GNSS space weather products: 2D maps



University of Bern





SWACI, DLR

Prospects: GNSS of tomorrow

- GPS (US) modernization: 2 new civilian frequencies, larger constellation
- GLONASS (RUS) becoming fully operational
- GALILEO (EU) deployment
- COMPASS (China) deployment

$\Rightarrow$ More than 100 GNSS satellites

$\Rightarrow$ Three carrier frequencies

$\Rightarrow$ Compatibility requirements for RO receiver design

$\Rightarrow$ Data management challenges (archiving, access, data policy)

Prospects: Coming RO missions

- RO becoming “routine” tool for NWP and climate monitoring

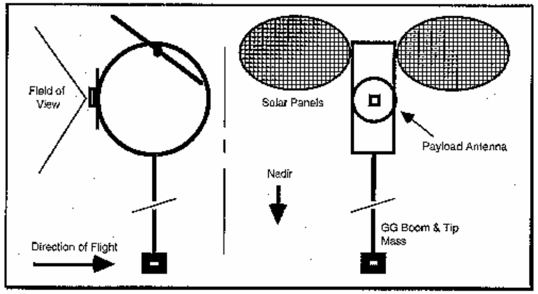
  => continuity of meteorological RO missions reasonably safe

  => more LEO satellites or constellations - uncertain

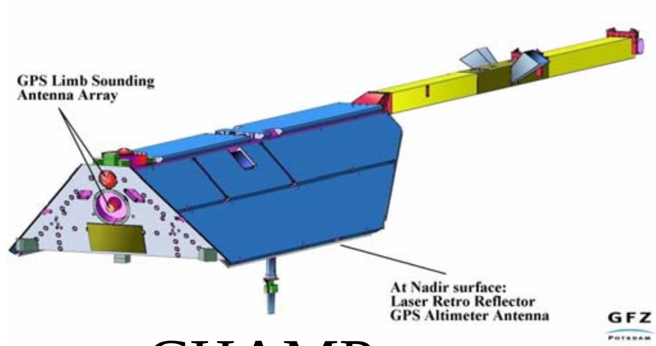
  => space weather/ionosphere community needs to act to ensure inclusion of requirements to RO mission specifications (e.g. Post-EPS)

- Future missions with RO payload: ROSA, GOCE, KOMPSAT-5, Post-EPS,…
- Potential next generation missions: ATOMMS-ACCURATE, CICERO, COSMIC-2, CHAMP-2, …
- Meteorological RO is already operational, ionospheric soundings will most likely follow the same path

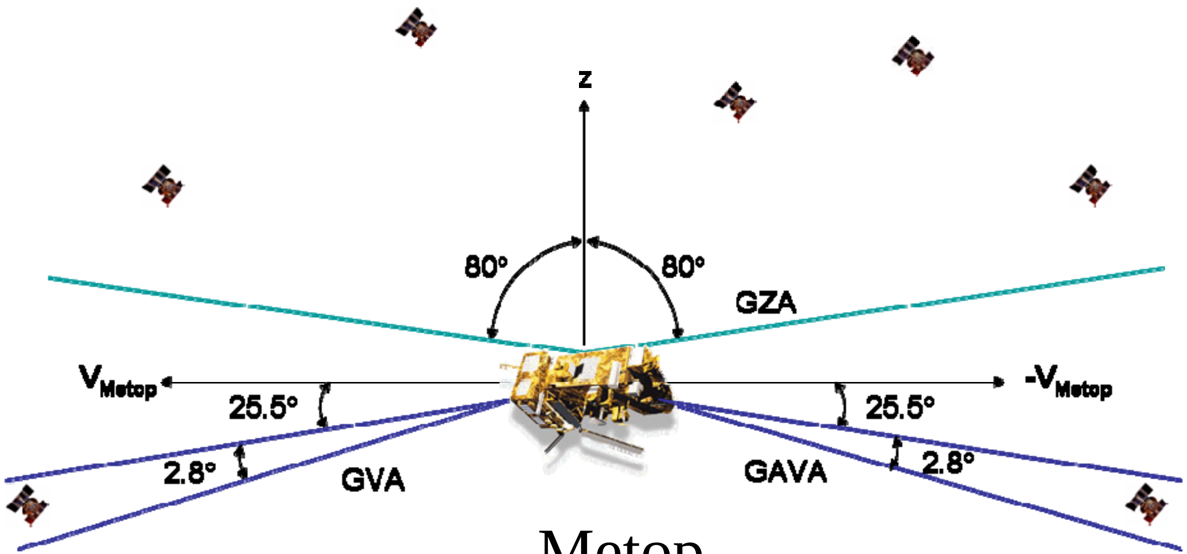
The issue of RO sounding FOVs



GPS/MET



CHAMP



Metop

Prospects: Scientific challenges

- Scintillation monitoring
- Polar regions
- Physical based model development => data assimilation
- Collaboration with traditional space weather community
- Space weather nowcasting and forecasting
- Onboard data processing algorithms

Prospects: Other challenges

- Programmatic challenges
  - Continuity of observations
  - Development of operational/commercial services

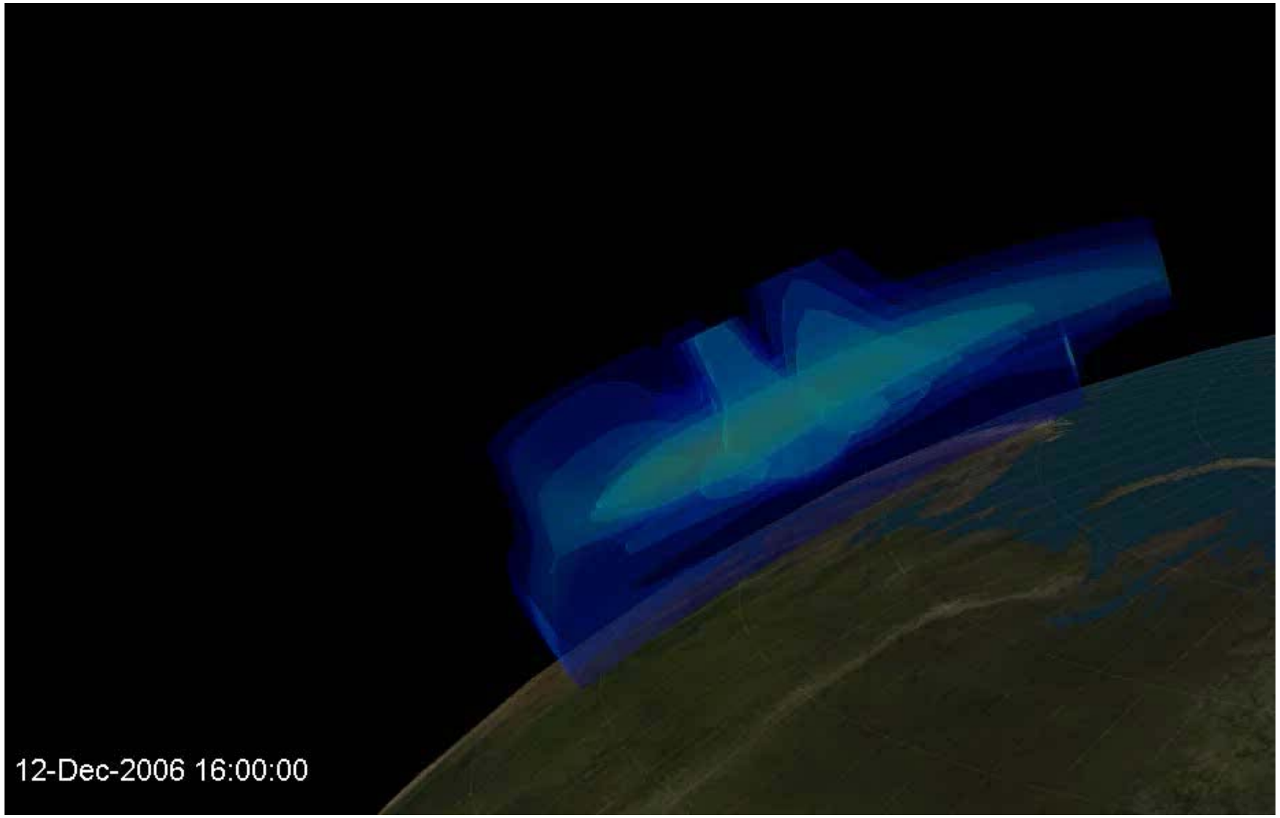
  => Identify and educate potential customers
  - Openness of the data policy

  => can it survive with commercial services
  - Coordination in mission implementation
- Technical challenges
  - Will all GNSS systems be open to everyone

  => receiver design, flexibility (software receivers)
  - Compatibility of meteorological and ionospheric requirements

Prospects: Near Real Time Tomography

- Combining ground based and space borne GNSS observations



Prospects: Data assimilation

- Assimilation models
  - **Utah State University Global Assimilation of Ionospheric Measurements (USU-GAIM) Model**
  - **Parameterized Ionospheric Model (PIM)**
- Advanced physical based space weather models
  - Assimilation of magnetic field, in-situ particle, auroral, etc. observations
  - Magnetosphere-ionosphere-atmosphere interaction

    => Feasibility of a combined model

    => Tracing ionospheric events to the solar activity

Summary

- The "brief" history of RO sounding is impressive

  => good continuity of missions, continuously improving technology and science, very active research community

- Today ionospheric RO status is very good
- Prospects:
  - GNSS is getting bigger and better - The future of RO science looks bright
  - The ionospheric RO soundings and ground based observations complement each other

  => links with other space weather observations via data assimilation