The Role of GPS Radio Occultation Observations in the Global Observing System for Weather and Climate

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Thanks to the National Science Foundation for its support of GPS RO!
GPS Radio Occultation (RO)

Deduce atmospheric refractivity based on precise measurement of phase delay and amplitude.
Atmospheric Refractivity $N$

$N: \text{ pressure } (P) \hspace{1cm} 
\text{ temperature } (T) \hspace{1cm} 
\text{ water vapor } (P_w) \hspace{1cm} 
\text{ electron density } (n_e)$

$$N = 77.6 \frac{P}{T} + 3.73 \times 10^{-5} \frac{P_w}{T^2} - 4.03 \times 10^7 \frac{n_e}{f^2}$$
GPS RO

- Limb sounding geometry complementary to ground and space nadir viewing instruments
- High accuracy (equivalent to < 1 K from 5-25 km)
- High vertical resolution (100m near surface - 1km tropopause)
- All weather-minimally affected by aerosols, clouds or precipitation
- Independent height and pressure
- Requires no first guess sounding
- Independent of radiosonde calibration
- No instrument drift
- No satellite-to-satellite bias
- Inexpensive
Issues with GPS RO

- **Representativeness**: Horizontal “average” ~300 km  *Fundamental to measurement*
- **Penetration to lower troposphere**
  - GPS/MET median penetration ~500mb
    
    Issue resolved-90% of CHAMP soundings reach below 900 mb
- **Negative N bias in lower troposphere, tropical regions**

 causes identified, partially resolved, QC issue
Penetration of RO into lower troposphere

Compared to GPS/MET with median cut-off height ~ 500 mb. Improved HW, firmware, and software have extended vertical coverage for RO.

“Depth” of RO Soundings Achieved by CHAMP
Use of GPS RO Data

• **Climate:**
  – Characterize variability and change (MSU controversy)
    • world’s best climate thermometer!
  – Evaluate global climate models and analyses

• **Meteorology:**
  – Improve global weather analyses, particularly over data void regions such as the oceans and polar regions
  – Improve skill of global and regional weather prediction models

• **Ionosphere:**
  – Characterize global electronic density distribution
  – Space weather.
<table>
<thead>
<tr>
<th>Mission</th>
<th>Launch-Duration</th>
<th># Soundings/day</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS-MET</td>
<td>4/1995</td>
<td>2+</td>
<td>~125</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Proof of Concept</td>
</tr>
<tr>
<td>CHAMP</td>
<td>11/2000</td>
<td>~5</td>
<td>~250</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Improved receiver, tracking</td>
</tr>
<tr>
<td>SAC-C</td>
<td>11/2000</td>
<td>~3</td>
<td>~500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Improved receiver, open loop tracking test</td>
</tr>
<tr>
<td>GRACE</td>
<td>5/2002</td>
<td>~5</td>
<td>~500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RO data not yet available</td>
</tr>
<tr>
<td>COSMIC</td>
<td>12/2005</td>
<td>~5</td>
<td>~2500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Real time-ops</td>
</tr>
<tr>
<td>TerraSAR-X</td>
<td>7/2005</td>
<td>~5</td>
<td>~400</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>COSMIC RX &amp; Antennas</td>
</tr>
<tr>
<td>EQUARS</td>
<td>7/2006</td>
<td>~3</td>
<td>~400</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>COSMIC RX &amp; CHAMP antennas</td>
</tr>
<tr>
<td>METOP</td>
<td>4/2006</td>
<td>~5</td>
<td>~500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Real time - ops</td>
</tr>
<tr>
<td>COSMIC II ?</td>
<td>3/2009</td>
<td>~5</td>
<td>~2500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Real time-ops</td>
</tr>
</tbody>
</table>
Satellite sensors available for NWP
(R. Saunders, UK Met Office)
Observations should cooperate, not compete!
Combined Soundings at CIMSS

- RMS and bias of temperature profile retrievals from ATOVS alone (blue) and ATOVS plus CHAMP (red) with respect to radiosonde measurements for the months of October 2001, January 2002, April 2002, and July 2002.
- (Borbas et al, CIMSS)
Information content from 1D-Var studies
IASI (Infrared Atmospheric Sounding Interferometer)  
RO (Radio Occultation)

(Collard+Healy, QJRMS, 2003)
Radiosonde Stations and Manufacturers

Vaisala/Australia
IM-MK3/India
Shang/China
MEISEI/Japan
Mars/MRZ
VIZ
AIR
Others

From Junhong Wang (NCAR)
Mean Abs Diff in N---CHAMP and Radiosonde

India - 0.82%

Australia - 0.18%

Japan - 0.26%

China - 0.19%

Russia - 0.30%
CLIMATE

GCOS Implementation Plan for the Global Observing System for Climate
October 2004

Action A20 (AF13): GPS RO measurements should be made available in real time, incorporated into operational data streams, and sustained over the long-term.

GCOS-92, WMO/TD No. 1219, October 2004
Kelvin waves near the tropopause

Bill Randel
NCAR
QBO over Equator

Deseasonalized T anomalies. 4S-4N. Downward prop patterns assoc with QBO.

Contours 0.5 K

Randel et al., 2003
Assimilation of GPS RO data over the Antarctic
Domain of 4DVAR Experiment

Area used for comparison with global analysis

Bill Kuo, NCAR
Impact of GPS data assimilation - Geopotential Height

Initial time: 1200 UTC 11, Dec 2001
6th Cycle: 36-h assimilation
Compared with ECMWF Analyses

Day0

Day2

Day5

Pressure (hPa)

r.m.s of GPH (m)
Comparison with ECMWF Analysis

AVN/MM5 FCST

No GPS

+ GPS

72 h forecast
UK Met Office Study (Healy et al. 2004)

• Forecast impact experiment run for 16 days of CHAMP data May/June 2001

• ~160 CHAMP profiles/day (0.35% of total data)

• All other available obs assimilated (ATOVS, sfc, aircraft, radiosonde Sat winds, SSMI winds)-~47,450 total

• N assimilated for 4<Z<30 km only

Healy, Jupp and Marquardt, Geophys.Res.Lett, 2004
RMS temperature differences at 250 mb and 50 mb between Control and GPS RO analyses.

Healy et al., 2004)
Mean and RMS fit to radiosonde T observations for control (red) and GPS RO (blue, dashed) experiments.

250 hPa SH (Ø<-20°)  50 hPa NH (Ø>20°)
COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate)

- 6 Satellites launched in late 2005
- Three instruments:
  - GPS receiver, TIP, Tri-band beacon
- Weather + Space Weather data
- Global observations of:
  - Pressure, Temperature, Humidity
  - Refractivity
  - Ionospheric Electron Density
  - Ionospheric Scintillation
- Demonstrate quasi-operational GPS limb sounding with global coverage in near-real time
- Improved retrievals over GPS/MET, CHAMP
Distribution of GPS Occultation events in 24 hrs with EQUARS (2006, inclination angle <20°) and COSMIC (2005, 6 LEO satellites at 72°)

- **EQUARS**: Dense data rate in equatorial region
- **COSMIC**: Global coverage, but less data at low latitudes
Getting COSMIC Results to Weather Centers

This system is currently under development by UCAR, NESDIS, UKMO
Concluding Remarks

• GPS radio occultation technique is a very promising atmospheric observing system for both weather and climate:
  – High vertical resolution
  – High accuracy
  – All weather
  – No instrument drift (important for climate detection)

• GPS RO data will be valuable to:
  – climate change analysis, validating of climate simulations
  – operational weather prediction
  – ionospheric research and space weather forecasting
  – calibrate other observing systems (e.g., radiosonde and other satellite obs.)

• GPS RO technique is here to stay (COSMIC is coming, and more missions are being planned)
EARTH SCIENCE AND APPLICATIONS FROM SPACE

A COMMUNITY ASSESSMENT AND STRATEGY FOR THE FUTURE

http://qp.nas.edu/decadalsurvey

THORPEX Workshop
7 December 2004
Montreal
CHARGE TO COMMITTEE

• Recommend a prioritized list of flight missions and supporting activities within NASA and NOAA to support national needs for research and operational applications of the Earth system during the decade 2005-2015.

• Identify important directions that should influence planning for the decade beyond 2015.
Study Products

• First report February/March 2005
  – Review and synthesis of recs in previous NRC, WMO etc. reports
  – Discussion of urgent near-term issues
  – Input for NASA earth science roadmap
  – Recommend small number of priority missions/programs

• Second and Final report (4/06)
Guiding Principles

• Vision for Earth Sciences
• Connecting to societal needs
• Examine research and operational uses of spaceborne measurements
• Build upon existing national and international studies
• Science and applications in context of Earth as a system—include all relevant disciplines
• Communication and community involvement
• Realistic costs
Organization of Study

- Executive Committee (~ 18 members)
- Panels (Seven, Organized Thematically)
  1. Earth Science Applications and Societal Needs
  2. Land-use Change, Ecosystem Dynamics and Biodiversity
  3. Weather (incl. space weather and chemical weather)
  4. Climate Variability and Change
  5. Water Resources and the Global Hydrologic Cycle
  6. Human Health and Security
  7. Solid-Earth Dynamics, Natural Hazards, and Resources
Executive Committee

- Rick Anthes, UCAR, co-chair, meteorology
- Berrien Moore, U. New Hampshire, co-chair, biogeochemical cycling
- Jim Anderson, Harvard Univ, atmospheric science, chemistry
- Bill Gail, Ball Aerospace, civil space
- Susan Cutter, U. South Carolina, hazards and risk
- Tony Hollingsworth, ECMWF, weather
- Kathie Kelly, U. Washington, physical oceanography/satellite obs
- Neal Lane, Rice, policy
- Aram Mika, Lockheed-Martin, remote sensing technology
- Warren Washington, NCAR, climate modeling
- Mary Lou Zoback, USGS, solid earth
- Risa Palm, LSU Provost, social response to natural hazards
- Otis Brown, U. Miami, physical oceanography
- Susan Avery, CIRES and CU, meteorology
- Eric Barron, Penn State, climatology and numerical modeling
- Dennis Lettenmaier, U. Washington, hydrology
- Mark Wilson, U. Michigan, infectious disease and remote sensing
- Brad Hager, MIT, solid earth
Criteria for setting priorities

• Identified as a high priority in previous studies (requirements)
• Makes a significant contribution to more than one area (theme)
  – Weather, climate, ecosystems, oceans, land space weather, research, operations, etc.
• Affordability
• Readiness
• Complementary to other systems
• Risk reduction, mitigation, independence of observations
Next Steps

- Finalize Panels (more than 600 nominations so far!)
- Executive Committee (EC) writes Phase I report
- Panels begin work on Phase II
- Solicit ideas and "proposals" from community
  - RFI out by 15 December
  - Response due March 1, 2005
- Town meeting at AGU
  - Tuesday Dec. 14, 11-12:30  Marriott Hotel
- Town meeting at AMS
  - Monday Jan. 10, 12:00-1:30
- Feb/Mar 2005-Phase I report done
Phase II

• First input from panels due June 2005.
• EC and panels meet in August 2005 at Woods Hole
• First draft by Nov 2005
• Discuss first draft at AGU in Dec 05 and AMS in January 06
• Final report April 06
CHALLENGES

- Breadth of the Field
- Recommendations for a Multi-agency Audience
- Research and Operations
- Future of Earth Sciences in NASA
Challenges

• Relationship to:
  – CCSP (Climate Change Science Program)
  – GEO (Group on Earth Observations)
    • Preparing a 10-year implementation plan for a “coordinated, comprehensive, and sustained Earth observation system or systems.” Plan due late 2004
  – NASA Roadmap planning

• Community Buy-in