An Interdisciplinary Approach at Studying the Earth-Sun System with GPS/GNSS and GPS-like Signals

C. Zuffada, G. Hajj, T. Mannucci, Y. Chao, C. Ao and J. Zumberge

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

Cinzia.Zuffada@jpl.nasa.gov
• Nominal 24 satellites at 20,000 km altitude
• Transmit L1 (19 cm) and L2 (24.4 cm) signals
• L1 modulated by P1 and C/A
• L2 modulated by P2
• L5 to become available soon, allowing for interferometry L2/L5
• Additional satellites to become available with the European system Galileo
Interdisciplinary Mission Concept

- Good example of interdisciplinary mission concept, with broad science objectives of high societal relevance, all resting on common cost-effective technology
- Down-looking antennas for reflections
- Side-looking antennas for occultations
- Up-looking antennas for electron density
- GPS receivers capable of processing all signals
Required Antenna Configurations

- Zenith: super-satellite TEC
- Fore: occultations
- Aft: occultations
- Side-viewing “scans”
- Nadir: reflections

- Instrument core is an antenna system and a GPS receiver
- Technologies for occultations and TEC well proven and of low complexity
- Antenna systems for reflections of moderate complexity
- GPS Receiver to process reflections on-board is the item of highest complexity; not currently available

Interdisciplinary Mission with GPS
Cinzia.Zuffada@jpl.nasa.gov
Reflections provide sea surface topography at higher spatial resolution and more frequent repeat time than the current radar altimeter satellites. Each occultation provides a high resolution (~100m) profile of atmospheric density, temperature, pressure and geopotential height in the stratosphere and upper troposphere, water vapor in the middle and lower troposphere, and electron density in the ionosphere. Upward measurements provide 2D tomographic images of electron density in the plasmasphere.

A Representative Occultation Daily Coverage

A Representative Reflection 6-hour coverage
Applications of GPS Reflections

• Oceanic mesoscale eddies, fronts, and boundary currents (most energetic elements of the oceanic general circulation)
• Eddy mean-flow interactions, eddy transports, and the role of eddies in climate
• Physical-biological interactions and the role of eddies in the carbon cycle
• Coastal tides and open ocean internal tides
• Diurnal cycle
• Develop and refine climatologies
• Reveal features diagnostic of underlying physical process
• Assess models (leading to their improvement)
From upper right, decreasing white space indicates closing of unsampled spatial gaps from TOPEX/Poseidon to WSOA to GPS.
Applications of GPS Occultations in the Atmosphere

- Ultra-stable temperature soundings
- Atmospheric mass, balanced wind and slab temperatures
- Atmospheric moisture
- Internal boundaries: Tropopause and Boundary Layer
- Diurnal cycle
- Fronts
- Small and large scale waves
- Contribute to knowledge of cloud top & base and conditions of formation, evolution and dissipation
- Improve analyses and initial conditions for weather prediction
- Develop and refine climatologies
- Reveal features diagnostic of underlying physical process
- Assess other observations and analyses
- Assess models (leading to their improvement)
- Early detection of changes in climatic behavior
Features of GPS Occultations

- Relies on precise measurements of time delay between transmitter and receiver
- No long term drift—ideal for global warming detection
- Global coverage
- All-weather remote sensing system
- Measures profiles of refractivity, density, temperature and pressure from surface to 50 km
- Measures water vapor profiles in the troposphere, with accuracy of 0.2 g/kg
- Provides profiles of electron density in the ionosphere with <1 km resolutions
- 0.5K accuracy for individual profiles, < 0.1K accuracy for averaged ensemble
- Sub-Kilometer vertical resolution, down to 20-50m in the lower troposphere
- Inexpensive
EXAMPLES OF TEMPERATURE PROFILES

Features:

- Relies on precise measurements of time delay between transmitter and receiver
- No long term drift—ideal for global warming detection
- Global coverage
- All-weather remote sensing system
- Measures profiles of refractivity, density, temperature and pressure from surface to 50 km
- Measures water vapor profiles in the troposphere, with accuracy of 0.2 g/kg
- Provides profiles of electron density in the ionosphere with <1 km resolutions
- 0.5K accuracy for individual profiles
- 0.1K accuracy for averaged ensemble
- ~100m vertical resolution
EXAMPLES OF WATER VAPOR PROFILES

Features:

- Relies on precise measurements of time delay between transmitter and receiver
- No long term drift—ideal for global warming detection
- Global coverage
- All-weather remote sensing system
- Measures profiles of refractivity, density, temperature and pressure from surface to 50 km
- Measures water vapor profiles in the troposphere, with accuracy of 0.2 g/kg
- Provides profiles of electron density in the ionosphere with <1 km resolutions
- 0.5K accuracy for individual profiles
- 0.1K accuracy for averaged ensemble
- ~100m vertical resolution
Subtracting off the estimated temperature gradient based on the ECMWF analysis, we compute the median and 1-σ confidence interval of the difference in temperature between coincident occultations that are <100, 200 and 300 km apart. The 1-σ is then scaled by 1/sqrt(2) in order to estimate the error due to each occultation, assuming they are independent. The results are shown below indicating a median of <0.1 K below 18 km and <1 K below 30 km. The 1-σ confidence interval (equivalent to standard deviation) is ~0.6 K below 15 km and < 1 K below 20 km. It grows to ~7 K above 35 km.
Temperature Climatology

- Climatologies based on CHAMP and SAC/C can be extremely important in many applications
  - Climate monitoring and trend detection
  - Corrections to potential biases in analysis for the removal of atmospheric loading effect and proper interpretation of geodetic and gravitational measurements (e.g., GRACE) to identify processes such as glacial melting and sea level rise.
- Even though CHAMP and SAC/C are consistent at <0.1K level in the mean, obtaining a climatological temperature map accurate to 0.1K requires a much higher density of coverage than afforded by CHAMP and SAC/C and sampling at all local times.
Statistics based on ~200 SAC/C and CHAMP occultations that are <1/2hr and <100 km apart show consistent mean T to < 0.1K (below-left). By contrast mean temperature of analysis (NCEP) shows differences of ~0.5K to SAC/C or CHAMP (below-right).

Climatologies based on ensemble averages of GPS occultations are sufficiently accurate to detect potential biases in NWP analyses. The figure below shows examples of the June-July-August (JJA) temperature climatologies over Antarctica at 5km altitude (~450 hPas) for three consecutive years. A careful examination of these climatologies and their comparisons to NCEP and ECMWF reveal some significant biases in the analyses.
Applications of GPS Remote Sensing in the Ionosphere

Capabilities:
• Electron density profiles at <1km vertical resolution
• Detailed 2D global maps of vertical TEC and ionospheric response to magnetic storms
• Global 3D images of electron density as a function of time
• Maps of ionospheric scintillations and irregularity statistics
• Potentially inferring ionospheric drivers such as electric field, neutral wind, neutral densities and temperatures, solar EUV radiation

Applications:
• Sun-Earth Connection science (Living With a Star)
• Improved navigation
• Mitigate effects on communications
• Improved geo-location and surveillance
• Improved understanding of ionospheric response to storms
• Improve understanding of ionosphere-magnetosphere coupling
• Improve understanding of ionosphere-lower atmosphere coupling
Space Weather Applications

Capabilities:

• Electron density profiles at <1km vertical resolution
• Detailed 2D global maps of vertical TEC and ionospheric response to magnetic storms
• Global 3D images of electron density as a function of time
• Maps of ionospheric scintillations and irregularity statistics
• Potentially inferring ionospheric drivers such as electric field, neutral wind, neutral densities and temperatures, solar EUV radiation

Applications:

• Improve navigation
• Mitigate effects on communications
• Improve geo-location
• Improve understanding of ionospheric response to storms
• Improve understanding of ionosphere-magnetosphere coupling
• Improve understanding of ionosphere-lower atmosphere coupling

Above: Example of electron density profile obtained with GPS occultations on SAC/C. Below: Example of global vertical TEC maps obtained by the Global Assimilative Ionospheric Model (GAIM) by use of SAC/C and CHAMP data.
Resolving Fine-scale Structure

Fine-scale structure in the “E-region” resulting from upper atmosphere-plasma coupling
Global Dayside TEC Response to Geomagnetic Storm

October 30, 2003
Interdisciplinary Mission with GPS

TEC above 400 km CHAMP altitude

20:32 UT
21:43 UT
22:04 UT
18:40 UT
19:00 UT
20:12 UT
21:43 UT

Vertical TEC Estimate ($10^{16}$ el/m²)

Magnetic Latitude (Dipole)

Elevation angle > 40

1 PM Local Time Passes

October 30, 2003
Interdisciplinary Mission with GPS

Cinzia.Zuffada@jpl.nasa.gov

Interdisciplinary Mission with GPS
Scientific Mission Drivers

- Improve understanding of the complex coupled Sun-Earth geospace system
- Determine the effects of long- and short-term variability of the Sun on the global-scale behavior of electron density
- Determine the solar and geospace causes of small-scale ionospheric density irregularities in 100-1000 km altitudes
  - Scientific priorities of the Living With a Star Geospace Mission
  - Ranked #2 mission priority by NRC