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

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Abstract - **The value of Global Positioning Satellites (GPS) measurements to atmospheric science, space physics, and ocean science, is now emerging or showing a potential to play a major role in the evolving programs of NASA, NSF and NOAA. The objective of this communication is to identify and articulate the key scientific questions that are optimally, or perhaps uniquely, addressed by GPS or GPS-like observations, and discuss their relevance to existing or planned national Earth-science research programs. The GPS-based ocean reflection experiments performed to date have demonstrated the precision and spatial resolution suitable to altimetric applications that require higher spatial resolution and more frequent repeat than the current radar altimeter satellites. GPS radio occultation is promising as a climate monitoring tool because of its benchmark properties: its raw observable is based on extremely accurate timing measurements. GPS-derived temperature profiles can provide meaningful climate trend information over decadal time scales without the need for overlapping missions or mission-to-mission calibrations. By acquiring data as GPS satellites occult behind the Earth's limb, GPS also provides high vertical resolution information on the vertical structure of electron density with global coverage. New experimental techniques will create more comprehensive TEC maps by using signals reflected from the oceans and received in orbit. This communication will discuss a potential future GNSS Earth Observing System project which would deploy a constellation of satellites using GPS and GPS-like measurements, to obtain a) topography measurements based on GPS reflections with an accuracy and horizontal resolution suitable for eddy monitoring, and b) climate-records quality atmospheric temperature profiles. The constellation would also provide for measurements of ionospheric electron density. This is a good example of an interdisciplinary mission concept, with broad science objectives of high societal relevance, all resting on common cost-effective technology.**

I. Introduction

As NASA and NOAA are defining their needs for the 21st century, they should consider a new class of cost-effective missions that lead towards continuous coverage of key aspects of the Earth system. Over the past two decades, GPS has proven valuable as a tool allowing observations of the Earth system across several fields of science. The time is ripe to assess the benefits of a continuing investment in GPS technology development from a multiprogram, multidiscipline point of view. In conjunction with the Fall 2004 AGU Meeting's Special Focus session *"Emerging Science Applications of Measurements From GPS/GNSS and GPS-Like Signals: Recent Results and Future Possibilities"*, a workshop was chaired by Jim Anderson of Harvard University, with the objective "... to identify and articulate the key scientific questions that are optimally, or perhaps uniquely, addressed by GPS (or more generally, the Global Navigation Satellite System, GNSS, to include other constellations such as Galileo) or GPS-like observations, and determine their relevance to existing or planned national Earth-science research programs." Based on the discussion amongst the participants and a record of publications, it is clear that three *emerging* science areas, in addition to those already well established, would be benefiting from continuing such investments: atmosphere/climate, space science, and oceanography.

In each of these science areas, there is a clear connection to high-level societal needs and related programmatic directions. For atmosphere/climate, these needs underpin the NOAA and NASA research and applications programs engaging Earth system change and climate studies. The U.S. Climate Change Science Program states objectives in terms of several hierarchical goals, including "Improve knowledge of the Earth's past and present climate and environment, including its natural variability, and improve understanding of the causes of observed variability and change" and "Improve quantification of the forces bringing about the changes in the Earth's climate and related systems".

In the space science community the realization that the extremes of space weather, particularly in the ionosphere, affect human activities and technical infrastructure has broadened the discipline to include predictive as well as discovery objectives. A recent National Research Council decadal survey of Solar and Space Physics emphasized improved understanding of the Earth's space environment, and development of "near real-time predictive capability for understanding and quantifying the impact on human activities of dynamical processes...in the ionosphere".

In the oceanography area, there is a major national effort to coordinate and develop an Integrated Ocean Observing System (IOOS), which is the U.S. contribution to the Global Ocean Observing System and the Global Earth Observation System of Systems. The IOOS consists of two interdependent components – coastal and global – that use both remote and *in situ* sensing to make measurements over the broad range of scales needed to detect, assess, and predict the effects of global climate change, weather, and human activities on oceans and coasts. The IOOS implementation plan states that "maintaining continuity and enhancing satellite remote sensing of the oceans are critical components".

We discuss a constellation concept, based on technology developed for GPS, which fills specifically identified gaps in the current knowledge, and allows for added scientific and societal benefits at significantly lower cost than traditional Earth-orbiting remote sensing missions.

II. Interdisciplinary Mission Concept

We consider a constellation of 6 low-Earth orbit satellites distributed in 6 evenly spaced planes at 40 deg. inclination and 800 km altitude tracking GPS and Galileo. Each satellite is equipped with multiple antennas pointed in such a way to provide a full view of the ocean at all viewing angles with 20 db gain. (see Fig. 1 for the reflection geometry for one satellite) The basic measurements are phase delay of the L1, civil L2 and L5 GPS signals anticipated to become available in 2005 and their counterpart in the Galileo system. Each satellite provides on average of ~20 simultaneous GNSS reflection measurements with surface height precision of about 10 cm for each 1-sec measurement, sampling all local times.

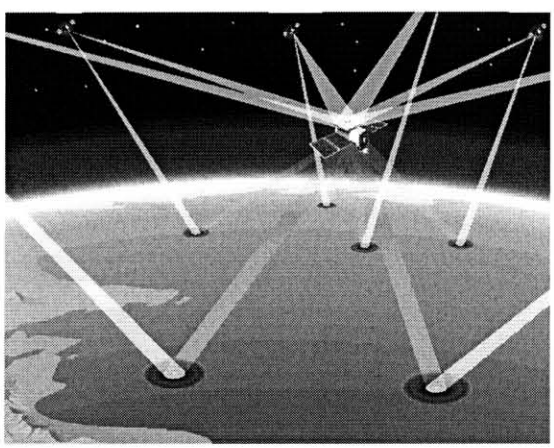

Figure 1. An Earth-orbiting receiver uses direct GPS signals for precise positioning, but also receives reflected signals to make several simultaneous bistatic altimetric measurements.

With the current constellation of GNSS, implementation of ocean altimetry by tracking GPS reflected signals from low-Earth orbit (LEO) is hampered by the need for a high gain antenna to obtain sufficient signal-to-noise ratios (SNR). Further complications arise from the fact that such an antenna must have a wide field of view in order to see multiple GPS reflections. Achieving both high gain and wide field of view require a large array of antenna elements and present a technological challenge. The cost of building and flying such an antenna array to obtain sub-decimeter ocean altimetry accuracy may be prohibitive. These requirements are based on the fact that the reflected GPS signal is incoherent over time scales larger than ~1 millisecond because of the ocean roughness. Under such conditions, one would have to rely on detecting the returned power rather than the phase of the reflected signal. This major drawback will soon be removed as a new generation of GPS (and Galileo) satellites are launched, which transmit a new frequency (L5 @ 1.17645 GHz or 25.5 cm wavelength) in addition to an unencrypted L2 (L2C @ 1.2276 GHz or 24.4 cm wavelength) and the L1 (@1.57542 GHz or 19.0 cm). Because of the proximity of the L2 and L5 wavelengths, the two signals can be combined interferometrically to achieve phase measurements accurate to the decimeter level with an antenna system of moderate complexity with 20 db gain or less. Obtaining such a gain in all directions where the ocean is visible from a LEO satellite can be accomplished by an electronically steerable array of antenna elements spread over a 1-2 meter diameter surface.

Figure 2 illustrates the coverage afforded by six receiving satellites in the constellation, in just six hours. It is noted that the coverage is global, with random distribution of measurements within any given size ocean cell, expanding the concept of along track and across track and of cross-over points. Such density is suitable to generate observations that could be used as a spaceborne component of a tsunami early detection system for process studies and impact prediction, leading to a) Reduction of false alarms through model calibration and validation; b) Determination of the relationship between earthquake magnitude and tsunami magnitude; c) Determination of the importance of detailed and higher order effects in propagation. Globally distributed ocean altimetry, in particular, would improve process studies by observing the wavefront structure.

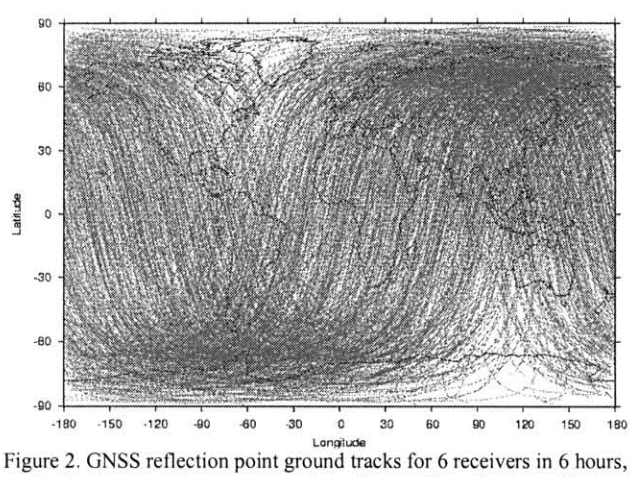

Figure 2. GNSS reflection point ground tracks for 6 receivers in 6 hours, assuming their antenna beams can capture all available reflections. Horizontal axis is longitude, vertical axis is latitude.

In contrast to traditional altimetry, GNSS topography measurements do not repeat with assigned periodicity, however their density is such that with time any given size cell will acquire many samples, including many cross over measurements. Careful averaging, including removal of known effects through models, in a manner analogous to what is performed for TOPEX/Poseidon and Jason 1&2, will allow to determine the mean sea surface globally and measure its small scale changes.

The very rapid coverage afforded by GPS reflections offers for the first time the possibility to monitor and study mesoscale processes. These processes, which are among the dominant global climate errors (see [1] for a review), are essential to understanding ocean circulation on all scales and are an important contribution to the carbon cycle, yet they cannot be observed with the current observing systems. On the regional scale, eddies can induce local upwelling and enhance biological production. In the equatorial Pacific, eddies associated with the tropical instability waves can increase the supply of iron and silicate to the euphotic zone resulting in enhancement of the biological productivity. On the global scale, mesoscale eddies play an important role in the overall transport of heat and momentum. Numerical model simulations with and without the inclusion of mesoscale eddies show a 30% difference in the equator-to-pole heat transport over the Atlantic Ocean [2]. Traditional altimetry offers too narrow (only a few km) view and broad track spacing (several hundred km) to resolve the two dimensional structure of eddies. Such nadir viewing satellite altimetry provides high-resolution information about sea surface topography only in the along-track direction, allowing the calculation of only the cross-track component of geostrophic velocity. However, knowledge of the two-dimensional velocity vector is required for accurate estimates of the transport of mass, heat, freshwater, and chemicals, as well as the statistical properties of the flow field such as mean and eddy energy, eddy/eddy, and eddy/mean flow interactions. GPS reflections will yield the first detailed global eddy-resolving maps of ocean topography, providing an opportunity to test and refine ocean circulation models for improved understanding of ocean circulation and transports.

The GPS-based ocean reflection experiments performed to date from airplane and fixed sites have demonstrated precision and spatial resolution suitable for altimetric applications that require higher spatial resolutions and more frequent repeat times than is feasible with the current generation of radar altimeter satellites. Such applications include monitoring of mesoscale eddies and possibly tsunami wave propagation and dynamics [3-6]. However, more work is needed to fully characterize the measurement error, particularly quantifying the impact of the troposphere on the ultimate attainable accuracy. In order to deploy a space-based system for high resolution sea-surface topography using GPS reflections, two key technology components must be developed and integrated: (a) a receiver capable of tracking and processing many simultaneous reflections and generating on-board correlation products and (b) a receiving antenna system with ample field of view and high gain, necessary to capture the multiple reflection points moving over the ocean.

Additionally, radio occultation soundings of the atmosphere will be obtained when the GNSS radio signals pass through the limb of the Earth's atmosphere. In this case, the phase delay of the received signal induced by the atmosphere will be inverted to recover profiles of the microwave index of refraction, which yields very high vertical resolution profiles of electron densities in the ionosphere, neutral atmospheric density, pressure and temperature (vs. height) with sub-Kelvin accuracy in the stratosphere and mid- to upper troposphere, and specific humidity in the mid- and lower troposphere down to the surface, accurate to better than 2 g/kg. Temperature profiles derived from GPS radio occultation have been validated to better than 1K accuracy above 5-8 km altitude, with sub-km vertical resolution. Additionally, they have been shown to be bias-free, i.e. they agree to within 0.1 K on average for different flying instruments launched in the last decade (see Figure 3 and [7]) Hence, they provide meaningful climate trend information over decadal time scales without the need for overlapping missions or mission-to-mission calibrations. This benchmark property makes this measurement a key climate-monitoring tool. In climate, a benchmark must give significant new information on a component of the climate system whose influence on climate change is highly uncertain or on a constituent of the atmosphere responsible for radiative forcing.

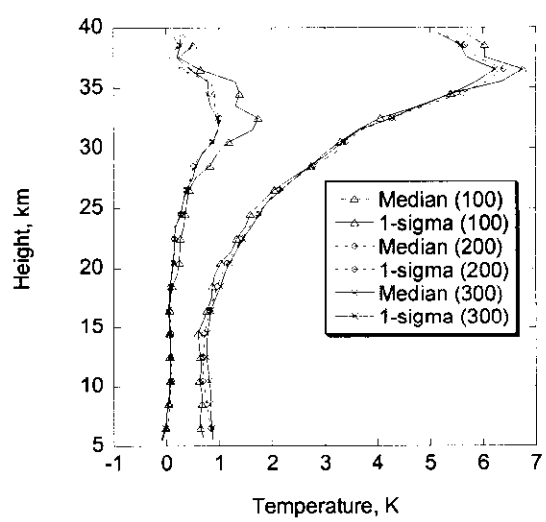

Figure 3. Median (left set of curves) and 68% confidence interval (right set) of temperature differences between CHAMP and SAC-C as a function of height for measurements < (100, 200, 300) km apart. (From [7])

The future direction for radio occultation in climate benchmarking is absorptive radio occultation with active transmitters and receivers in a cross-link geometry, if it is proven that it gives information on climate feedbacks not inherent in the microwave refractivity obtained by GPS

occultation. To distinguish the influences of water vapor and other molecules on the real part of the refractive index, and separate them from the temperature contribution, absorptive radio occultation would accurately measure the amplitude of a radio occultation obtained near a water vapor absorption feature in the microwave range (i.e., 22 and 183 GHz).

GPS occultation also provides high resolution information on the vertical structure of electron density with global coverage, useful for Space Weather. A recent study conducted by NASA's Geospace Mission Definition Team defined focused scientific questions, to characterize and understand mid-latitude ionospheric variability and the irregularities that affect communications, navigation, and radar systems. Mid-latitudes were chosen because it is the region where the extremes of space weather are least well understood and because it hosts the technical infrastructure most sensitive to space weather. Three key goals emerged from this study: a) Determine the effects of long- and short-term variability of the Sun on the global-scale behavior of the ionospheric electron density; b) Determine the solar and geospace causes of small-scale ionospheric density irregularities in the 100 to 1000 km altitude range; and c) Determine the effects of solar and geospace variability on the atmosphere enabling an improved specification of the neutral density in the thermosphere.

GPS receivers (notably the CORS network in the US) have provided the impetus for a profound change in our understanding of the mid-latitude ionosphere, long thought to be relatively benign. Images created from these receivers have revealed the existence of global storms that sweep waves of plasma from the equator to the poles via highly-structured narrow "tongues" of plasma that are connected to features observed in the inner magnetosphere. The physics of these geospace connections is not understood. Typically, during storms, the total electron content (TEC) distributions exhibit drastic increases in peak values and sharp gradients across regions such as the central USA, as illustrated in the example of Figure 4. The physical processes causing such large TEC changes in a matter of a few hours are not well understood, nor are the upper atmospheric and ionospheric implications of such large scale changes.

The future of GPS as a scientific tool for investigating the ionosphere and its larger connection to geospace will continue to evolve. Understanding and predicting space storms is a goal of the National Space Weather Program, NASA's Living With a Star program, and the Geospace Ionospheric-Thermospheric Storm Probes as well as the Radiation Belt Storm Probes. Additional orbital GPS receivers will enable a global characterization of the ionospheric footprint of space storms, particularly their evolution in altitude (through occultations from receivers in low-Earth orbit). These same receivers can be used to map globally both large and small scale structures, including those causing scintillations. New experimental techniques will create more comprehensive TEC maps by using signals reflected from the oceans and received in orbit.

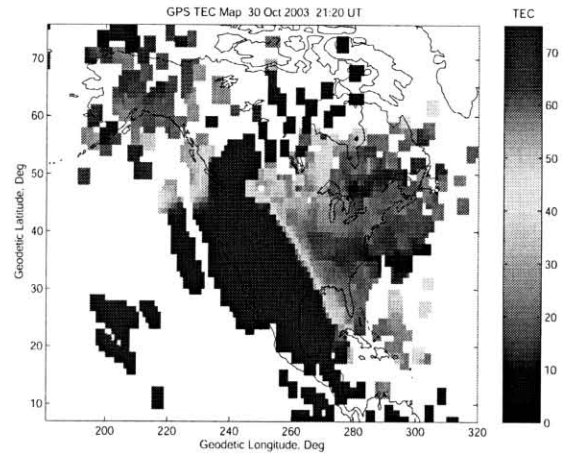

Figure 4. Example of a mid-latitude ionospheric storm showing a region of storm enhanced density with large gradients.

ACKNOWLEDGMENT

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