JPL D-34579

GPS System of Systems for Science Study

Prepared by:

Rob Sherwood, Anthony J. Mannucci, Cinzia Zuffada, and Casey Heeg

August 10, 2006

Jet Propulsion Laboratory
California Institute of Technology

Table of Contents

Executive Summary

The 2006 National Research Council (NRC) Decadal Report will stress that future directions for Earth science at NASA/NOAA will focus on achievement of a national strategy for the Earth Sciences that balances international economic competitiveness, protection of life and property, and stewardship of the planet for this and future generations. Because of the urgent need for climate measurements identified in the report, a small group from JPL was formed in late 2005 to write this report to explore the science benefits of maintaining GPS receivers in orbit for climate science. This is a particularly timely topic since 7 new GPS-science capable satellites will be launched in 2006 (COSMIC 1-6, MetOp1), resulting in 10 GPS-science capable satellites in orbit (including CHAMP, SAC-C, GRACE). In this report, we include a summary of GPS science and simulations of future constellations to achieve new science. In addition to atmospheric observations we also included ionosphere observations and ocean science. We have written additional material on GPS receivers, current and future GPS science missions, and GPS receiver integration issues that is available at http://sensorwebs.jpl.nasa.gov/gps .

For climate observations, we simulated a constellation of ten satellites in a configuration similar to COSMIC, and performed a multi-year analysis of how such a constellation would be able to characterize long-term trends in temperature. We find that such a constellation is adequate to compute zonally-averaged, monthly mean temperatures with a precision adequate to address expected climate trends of order ~0.1 K per decade. Such a constellation also has adequate local time coverage to avoid aliasing diurnal cycle trends with global climate trends. The high accuracy and consistency of GPS-based atmospheric retrievals suggests that continuously maintaining an operating constellation of such receivers is an important global observation asset for characterizing long-term climate trends.

We also performed a series of simulations to determine the science returns that could be achieved with varying sizes of GPS receiver constellations. This study can be used to consider the advantages of including GPS science receivers on future satellites as dedicated constellations or constellations of opportunity. For ocean science, we assumed each satellite would be equipped with a Toga receiver (now in development under NASA's Instrument Incubator Program), and a steerable 20-dB gain antenna with field of view capable of intercepting all available reflections.

The conclusions drawn from this study are as follows:

- For atmospheric science, a constellation of 9 satellites in reasonably diverse orbits is enough to satisfy anticipated requirements for climate observations. This can be done with either a dedicated constellation (such as COSMIC) or a constellation of opportunity, which could be formed by placing GPS receivers on all new NASA satellites. Current projections indicate that there will be 9-12 total NASA/NOAA satellites orbiting in 2012, and we expect the local-time diversity of the orbits will be sufficient for climate.

- For ionospheric science, the near-term, 10-satellite constellation is sufficient to produce major advances in our understanding of space-weather dynamics and to characterize the global conductivity structure of the ionosphere. An even larger constellation would benefit studies of smaller-scale structures in the ionosphere, such as occur at high latitudes during aurora.

- For ocean/ice science, a constellation of six satellites equipped for processing ocean and ice reflections would satisfy basic needs. We would encourage in-space testing of the next generation Toga receiver as soon as possible after its completion in 2008, to validate the instrument and demonstrate the benefits of GPS ocean reflection science. If that flight test is successful, a constellation of six GPS receivers could be built up to perform ocean/ice science.

We recommend the following actions:

- NASA studies the feasibility of requiring all future GPS compatible Earth-orbiting missions to carry a Global Navigation Satellite System (GNSS) science receiver. Accommodating a receiver for atmospheric and ionospheric science is simpler than for ocean science.
- Improve the integration of GPS radio occultation observations into the Global Climate Observing System from a technical and programmatic standpoint.
- NASA establishes a GNSS science working group that identifies opportunities and strategies for meeting agency needs with GNSS-based science. A key group focus should be exploiting the planned modernization of GNSS, including new GPS signals and deployment of the European Galileo system, permitting significant increases to the quality and quantity of GPSRO data in the near future.

1. Introduction – Purpose

Following the EOS (Earth Observing System) era of Earth remote sensing, NASA is looking to plan the next 25-30 years of Earth science exploration. The National Research Council (NRC) has been engaged in a decadal study to generate prioritized recommendations from the Earth and environmental science and applications community, regarding a systems approach to the space-based and ancillary observations that encompasses the research programs of NASA and the related operational programs of NOAA. The work will lead to the identification of NASA's future directions, specifically to develop strategic roadmaps that will be traceable to the 3 Presidential Directives on 1) Climate Change, 2) The US Integrated Earth Observation System and 3) The Space Exploration Vision, put forth at the beginning of 2004.

At the same time, as NPP and NPOESS platforms are launched, many environmental/climate measurements currently provided by NASA will transition to NOAA, and NASA is looking for a new role beyond the Earth system characterization by first-of-a-kind global observations. One possibility for NASA is to lead a future wherein decisions and actions for the benefit of humankind are informed by coordinated, comprehensive and sustained Earth observations and information. This goal could be attained through an architectural framework, the Global Earth Observing System of Systems (GEOSS) to:

- Monitor continuously the state of the Earth, to increase understanding of dynamic Earth processes
- Enhance prediction of the Earth system
- Further implement our international environmental treaty obligations

In this framework, new and past Earth observation systems (satellites, in-situ and sub-orbital) would provide data to Earth system's models to perform analysis and generate predictions, with use of ancillary data sources (i.e. socio economic), and be part of an overall decision support system used in management and policy decisions.

The new measurements NASA will be pursuing are constantly undergoing reassessment and are currently the object of work by panels formed by the NRC's "Decadal Survey" of Earth science and applications from space. Independent of the final choice, we discuss the possibility of providing to any future mission (at a small added cost) additional science capabilities from a Global Positioning System (GPS) receiver (and suitable antenna system) for scientific applications, as part of a system-of-systems framework.

The contributions of GPS are valuable as:

- Climate benchmark measurements - Unambiguous retrieval of temperature, from mid-troposphere up to the mid-to-lower stratosphere, with ~200m vertical resolution, implying capability to characterize tropopause temperature globally
- Accurate observations for weather forecasting – including polar weather
- Benchmark observations for characterizing other sensors
- Absolute calibration: GPS occultation is based on a timing measurement using atomic clocks
- Diurnal cycle coverage with compelling cost effectiveness
- All-weather capability: Insensitive to clouds
- Insensitive to instrument generation: absolute record in perpetuity

For climate monitoring, GPS radio occultation (RO) temperatures will become the key benchmark measurement for temperature. This will significantly reduce uncertainties in long-term temperature change, especially in the upper troposphere and stratosphere. Hence, it is an important component of the observation portfolio needed for climate. GPS is also expected to be important for improving weather forecasting, as demonstrated by an active program to assimilate COSMIC data. Finally, GPS RO temperatures can be used to validate and vicariously calibrate temperature profiles from other observing systems (microwave sounders, radiosondes).

The precise and unbiased nature of the GPS retrieval is shown in Figure 1, the result of comparing nearby soundings from the CHAMP and SAC-C spacecraft, indicating a mean difference of less than ~0.1 K over altitudes 5-18 km (Hajj et al. 2004), confirming that GPS measurements are precise and suitable for the most stringent climate applications. Climate trends could be as small as 0.1 K *per decade*, requiring a very reliable and stable measurement of temperatures.

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. Global, long-term climate records will receive increasing scrutiny and will be submitted to increasingly intense criticism as they become more relevant to the public policy debate. At present, they do not satisfy the necessary standards. Climate requirements differ in fundamental ways from weather requirements. There is a serious need to more fully engage the metrology community in the creation of long-term climate records. Accuracy pinned to irrefutable SI traceable standards on-orbit is an essential strategy.

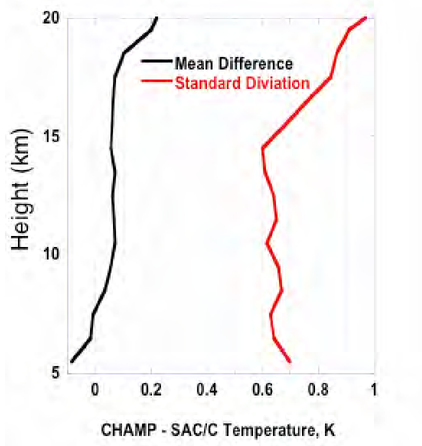

Figure 1 – Statistical differences between 212 nearby CHAMP and SAC-C soundings from the GPSRO database at JPL. Profiles acquired within 30 minutes and 200 km of each other, with first-order atmospheric gradients accounted for (from Hajj et al., 2004).

By acquiring data in limb geometry at ionospheric altitudes, GPS also provides high vertical resolution information on the vertical structure of electron density with global coverage. The scientific benefits of this new measurement are discussed in a later section. New experimental techniques will create more comprehensive maps of ionospheric total electron content (TEC) by using signals reflected from the oceans and received in orbit.

An experimental technique has been tested for ocean remote sensing based on detecting a GPS signal after it is reflected off the ocean surface, to measure sea surface topography and roughness (from which wind speeds are retrieved) at high spatial resolution and rapid temporal coverage. 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.

To implement GEOSS, it is particularly compelling to consider options that are cost effective and offer elements of interdisciplinary science. The cost-effectiveness of GPS technology for scientific applications has been demonstrated incontrovertibly; hence, the combination of interdisciplinary science applications and low cost makes it a very attractive component of a sustained program for Earth monitoring, particularly since it might be filling measurement gaps between missions (such as temperature soundings, from AIRS on Aqua and CRiS on NPP). (See Figure 2.)

Mission	2004	2006	2008	2010	2012	2014	2016
Aqua (AIRS)							
NPP (CRiS)							
measurement gap							

Figure 2 – Timeline for Current Missions Monitoring Temperature & Water Vapor

This report discusses the science benefits stemming from a potential future GNSS Earth Observing System project that would in time become a “constellation of opportunity” of satellites using GPS measurements. It assumes that GPS receivers and antennas would be available on future missions (whose orbits would remain substantially the same as those of missions existing today) as instruments of opportunity: in this situation, the study examines the progressive coverage that this “growing” constellation provides, and compares the science of opportunity to what is achievable with the current GPS receiver constellation by design (i.e. COSMIC, CHAMP, SAC-C, MetOP, GRACE). Our study is conservative in that we do not include the benefits of future GNSS enhancements expected in ~2010 and beyond, including enhanced GPS signal structure and a new 30-satellite Galileo constellation. The actual benefits will probably exceed the conclusions of our study.Additional information on GPS receivers, current and future GPS science missions, the new GPS signals and GPS receiver integration issues is available on the Web at http://pearljam.jpl.nasa.gov/gps.

2. Simulations to Determine Required Constellation Size

We have initiated a study to analyze how scientific objectives can be met with GPS constellations of varying sizes, to understand the benefits of a “constellation of opportunity” approach that would, at relatively small incremental cost, place a science-quality GPS receiver on most if not all future NASA and NOAA missions. Two constellations are considered: the “near-term” constellation that will be in orbit in 2006, consisting of six COSMIC satellites, CHAMP, SAC-C, MetOP and GRACE; and a possible future “constellation of opportunity” consisting of the 31 low-Earth orbiting NASA and NOAA satellites (see Appendix 2 for a list). We assume the source of GNSS signals to be the existing GPS constellation. This will almost certainly be augmented in the coming decade.

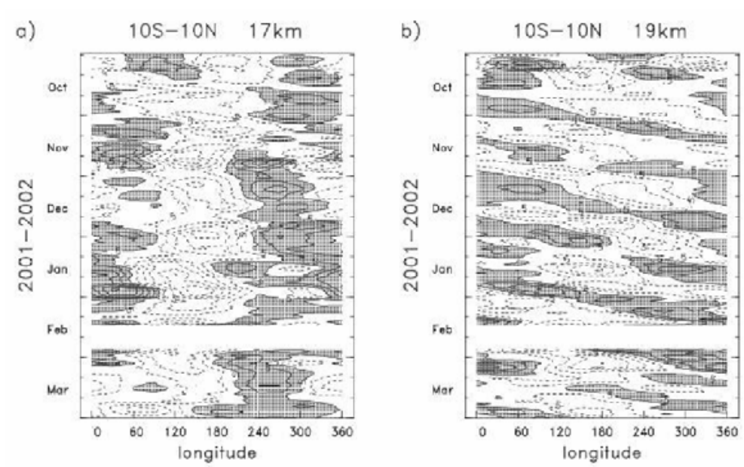

Figure 3 – Temperature anomalies in the equatorial tropopause region, characteristic of Kelvin waves observed in GPS radio occultation measurements captured at two different altitudes, 17 and 19 km; from Randel and Wu, 2005.

For atmospheric science and space weather, the capabilities of the instrument are mature and science return is largely a matter of constellation size. For atmospheric science, GPS occultations do not generally measure properties that are not available in some form by other techniques, however they provide accuracy and resolution that are significantly better than other *space-borne* methods. In the case of ionospheric science, radio occultations are the only available method of obtaining topside and bottomside vertical profiles of electron density from space. (Recently, UV imagers have been generating limb profiles of electron density, but the number of these instruments is limited and there are limits to what can be retrieved in daytime).

Extracting science from GPS is a matter of exploiting the measurement properties with sufficient density to produce significant new results. The nature of radio occultation measurements is that they are relatively sparse and randomly located: a single satellite in orbit with two antennas (fore and aft) might produce 600 profiles/day. The precision, accuracy and resolution of the observations is leading to new scientific results on subtle but important modes of atmospheric variability that effect long-term climate trends, for example, the detection and analysis of equatorially-trapped Kelvin waves (See Figure 3).

In this document, we explore the science questions that GPS can address and that require multi-satellite constellations. At a summary level, the considerations that determine constellation size for *atmospheric* science are:

> ***Climate Science:*** To take full advantage of the benefits of radio occultations for climate studies, a sufficient number of measurements are required so that meaningful climatological averages can be computed from the temperature profiles. If there are too few profiles in a reasonable period (*i.e.* one month), then zonal temperature averages will be imprecise due to natural fluctuations (weather patterns), and computed average temperature will not reflect the "true" climatological average.
>
> ***Modes of Atmospheric Variability:*** Important contributions to temperature variability in the atmosphere are related to identifiable dynamical modes that operate over a wide range of spatial and temporal scales (km-scale to global; hours to months). The precision, accuracy and vertical resolution of GPS observations are being exploited to study a variety of such modes (for example, upwardly propagating gravity waves and equatorially trapped planetary-scale waves). Measurement density sets a strong constraint on spatial and temporal scales that can be resolved in the data set.
>
> ***Weather Forecasting:*** Weather forecasting skill is affected by the number of measurements available per forecast period, currently six hours. Weather impact studies suggest that GPS occultations have a high positive impact *per profile* that compensates for the relatively small number of daily measurements. Determining impact as a function of measurement number is difficult and the published literature is not definitive, however numerous studies suggest a significant impact is probable with the six COSMIC satellites, which will provide timely data for evaluating operational forecasts (Healy et al, 2005; Huang et al., 2005; Liu et al., 2001; Anthes et al, 2000; Kuo et al, 2000). We note in particular that GPS constellations will improve surface pressure maps in the polar regions where existing weather models are least accurate. This is expected to improve retrievals of time-variable gravity from satellites such as GRACE, which are hampered globally by poor estimates of the atmospheric mass distribution near the poles.

The following scientific areas are important to consider for radio occultations, but deriving science requirements for constellation size is difficult at this time:

> ***Tropopause Structure and Variability:*** The tropopause region, or the lower boundary of the stratosphere, has been studied using GPS occultations to understand its vertical structure and global characteristics, however, the lack of a consensus theory of how this region will vary globally, and with climate change, hinders developing scientific requirements for a constellation study. It is likely that a great deal will be learned from the near-term constellation, which will inform future studies.
>
> ***Moist Processes and Climate Modeling:*** The ability of GPS occultations to measure water vapor content in the lower troposphere in the presence of heavy cloud cover is clearly of interest for studying important moist processes at equatorial latitudes, and for understanding the atmospheric energy budget for climate. However, the scientific objectives of GPS water vapor measurements need to be clearly defined before they can serve to drive constellation requirements.
>
> ***Polar Science:*** GPS occultations have excellent polar coverage (as shown in Figure 4 and **Error! Reference source not found.**) and have been used to study stratospheric temperatures of interest to ozone science (De La Torre Juarez, 2006, under review). The polar region, particularly near the surface, may play a large role globally in modifying a warming climate. However, the needed density of GPS measurements in this region is difficult to derive at this time.
>
> ***Coupling between ionospheric waves and Earth's surface:*** The ability of ground-based GPS to detect ionospheric perturbations following solid-Earth events such as Earthquake and tsunami has been proven. There may be a future role for GPS occultations in detection of these events. Basic research is still needed to determine constellation requirements.

At a summary level, the considerations that determine constellation size for *ionospheric* science are:

> ***Coupling Processes In Space:*** Several years of research has made it clear that the Earth's ionosphere and the underlying neutral component (*thermosphere*) are *strongly driven* systems, meaning that external factors such as solar radiation, the solar wind flow, the magnetospheric configuration, and thermosphere composition and winds play a critical role in determining the behavior of the Earth's ionosphere over a variety of spatial and temporal scales. Vertical profiles of electron density available from GPS will help reveal and clarify the relationships between ionospheric behavior and these external factors, because of the unprecedented detail revealed by the profiles. Scientific requirements determining constellation size are based on the horizontal scale lengths that can be resolved for a given constellation size.
>
> ***Global Conductivity Structure:*** Knowledge of the Earth's global electrical conductivity structure remains a significant unknown, due to lack of measurements of the important E-

region (~120 km altitude) which has been a region inaccessible from space. The global conductivity structure is very important for understanding the transmission of electric fields in the ionospheric conductor, which has a major impact on plasma flow and structure during both quiet and disturbed conditions. GPS will provide the first global measurements of the E-region, and therefore the first continuous global measurements of ionospheric conductivity. Constellation size will determine the degree of spatial structure that can be resolved, as well as determine the probability of detecting small-scale disturbances leading to sporadic-*E* (anomalous fluctuations in the electron density at altitudes ~100-120 km).

Mesoscale Structure: The ionosphere forms structure at a variety of scales associated with different processes at auroral, mid-latitude and equatorial regions. Constellation size will determine how well these mesoscale structures can be characterized on a global basis, and how they are related to external processes as mentioned above. Recent discoveries of such structures using dense ground-based GPS receiver networks in the US and Japan are creating significant interest in understanding the global distribution of such structures and how they form.

Irregularities: The ionosphere is subject to small-scale irregularities that cause detectable scintillation (phase and amplitude noise) of radio signals including GPS. The global distribution of these irregular structures has been studied as a function of latitude from ground-based instruments where available, but not from the global perspective of space. (The exception is one publication on scintillation occurrence from the IOX experiment; Straus et al., 2003). Characterizing the global distribution of irregularities depends on constellation size.

2.1. Traceability Matrix for Atmosphere Observations

Table 1 contains science objectives related to atmospheric GPS occultation measurements. The science that can be achieved with different numbers of receivers is estimated.

Science Question		**Measurement Objective**	**Constellation Size**	
			9	**31**
What is the long-term trend in global upper-atmospheric temperatures, including the lower stratosphere?		Absolute traceable temperature accuracy of 0.1K, 5 km-25 km altitude; adequate diurnal sampling	100%	100%
What are the dominant wave modes of the atmosphere and how are they changing?	Planetary scale (daily periods)	Same	100%	100%
	Gravity waves (> 6-hour periods)	Same	10%	20-50%
What is the diurnal cycle of atmospheric temperature, and how is it changing?		Same	100%	100%
When are expected forecasting benefits fully achieved with a GPS occultation?		Same	Unknown	100%

Table 1 – Traceability matrix, GPS atmospheric science

2.1.1. Science Requirements for Atmospheric Science

The scientific benefits of radio occultations are a result of: high accuracy, the lack of appreciable inter-satellite bias in the temperature observations, and the rapid repeat time of observations over a given location, due to the constellation geometry. These features are not available from other Earth science measurement systems. In this section, we describe scientific return as a function of constellation size.

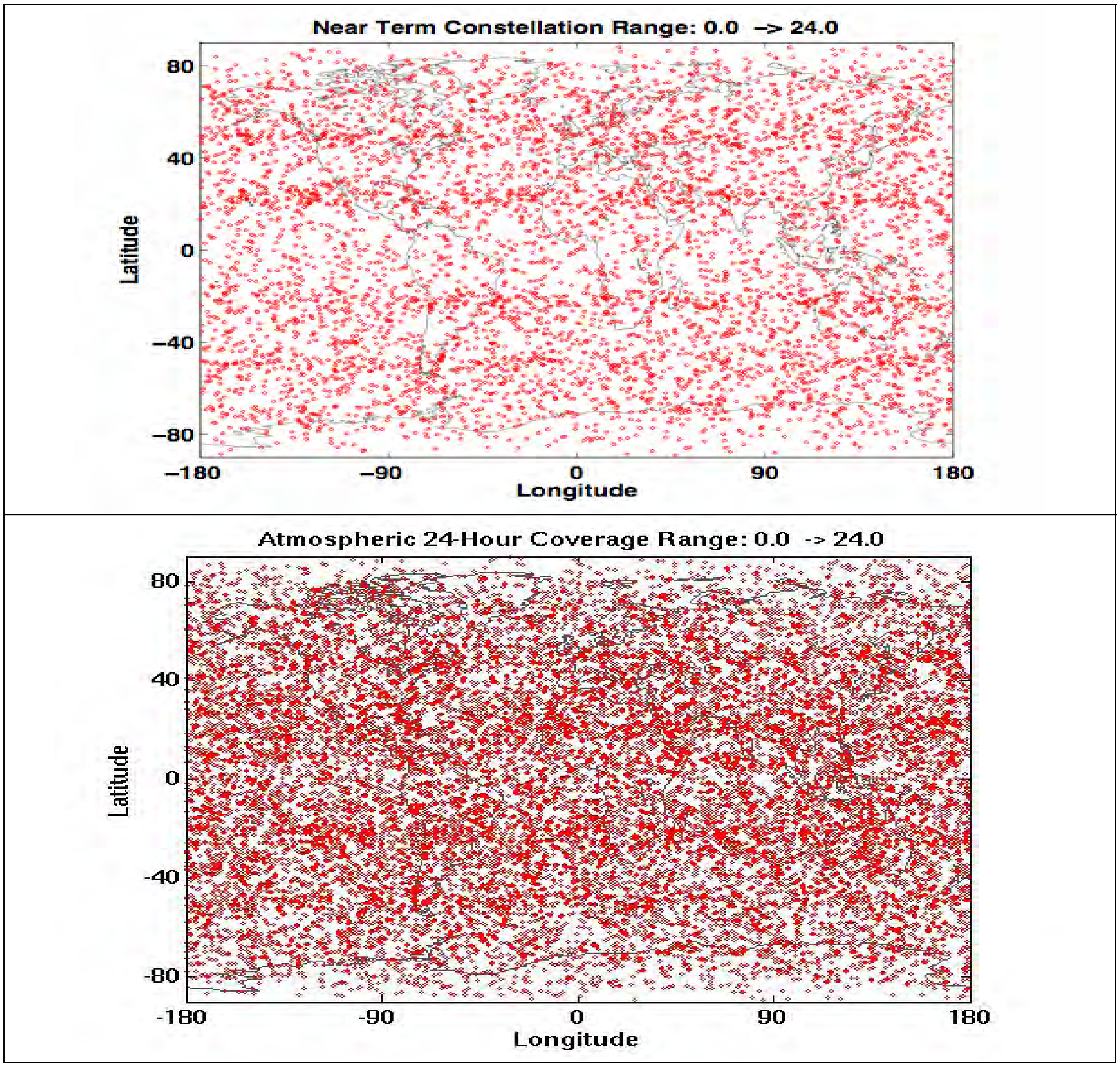

Figure 4 – Atmospheric profile distribution in a 24-hour period for near-term and "full" constellations.

Our starting point is a possible future constellation of opportunity that might be similar to the existing NASA+NOAA constellation of approximately 31 low-Earth orbiting satellites. (A listing is found in Appendix 2.) We have simulated this orbital configuration and assessed the science questions in Table 1 taking into account measurement location and density. Figure 4 shows where occultations would occur over a 24-hour period. **Error! Reference source not**

found. shows the distribution of the measurements as a function of latitude band. There are over 1000 occultations at high latitude per pole per day (> 60 degrees N or S) providing an excellent set of data for polar science, particularly since frequent cloud cover at these latitudes does not degrade GPS retrievals. The numbers in these figures should be regarded as lower limits because we have not included the Galileo transmitting constellation, planned for 2010 and beyond. Galileo will likely double the number of observations.

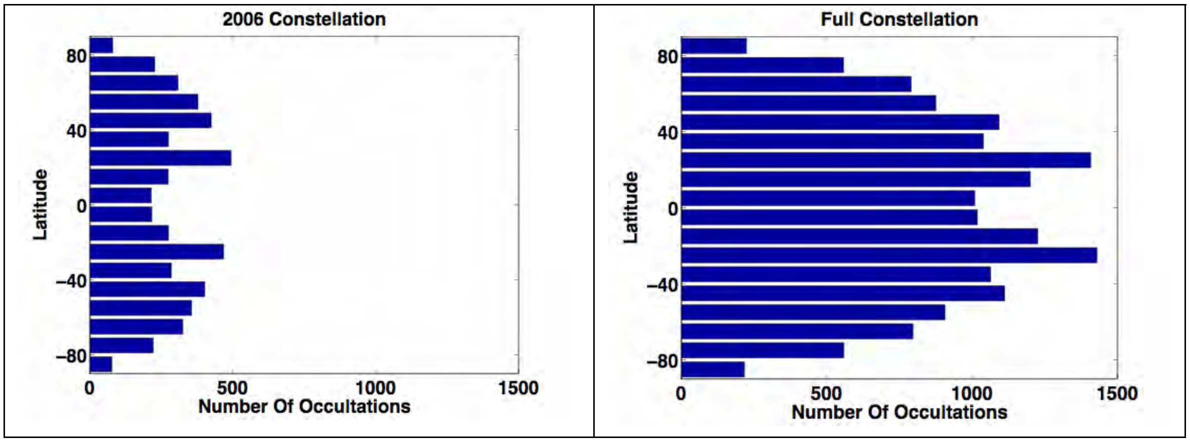

Figure 5 – Histogram of measurement number by latitude for the two constellations considered.

Constellation Size and Climate Sensitivity

An important consideration for climate observing systems is whether sufficient measurements are obtained per unit time to produce meaningful averages of air temperature. An observation of "climate" is meant as an observation of average behavior that is not strongly influenced by short-term variations due to weather. If occultation sampling is not sufficiently dense or evenly distributed, climatological averages determined from these data will not be sufficiently precise to determine expected temperature trends, which are in the range ~0.1 K per decade.

To understand the constellation size needed to characterize climate, we have used weather reanalysis from the National Center for Environmental Prediction (NCEP) of NOAA to estimate atmospheric fluctuations over several decades, and determine whether the near-term constellation provides a sufficient distribution of measurements. The results for a six-satellite constellation similar to COSMIC are shown in Figure 6 for two pressure levels and two latitudes reported by NCEP[†]. This is a plot of the difference of two averages extracted from the weather model for the month of June over the last 58 years: 1) the average of NCEP values computed at the locations of simulated radio occultations for the month, versus 2) the mean value of NCEP computed directly from the NCEP grid, over that same month. We computed zonal averages over all longitudes (and local times) within a given latitude band for the month.

The differences in Figure 6 simulate how well a six-satellite occultation constellation can capture monthly-mean temperature trends over a multi-decadal period. The differences between the average temperatures computed from the constellation and the "true" temperature averages are quite small year-to-year, and show a negligible trend (the linear fit to each data series is shown).

[†] Resource limitations prevented us from running month-long simulations of the near-term and full constellations. A reasonable LEO constellation was decided on for the near-term case.

This suggests that sampling error will not cause spurious trends in monthly-mean temperatures. The results are shown for two pressure levels (850mb and 100 mb) and two latitude bands (77.5 and 12.5 degrees). The yearly temperature fluctuation (RMS) is smaller than 0.1 K for the bottom three panels, suggesting that the averages are precise enough to discern small trends (~0.1 K/decade) within a few years, if these trends are detectable over background variability. The fluctuations at high latitude near the surface (850 mb, top panel) are larger, requiring more years of averaging to constrain a trend. In either case, these results suggest that if the expected number of NASA research satellites (9-12) carried GPS radio occultation receivers, the measurements would be dense enough to form useful climatological averages. Results will improve for receivers capable of acquiring the new Galileo signals expected after ~2010.

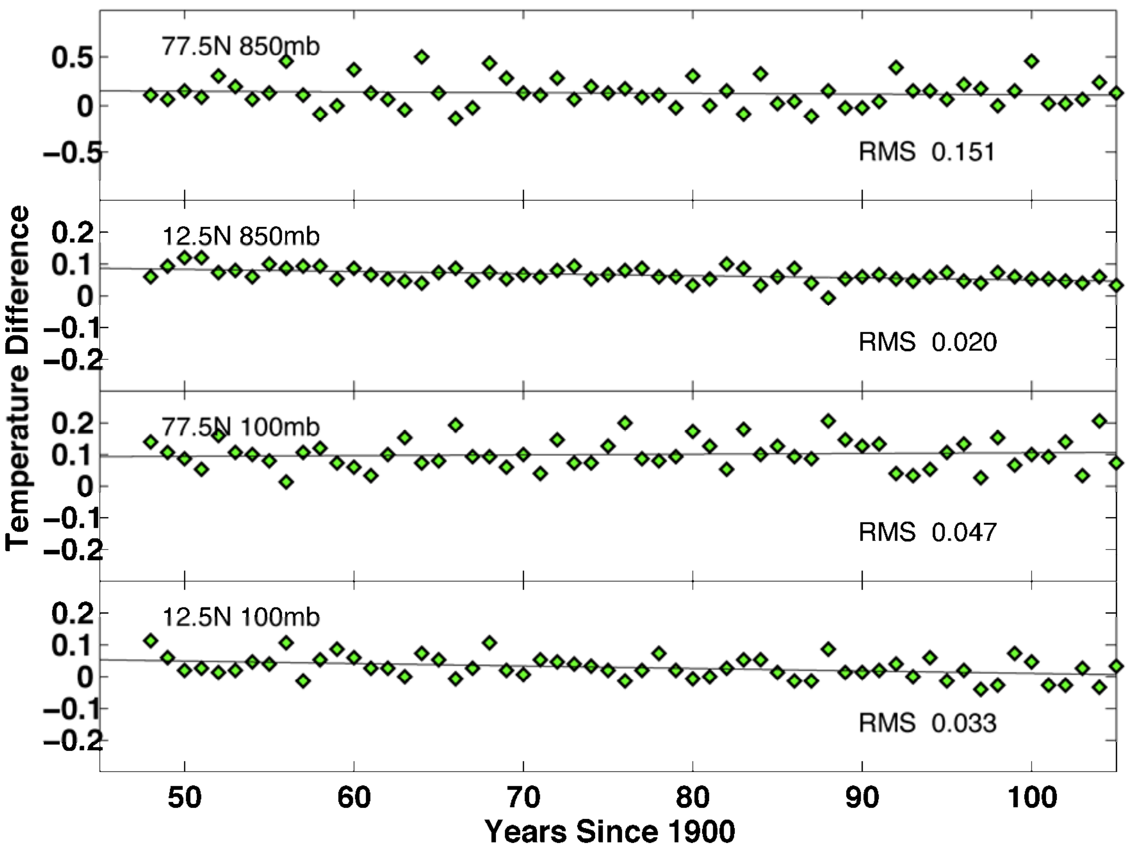

Figure 6 – Temperature differences are computed for the month of June spanning decades of NCEP reanalysis data. The differences are between the "true" zonal-average temperatures from NCEP versus the average computed from a simulated radio occultation constellation. Temperature differences between these two averages are sufficiently small suggesting that a COSMIC-like constellation provides sufficient sampling to discern small (~0.1 K/decade) monthly-mean temperature trends.

Climate and Local Time Coverage

The zonal climatological averages computed in the previous section were averages over all temperatures in a given latitude band for one representative month per year. The averages were explicitly over longitude, but local time averaging occurs as well because of the distribution of orbital planes. It turns out that local time coverage is critical for meaningful measurements of long-term climate, because significant local-time gaps bias the averages to what is occurring at the well-sampled local times, which may not represent true global averages. It is well known that atmospheric temperatures are subject to diurnal and semi-diurnal (12-hour) cycles, and higher harmonics of the diurnal cycle. Leroy (2001) showed that climate trends deduced from orbits with limited local time coverage are biased with respect to the global trend. Therefore, we have studied the local time coverage of the near-term and full constellations (Figure 7a & b). Figure 7a demonstrates that local time coverage is excellent for even the near-term constellation, which is primarily due to the final placement of the six COSMIC satellites, ensuring that the zonal averages computed from upcoming radio occultations are in fact good representations of the "true" zonal average.

Modes of Atmospheric Variability

Understanding the variability of key atmospheric parameters (such as temperature) is scientifically important because it underlies our ability to understand global-scale changes over time, or changes in global climate. A component of atmospheric variability is caused by vertically-stratified wave motion that is important in its own right as a mechanism for transporting atmospheric momentum over vast distances and between altitudes. It is clear that accuracy better than ~1K and vertical resolution better than ~1 km are very useful for these sorts of studies. The high vertical resolution and accuracy of GPS temperature retrievals has been exploited recently by scientists interested in atmospheric variability caused by planetary-scale waves (large-scale waves with periods of several days) and gravity waves. See for example Randel and Wu (2005); Tsuda and Hocke (2004).

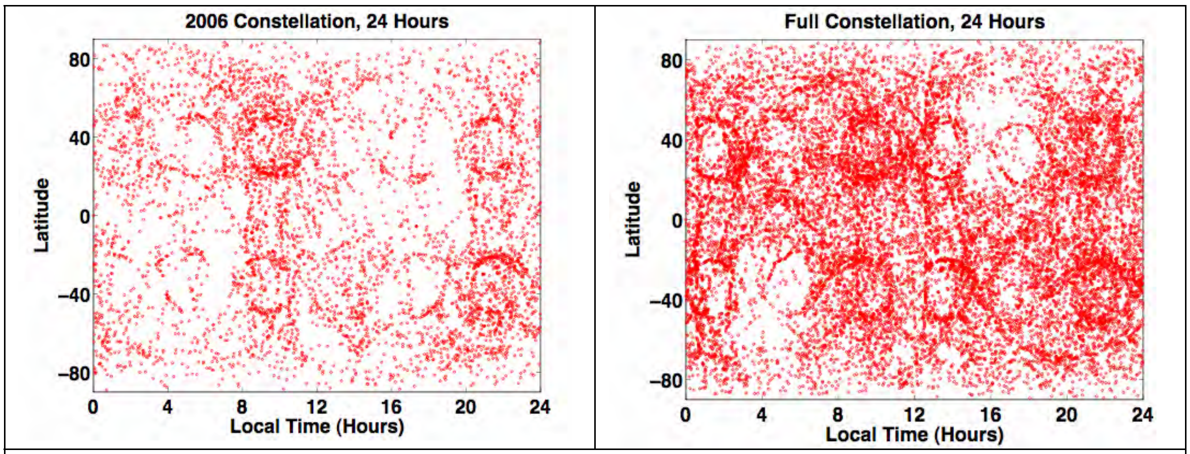

Figure 7 – a) shows the local time coverage for the near-term 12-satellite constellation, and b) shows the local time coverage for the full 31-satellite constellation.

We assessed the potential of a GPS-based constellation of opportunity in studying a spectrum of variability (wave) modes that are known or thought to exist but are poorly characterized at present. The Randel and Wu (2005) study analyzed Kelvin waves with periods of several days and wavelengths of several thousand km using data from only two satellites: CHAMP and SAC-C (one antenna each). Here we analyze the extent to which GPS constellations can detect waves over a broad spectrum of scales, from a few hundred to several thousand-kilometer horizontal wavelengths. An interesting region of the spectrum carrying significant momentum is from waves with short periods and small horizontal wavelengths. Unfortunately, waves with long periods and long wavelengths are much more easily observed. Our analysis shows that the full 31-satellite constellation would do a reasonable job of measuring a useful regime of the spectrum. Figure 8 is a plot of wave period versus wavelength for well sampled wave modes, assuming 400 measurements per day constitute sufficient sampling of a particular mode (for a derivation of this plot, see Appendix 1 at http://pearljam.jpl.nasa.gov/gps). This graph is interpreted as follows: for a given wave period (x-axis), the red line shows the minimum wavelength that could be detected with sufficient sampling. Waves shorter than this minimum will be difficult to capture using the full constellation.

Also plotted in Figure 8 is the maximum detectable speed of the wave corresponding to the detectable periods and wavelengths. The speed is important, because it will rarely exceed ~170 m/sec (green line) and therefore the shortest period waves (<~6 hours) are marginally observable because only waves approaching the maximum speed can be detected. For a given wave period, waves with speeds slower than the blue line are observable. See Appendix 3 for details.

This analysis is simplified because we have not taken into account that the shorter-period waves are intermittent, that is, they are not always present to be observed by the (also intermittent) measurements. Therefore, even the full constellation cannot fully characterize wave periods of six hours or longer. We estimate that 20-50% of the science can be accomplished, limited by intermittency and other factors. It is important to note that a full constellation of GPS receivers represents a major advance compared to what is now available or planned for characterizing and understanding atmospheric variability at these smaller scales.

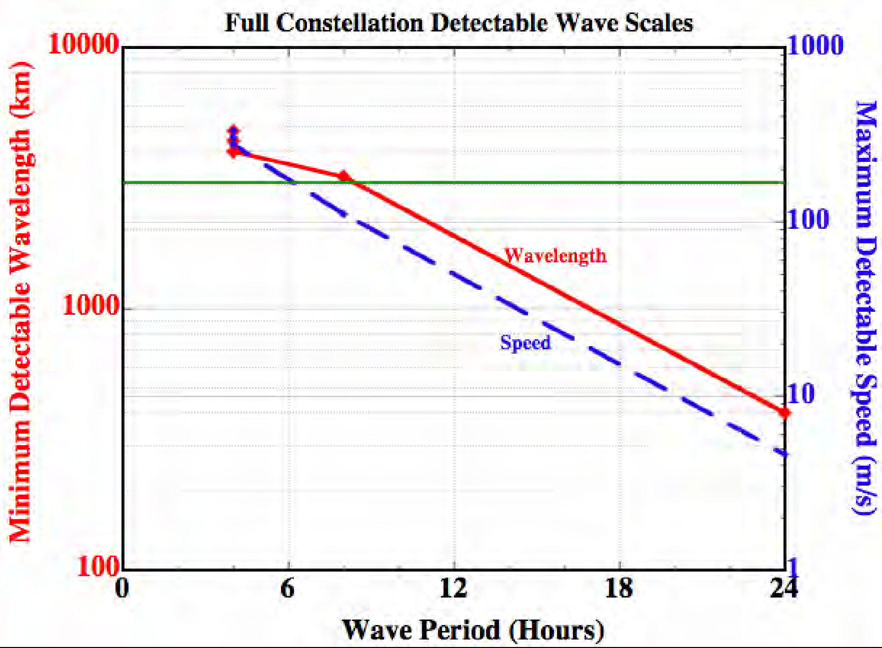

Figure 8 – A plot of wave periods and wavelengths observable by the full constellation, assuming 400 measurements/day are available for the given scale and period (see Appendix 3 for details). Wavelengths above the red line are resolved for a given period. The blue line is the maximum wave speed observable corresponding to the given period and wavelength. The green line is the maximum expected wave speed over a broad range of spatial and length scales.

Weather Forecasting

A major impetus for the six-satellite COSMIC constellation is an expected improvement to weather forecasting. Studies conducted over the last several years have shown that GPS occultations will be a useful addition to the global weather observing system (for a recent example, see Healy et al., 2005 and also Huang et al., 2005; Liu et al., 2001; Anthes et al, 2000; Kuo et al, 2000). Weather forecasting offices in the United States (NCEP) and Europe (ECMWF) are preparing to incorporate radio occultation data from COSMIC and the GRAS GPS receiver onboard the European MetOp satellite. However, in advance of prossessing the actual data, it is not a simple matter to assess accurately the expected weather forecasting benefits versus constellation size, and no published study exists for radio occultation constellations. It is widely believed that COSMIC's six-satellites will have a demonstrable positive impact (Healy et al.'s 2005 study suggests a benefit with only a single satellite) but the relative impact of more satellites is not known and there is no quantitative information to derive constellation size requirements. Therefore, in Table 1 we list as "unknown" the degree to which the near-term constellation fully realizes the weather potential of GPS, but we expect that the full constellation of 31 satellites does reach that potential, certainly as far as global weather forecasting is concerned. (Mesoscale forecasting could probably benefit from hundreds of orbiting receivers, but this is beyond our scope).

We expect GPS measurements in the polar regions will greatly increase our understanding of how polar weather impacts weather in the lower latitudes. Current weather measurements collected in the polar regions are very limited. Improved polar weather maps will also aid gravity retrievals from the GRACE spacecraft, and similar follow-on missions. This is becoming particularly important as new scientific results indicate that the mass distribution of polar ice sheets is changing rapidly.

2.2. Traceability Matrix for Ionosphere Observations

Table 2 contains the science objectives related to GPS occultation signals in the Earth's ionosphere.

Science Question	**Measurement Objective**	**Constellation Size**	
		9	**31**
What is the large-scale global distribution of ionospheric conductivity, and how does it vary under quiet conditions and disturbed conditions?	Electron content to 0.01 TECU, 50 Hz data rate; good polar coverage	100%	100%
What are the dynamics and causes of mesoscale structures in the ionosphere?	Electron content to 0.1 TECU	30%	100%
What is the long-term climatology of mesoscale structures, and irregular structures causing scintillation of radio frequencies?	Electron content to 0.01 TECU, 50 Hz data rate; good polar and equatorial coverage	100%	100%
How well do low-to-mid latitude ionospheric instabilities correlate with weather and/or geomagnetic activity?	Electron content to 0.01 TECU, 50 Hz data rate; good equatorial coverage	30%	100%

Table 2 – Traceability matrix, GPS ionospheric science

2.2.1. Considerations for Ionospheric Science

Ionospheric science will benefit greatly from constellations of GPS receivers. These measurements will constitute the first simultaneously global sampling of the vertically-resolved electron density distribution, which has been measured only sporadically before now. The types of science that can be accomplished depend on the spatial and temporal scales of the phenomena under study.

Space climate: The near term constellation provides sufficient coverage for studying phenomena on monthly to multi-year time scales. Recent results using GPS ground observations demonstrates that interesting and poorly understood trends exist at these longer times (Mendillo et al., 2005).

Mesoscale structures: To answer questions regarding mesoscale structures, Figure 9 shows the number of occultations available on average per 100x100 km square area per day. The following should be considered for mesoscale structures of scientific interest in the ionosphere:

- Spatial scales ~100-1000 km
- Temporal scales ~20 minutes – few hours

Figure 9 shows there is of order 0.3 measurements per 100x100 km square area every day with the full constellation. Clearly, this is insufficient to *fully* characterize structures of ~100s-of-km scale, which vary substantially in 1-3 hours, corresponding to structures that form under disturbed conditions. However, even one or two height-resolved measurements taken within these structures, that may be detected for example using other methods such as ground-based radar (reference to SuperDarn) or imaging (Polar, TIMED, ground-based GPS networks) can provide a wealth of scientific information on the processes working to create and maintain the phenomena. Larger structures of ~1000 km extent are sampled with 100 times more density, so that a fuller characterization is available from the full constellation on these distance scales.

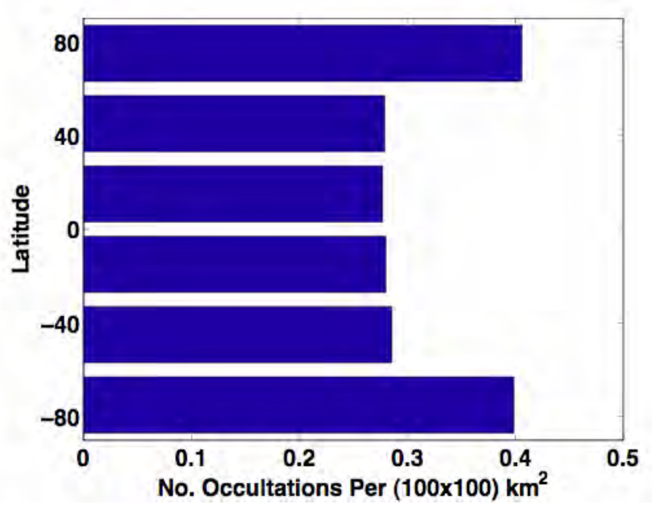

Figure 9 – The number of ionosphere measurements landing in a 100x100 km^2 area per 24 hours from the full constellation, by 30-degree latitude band.

Table 2 lists several science questions that can be addressed by the full constellation. This list is only a high-level description of the possible questions that can be addressed. Clearly, the near-term constellation will provide important new science on global-scale characterization of the ionospheric conductivity by providing E-region densities. There will be fortuitous coincidences between occultations and mesoscale structures yielding interesting information. And climatic effects, or large scale phenomena during storm onset and recovery phases, such as continental-scale regions of depletion and enhancement, will be measured by the near term constellation.

The global distribution, causes and consequences of mesoscale structures (~100 to 1000 km extent) are best addressed by a constellation of ~30 satellites. Full characterization of the formation and distribution of small-scale irregular structures is best addressed with the full constellation combined with ground measurements and satellite imagers (nightside). However, longer term averages of the climatology of irregular structures (how often they form at certain longitudes and local times, etc.) will be addressed well by the near-term constellation.

2.3. Traceability Matrix for Ocean Observations

To evaluate the needed size of receivers' constellations as a function of the ocean science capabilities, simulations were performed using the following assumptions:
The current GPS constellation as available as transmitters
Reflection-capable receivers are available on constellations of 6, 18, and 37 LEO satellites
In the first case only the orbits of the COSMIC constellation were chosen, whereas the third case simulates the situation where all existing NASA satellites (assuming their orbits are representative of future satellites) are equipped with GPS receivers capable of tracking and processing reflections. The intermediate case assumes that an additional set of twelve LEO satellites, chosen randomly among the existing NASA satellites, have been added to the COSMIC set. The receiver is equipped with a steerable 20 dB gain antenna, with field of view capable of intercepting all available reflections. An antenna array and GNSS receiver system with multiple steerable beams is currently being developed at JPL and could potentially be used in future missions for GNSS reflection. Each single reflection measurement is integrated over 1 sec. The characteristics of a single measurement are summarized in Table 3.

TOGA(multilag processing and 20 dB antenna gain)	Integration time	Height prec, cm	Footprint, km
	1 sec	Near nadir, 5	Along track,<10
		Near grazing, 25	Cross track, <10

Table 3 – Instrument Characteristics of TOGA Receiver

The traceability matrix summarizing the flow down from science questions (Table 4) to observations' requirements and constellation size is presented in Table 5.

#	**Science Question**
1	Can we measure sea ice surface topography (freeboard), to determine sea ice thickness and mass balance?
2	Can we measure wind for a) improved vertical mixing at the mesoscale; b) monitoring and prediction of severe weather systems; c) high resolution wind forcing and attendant coastal ocean response (e.g., local upwelling)?

3	Can we measure the sea surface topography with sufficient spatial and more importantly temporal resolutions to monitor the evolution of mesoscale ocean eddies and coastal oceans?

Table 4 – GPS Ocean Reflections Science Questions

Cellsize (km)	Science Question	Latitude Bin	Time Scale	Precision (cm)	Constellation size		
					6	**18**	**37**
2	#1	> 60	15 days	5~10	<78%	<90%	<95%
	#1		30 days		<95%	100%	100%
	#2	All lats	6 hours	N/A	-	-	-
5	#2	All lats	6 hours	N/A	-	<20%	<25%
	#3		1 day	2~10	<23%	<52%	<75%
	#3	-60< x < 60	1 day	2~10	<52%	<78%	<90%
10	#3	-60< x < 60	1 day	2~10	<63%	<94%	100%
	#3		5 days		<99%	100%	100%
25	#3	-60< x < 60	1 day	2~10	<95%	100%	100%
	#3		5 days		100%	100%	100%

Table 5 – Traceability Matrix from Science Questions to Observation Requirements for GPS Ocean Reflections Measurements

Two science areas have been addressed: ice-free sea surface topography and sea ice topography and mass. Correspondingly, the observational requirements are mapped into latitudinal bins, cell sizes and revisit times. For each case, the percentage of cells that records at least one (in some cases more) reflection is reported. The table quantifies coverage, and required precision. It is very difficult to establish how the precision requirement is met. In fact, this depends on the reflection angle, as reported in Table 3, for the individual measurement as well as on the number of reflections in a given cell and time. The required precision is met with the highest confidence for the situation of 25 x 25 km cell size, both 1 and 5 days repeat cycles. By contrast, the simulations clearly show inadequate coverage for the situation of 5 x 5 km cell size (and below), 6 hours repeat cycle. It is noted that when the Galileo constellation doubles the number of transmitters, the number of measurements in any given cell increases commensurately, thus improving the precision. The coverage (repeat time) of the system will not improve dramatically, since it is ultimately determined by the number and position of the receivers.

3. GPS Atmosphere Science

The Global Positioning System, which was first conceived and built for the purpose of navigation, has been utilized in the last decade to study the Earth's interior, surface and environment in ways that far exceed anyone's original expectation. Scientific applications of the GPS include measuring seismic tectonic motions, Earth orientation and polar motion, gravimetry, neutral atmospheric temperature and water vapor profiling, and ionospheric electron density profiling and global monitoring. [Beutler et al., eds., 1996] All of these applications have been well proven and provide new ways to enhance our knowledge about the Earth and its environment. The advantage of GPS is twofold: the transmitted signal is always globally present and the receiver technology is inexpensive, compared to alternative remote sensing systems.

3.1. Approach

GPS limb soundings or “radio occultations” (GPSRO) are an innovative way to measure temperature, pressure, and humidity profiles in the Earth’s atmosphere with very high accuracy, precision, and vertical resolution. GPSRO are active limb soundings in which a GPS receiver onboard a Low Earth Orbiter tracks the coherent signals broadcast by one of the 24 GPS satellites as it occults behind the Earth's atmosphere. High-precision tracking data can be used to retrieve high-resolution vertical profiles of temperature and pressure in the troposphere and stratosphere, and humidity profiles in the lower troposphere. These data have a variety of scientific applications that are discussed elsewhere in this report.

GPS signals traversing the atmosphere are bent by the atmospheric density gradients perpendicular to the ray path (see Figure 10). This bending introduces a delay in the signal which is measured precisely. The signal's delay rate of change is used to calculate atmospheric temperature and pressure profiles as a function of height [e.g. Kursinski et al 1996, Hajj et al. 2002]. The vertical resolution of GPSRO profiles is typically from 100 m in the lower troposphere to 1000 m in the upper stratosphere, and the horizontal resolution is approximately 200-300km. This vertical resolution is higher than any other space-based remote sensing technique, and is an important feature of the measurements for scientific investigations. Since the fundamental quantity being measured is a time delay, it is relatively straightforward to absolutely calibrate the data, which is a very important feature for establishing the atmosphere’s long-term climatic trends. The power consumption and mass of the receivers is relatively modest, as is the cost of reproducing a given receiver design, making it highly desirable and cost-effective to deploy several RO receivers simultaneously in a constellation. The combination of high precision, high accuracy, vertical resolution and affordable constellation scenarios are generating great interest in GPS as an atmospheric remote sensing tool.

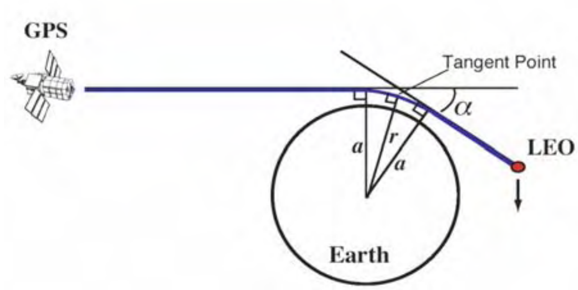

Figure 10 – The geometry of GPS radio occultations. Atmospherically-induced signal bending (α) is used to infer vertical profiles of temperature and pressure, and moisture below about 5 km. Each GPS satellite transmits a signal at two frequencies (L1 and L2) to facilitate removal of ionospheric delays. *a* is the asymptotic miss distance or “impact parameter”.

This report contains a science traceability matrix that relates parameters of a GPS constellation to a focused set of science objectives, including:

- **Climate benchmarking:** use the accurate calibration of GPS-derived profiles to generate a climate data record meeting the needs of climate science.
- **The diurnal cycle:** a well-distributed constellation can measure diurnal variation of tropospheric and stratospheric temperatures, important for understanding the sources of atmospheric variability that affect our understanding of long-term climate change.

- **Atmospheric waves and variability:** use the high vertical resolution and accuracy to characterize important "hidden" modes of atmospheric variability that drive large-scale circulation and variability. For example upward propagating gravity waves and other modes such as Kelvin waves and planetary-scale waves.
- **Weather forecasting:** GPS provides cloud-penetrating, high-resolution vertical temperature and refractivity profiles that studies show will have a significant positive benefit in weather forecasting.

3.2. Limitations

The major limitations of GPS remote sensing occur near the upper and lower boundaries of the altitude range covered by the science profiles, approximately 30 km to the surface. At high altitudes, the sensitivity of the technique gradually drops off as the atmospheric density decreases with altitude, increasing the impact of thermal noise and residual non-calibrated error sources.

At lower altitudes, in the range approximately ~0-5 km, the increasing presence of water vapor prevents unambiguous interpretation of atmospheric bending in terms of atmospheric density, temperature and pressure. Refractivity and bending itself is accurately retrieved at these altitudes, and could be used for certain investigations, but this quantity is a somewhat "non-standard" and unfamiliar scientific observable. Water vapor, an important greenhouse gas, can often be retrieved to high accuracy (~20%) using temperature estimates from an accurate analysis field such as from the European Center for Medium Range Weather Forecasting (ECMWF), but independent temperature retrievals are not available from GPS in the lower 5 km of the atmosphere.

Another problem at low altitudes is due to an atmospheric phenomenon known as "ducting" that occurs when large vertical refractivity gradients bend the GPS signal to such a degree that it remains "trapped" in an atmospheric layer within a few km of the surface. Existing processing techniques result in a cold bias in retrieved temperatures of order ~ 1-3 K. Mitigating the impact of ducting is an active area of research, but as a practical matter ducting limits the applicability of climate-quality GPS observations to above 5 km altitude.

3.3. Programmatic Considerations

Several countries and U.S. agencies are participating in the growth of GPS occultation science research and operations. The World Meteorological Organization has recommended an operational constellation of radio-occultation satellites as part of the Global Climate Observing System (GCOS). To date, several successful GPS occultation instruments have been flown on a variety of spacecraft platforms, including: Ørsted, SUNSAT, CHAMP, SAC-C, GRACE, IOX, and COSMIC. The COSMIC six satellite constellation, launched in April 2006, is a particularly important development in GPS occultation science. As detailed in the previous simulations section of this report, by including GPS receivers on future NASA LEO satellites we can continue where COSMIC leaves off by establishing long term records of atmospheric parameters. GNSS modernization over the next decade will increase the quantity and quality of the measurements, by increasing the number of transmitters (Galileo system) and removing signal encryption (GPS and Galileo).

An important development in GPS occultation research is the existence of multiple science data analysis centers that generally have full access to data from several GPS occultation receivers. This permits continuous cross-comparison of science products from the different centers, which is of great utility for establishing the climate quality of atmospheric data derived from GPS. Each center uses different processing strategies, and the degree of agreement between the different centers permits processing errors and systematic effects to be detected and characterized.

4. GPS Ionosphere Science

4.1. Approach

The GPS system provides information on the delay of a radio signal propagating through charged particle media such as the ionosphere and plasmasphere. This delay is proportional to the path-integrated density of electrons between the transmitting GPS satellite and the receiver, and has proven to be extremely useful scientifically because it reveals a great deal of information about plasma structure over a range of spatial scales. Plasma structure, in turn, is extremely sensitive to the geophysical environment in which it forms and is transported, and reveals information about the solar spectrum, thermospheric composition, density and winds, electric fields, auroral precipitation, and a number of physical phenomena that cause plasma instabilities and resultant small-scale structures to form within the plasma. Therefore, studying plasma structure using GPS is becoming an important tool for understanding the interrelationships of a wide range of geophysical phenomena that affect the Earth's geospace environment.

The following features of GPS are used to advantage for scientific investigations of the ionosphere and plasmasphere:

1. ***High precision and accuracy:*** GPS total electron content (TEC) accuracies are in the range 1-3 TECU (1 TECU = 10^{16} el/m^2), and TEC precision is of order 0.01 TECU or better using geodetic quality receivers, providing data very useful for scientific investigations of the ionosphere, plasmasphere and small perturbations therein.
2. ***Sensitivity to vertical plasma distribution:*** TEC acquired from a low Earth orbiter in occultation geometry provides information about the vertical plasma structure, achieving sub-km vertical resolution profiles.
3. ***Sensitivity to small-scale ionospheric irregularities:*** Scintillation of the L-band GPS signal provides information on the location and, for some studies the scale size and velocity, of small-scale (~100s meters) irregularities that arise in the ionosphere at high (auroral) and low latitudes (for different reasons), and at mid-latitudes during geomagnetically disturbed periods.

A schematic representation of the GPS measurement system is shown in Figure 11 within the context of the physical regimes that are being studied. GPS satellites orbit at 20,200 km altitude, and are often beyond or near the outer edge of plasmasphere (the tenuous extended region of the ionosphere beyond about 1000 km altitude consisting primarily of H+ ions). An example profile obtained by this method is shown in Figure 12. We note in particular the retrieval of fine-scale vertical structure in the E-region, an important region of the ionosphere where conductivities are usually largest and the majority of ionospheric currents flow, but for which limited information exists on global scales.

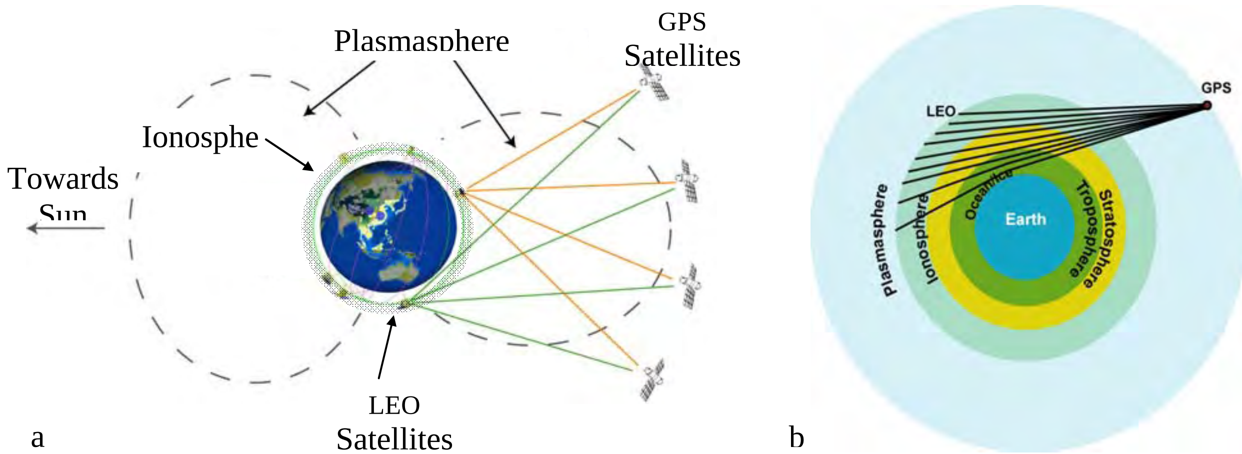

Figure 11 – Schematic representation of total electron content measurement geometries provided by GPS for low-Earth orbiting (LEO) receivers and from the ground. (a) zenith and side-viewing acquisition. (b) occultation geometry. Not shown is acquisition of reflected signals.

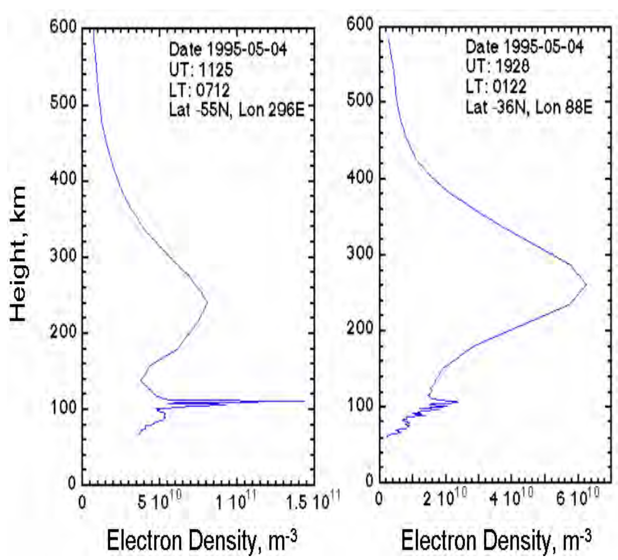

Figure 12 – Electron density profiles obtained by the GPS/MET occultation experiment, from Hajj and Romans, 1998.

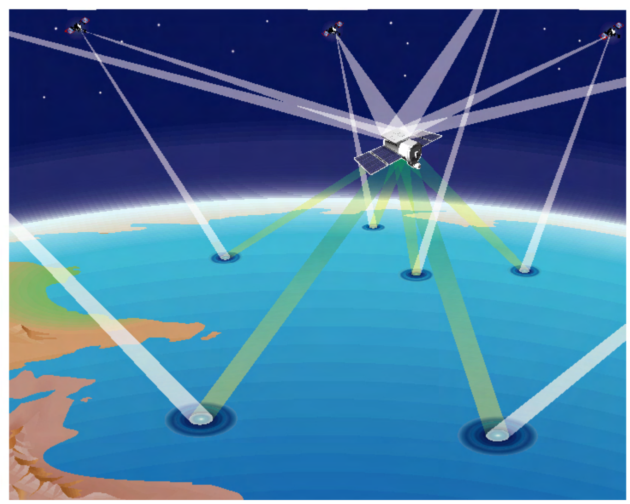

Figure 13 – An Earth-orbiting instrument uses direct GNSS signals for precise positioning, but also receives reflected signals to make several simultaneous bistatic altimetric measurements.

The ionosphere science objectives that are well-addressed by GPSRO are as follows:

- **Storm-enhanced hemispheric-to-mesoscale density structures:** recently discovered plasma structures that develop in response to geomagnetic storms can be studied from space, providing information on their vertical and horizontal structure and their global distribution (Ho et al., 1996; Foster et al., 2002).
- **Global conductivity structure:** the impact of electric fields from wind-driven dynamos, and the external magnetosphere, can be better understood by measuring E- and F-region electron densities globally using GPS occultation (Kelley et al., 2005).

- **High-latitude plasma structures:** complex electron density structures in the high-latitude ionosphere, which form for a variety of reasons and in turn affect magnetosphere-ionosphere coupling, can be studied using the polar distribution of GPS occultation measurements.

4.2. Limitations

The GPS science instrument can measure the distribution of plasma, but not the underlying causes that determine that distribution. Combining GPS measurements with in-situ sensors that measure winds and electric fields is useful for scientific investigations. However, for wind measurements, in-situ technology requires altitudes of ~450 km or lower, which is not ideal for GPS technology because the occultations cannot probe vertical structure above the orbit altitude. Therefore, a constellation optimized for GPS observations could not have the full complement of in-situ sensors, assuming existing technology.

4.3. Programmatic Considerations

Constellations placed in orbit for atmospheric science are well-suited for ionosphere science if they are of sufficient altitude to orbit above most of the ionosphere, for example 750 km or higher. The receiver technology is largely similar to that deployed for COSMIC, although software enhancements to measure rapid fluctuations due to scintillation are a necessary addition. Both the COSMIC constellation and the CORISS instrument (C/NOFS Occultation Receiver for Ionospheric Sensing and Specification), on the future Air Force C/NOFS (estimated launch in January 2008) satellite will provide valuable ionosphere data but do not have the temporal coverage to answer all the relevant science questions. Once again, there is an opportunity to fill this data gap by adding GPS receivers to future NASA LEO satellites.

5. GPS Ocean Science

This section discusses a technique for ocean remote sensing based on detecting a GNSS signal after it is reflected off the ocean surface, to measure sea surface topography and roughness (from which wind speeds are retrieved) at high spatial resolution and rapid temporal coverage. (See Figure 13.) The weak reflected signals require a high-gain multi-beam steerable antenna. The topography measurement is suitable for the global monitoring of ocean eddies, which is currently precluded by the existing altimeters, due to their track separation and repeat cycle.

5.1. Global Ocean Altimetry

The Oceans, and their interactions with the atmosphere and the lithosphere, play a significant role in Earth's climate. Understanding climate variability is very important to insure the well being of our planet; this implies quantifying all the significant processes that contribute to climate and its changes. One such process, mesoscale ocean eddies, analogous to atmospheric storms, represent one of the dominant global climate errors [see HOT_SWG 2001 for a review]; they are essential to understanding ocean circulation on all scales and are an important contribution to the carbon cycle.

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 [Barber, et al., 1996]. 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 [Smith, et al., 2000]. Ocean eddies have a typical spatial scale on the order of 10 to 100 km and a temporal scale from days to weeks. The sea level signal associated with mesoscale eddies is usually 10 cm or more.

At present, quantifying the role of mesoscale eddies in the ocean circulation and therefore climate variability cannot be done simply because their spatio-temporal structures are not resolved by the conventional remote-sensing techniques. Observations of sea surface temperature (e.g., those from Advanced Very High Resolution Radiometers) are frequently contaminated by clouds in the atmosphere. The conventional satellite radar altimeter measures the sea surface height at high spatial resolutions along its ground track (e.g., 7-km for TOPEX/Jason). However, the cross-track distance is usually quite large. For a 10-day repeat orbit with TOPEX/Jason, the cross-track distance is more than 300-km at the equator, which is too coarse to resolve the evolution of ocean eddies.

Another limiting factor is the long repeat cycle of a given satellite, e.g., 10 days for TOPEX/Jason, 17 days for the Geosat-Follow-On (GFO), and 35 days for ERS. Because of the long repeat cycle, some fast propagating ocean waves cannot be properly resolved by satellite altimetric observations. Additionally, some barotropic (i.e., vertically uniform) waves with a periodicity of 20 days or less can be aliased into the 10-day sea level map produced by the TOPEX/Jason data. Hence, there is a need for high spatial and temporal resolution altimetry.

High-resolution ocean altimetric measurements will allow oceanographers to compute high-order quantities like vorticity and eddy fluxes, which will be used to study the interactions between the eddy fields and the time-mean flow. Several important science questions can be addressed by such a high-resolution data. For example, what is the role of mesoscale (ocean) eddies in the large-scale ocean circulation and climate variability? What is the impact of mesoscale eddies on the biological production and therefore the global carbon cycle? If mesoscale eddies are important in modulating the large-scale ocean circulation and climate, there is a need to resolve (or parameterize) ocean eddies in the Earth System Model (coupled atmosphere-ocean-land) for climate prediction purposes.

Traditional altimetry is limited to looking in the (nominal) nadir direction and obtaining one height observation at a time below the altimeter, following very nearly repeatable tracks passing over the same point every ten days. The track separation varies, being largest at the equator where it is about 300 km. The concept of wide-swath ocean altimetry improves the coverage and spatial resolution of traditional altimetry by filling the gaps between satellite tracks. However, the wide-swath ocean altimetry uses the same ground tracks of TOPEX/Jason repeating every 10 days. By contrast, a GPS receiver in low-Earth orbit (LEO) with an antenna pointed toward the Earth’s surface can, in principle, track about 10 GPS reflections simultaneously, therefore providing a coverage that is an order of magnitude denser than nadir-viewing altimeters. For example, the reflection ground tracks of one single satellite at the altitude of 400 km would cover the Earth nearly uniformly in just 1 day, with at most about 75 km across-track separation, as shown in Figure 14. Such dense coverage can be translated into a higher temporal and spatial resolution than that of TOPEX/Jason or the proposed wide swath coverage, thereby providing the ability to recover certain ocean topography features or processes that are precluded with traditional altimeters. A feasibility study (Zuffada et al., 2000) shows that already a single GPS receiver in LEO can achieve 8 cm ocean altimetry measurements in 10 days, with 50 km^2 spatial resolution. Because this system primarily consists of a GPS receiver and an antenna, a system of several satellites could be deployed within reasonable cost constraints. With many receivers, and the availability of the European GPS system (Galileo) in the near future, the measurement density could improve by an additional order-of-magnitude. These preliminary conclusions need further corroboration, obtained with data sampled at different altitudes, angles, and sea state conditions.

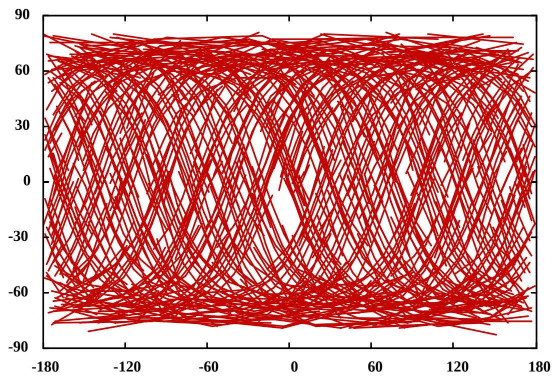

Figure 14 – Reflection point loci for one receiver at 400 km altitude, assuming its antenna beam can capture all available reflections, per day. Horizontal axis is longitude, vertical axis is latitude.

5.2. Ocean Surface Statisitics and Wind Retrieval

GNSS reflections from the ocean can be used to infer statistical properties of the surface, namely the slope distribution of sea-surface gravity waves, with high spatial and temporal resolution. Such measurements would likely be made concurrent with altimetric measurements (see Ocean Altimetry section above) because the measurement techniques are quite similar. The primary observable is the mean-squared slope (MSS), and recent studies [Germain et al., 2004] have shown a 2D directional-MSS can be obtained. The MSS field provides useful input to ocean-atmosphere coupling phenomena such as surface breaking waves and gas exchange. For example, CO2 flux measurements may be derived from MSS. MSS measurements could also support the Aquarius mission, where its brightness temperature measurements require surface-roughness calibrations to obtain the desired salinity accuracy. With additional assumptions, wind speed or wind vector retrievals can also be obtained from MSS measurements [Garrison et al. 1998, 2002, 2003] [Komjathy et al. 2000] [Cardellach et al. 2003] [Zuffada et al. 2004]. Finally, MSS measurements may clarify the relationship between surface-height dynamics and wind-driven surface velocities [Chelton, et al., 2004].

Analysis of the GPS reflection waveform also provides an estimate of the wind speed and direction. While scatterometers such as QuikScat or SeaWinds provide near global coverage in one day, the observations are not necessarily collocated in time and space with the GPS altimetry observations. Instead, GPS reflections provide a unique set of collocated sea surface height and wind observations with near-global daily coverage and with resolution suitable for studying mesoscale features. Accurate sea surface height retrieval requires simultaneous measurements of ocean vector winds. The accuracy of GPS wind measurements is about 2 m/sec for wind speeds ranging from 3 to 15 m/sec (Komjathy et al., 2002), comparable to the traditional radar scatterometer. Thus, the GPS-measured ocean winds will complement the existing radar scatterometer wind observations and, in the context of sea surface height measurement, will provide the needed data set to retrieve the sea surface height with high accuracy.

It is anticipated that the GPS altimetry will improve our current capability in 2 important ways:

- High-spatial-resolution ocean topography
- Improved temporal resolution through rapid coverage

Another possible application of very rapid coverage of the ocean is the monitoring of fast moving barotropic waves that propagate across ocean basins too quickly to be seen by the TOPEX/Poseidon 10-day repeat cycle.

5.3. Ice Science

Detection of GPS reflections at low or grazing angles has the advantage of being coherent and, when combined with the direct signal, provides interferometric fringes from which a very precise estimation of bi-static path delay (down to sub-centimeter) can be detected. In the presence of strong L1 and L2 signals to calibrate the ionosphere, this can be translated into accurate height surface measurements at the specular reflection point.

Recent analysis [Cardellach et al., 2004] used this interferometric signal, detected with the CHAMP radio occultation experiment, to demonstrate a surface height precision of 0.7 meter after 0.2 second of integration with a reflection angle of <1 deg (i.e., 89deg. incident angle). The GRSPI instrument will allow the detection of the coherently reflected signal at a higher elevation angle reducing the error in inferred ice surface height to less than 10 cm.

Global observations of sea ice, ice sheets, ice caps, glaciers and their surrounding seas, are paramount in order to determine their mass balance, contributions to sea level change, global circulation and climate change. In fact, model simulations and recent observations suggest that the ice-covered regions of the Earth are the most sensitive to climate change. In the polar region the combination of atmospheric, cryospheric, and oceanographic processes have a large influence on the global climate. Unfortunately, these climatic processes are poorly understood, principally because of a dearth of observations for diagnosing the processes and validating numerical models.

Changes in ice thickness are an indicator of climate change in the polar region as a result of heat exchanges between ocean and atmosphere, and are themselves a primary driver of climate change through the effect of these heat fluxes on atmospheric circulation patterns and the strong positive planetary albedo feedback provided by changes in sea ice, snow cover and melt water.

Given the multi-beam bi-static reflections of GPS, a GPS cryospheric sensing system can provide a substantially denser and more rapid coverage than traditional ice altimetry instruments and allow the determination of seasonal and annual variations in sea-ice and land-ice thickness.

5.4. Soil Moisture

Soil moisture is an important part of the land hydrology cycle, where it represents the immediate store of infiltrating rainfall, before it either evapotranspires or contributes to groundwater recharge. When the soil gets too dry, plant transpiration drops because the water is becoming increasingly bound to the soil particles. Conditions where soil is too dry to maintain reliable plant growth is referred to as agricultural drought, and is a particular focus of land management. Soil moisture may be measured in situ with different instruments, such as Time Domain Reflectometry (TDR), neutron probe, capacitance probe, etc. but no global remote sensing measurements are currently available. The potential for measuring soil moisture with GPS has been explored through some ground-based and airborne experiments over smooth terrain, led by the University of Colorado in Boulder and NASA Langley Research Center. Theoretical models show that moist soils generate strong reflective layers at the GPS frequencies, due to high gradients in dielectric constant. It was experimentally observed that variations in the reflected signal are uniquely related to changes in the dielectric permittivity, and therefore, to soil moisture because roughness of the area with low grass remains constant. More work is needed to assess requirements, including antenna gains, for potential GPS-based systems for global soil moisture measurements.

5.5. Technology Development for GPS Ocean Science

The BlackJack receiver does not have reflection processing capabilities to track and process reflections on board. Aided open-loop acquisition software for SAC-C and CHAMP BlackJack receivers has been developed experimentally. However, much work remains to be done to implement multi lag synchronization in order to output reflection waveforms possibly spanning 30-50 lags.

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. Specifically, (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. The antenna requirements can be met by a steerable multi-beam system, with a large enough aperture (about 2 m^2) to achieve gain of about 30 dB. Existing switched-beam or phase-array technology could be suitable for this application, although their cost is high. JPL is currently developing the Toga receiver that will address the needs of GPS ocean science.

6. Recommendations

A workshop entitled "Emerging Science Applications of Measurements From GPS/GNSS And GPS-like Signals: Recent Results And Future Possibilities - II", was held in December 2005 at the Fall AGU conference in San Francisco. The workshop, chaired by Jim Anderson and focused on Atmospheric Science and Climate, was convened to encourage and maintain a dialog on science enabled by GPS-based observations and provided the opportunity for exchanges between the science community and program managers at NASA, NSF and other agencies. The following recommendations were made at this workshop:

- The climate community should remain engaged with the instrument developers to insure that further receiver improvements/modifications are consistent with the scientific needs.
- The GPS science community needs to establish closer links with the metrology and sondes community.
- NASA should support integration of the GPS radio occultation observations into the Global Climate Observing System.
- Observation System Simulation Experiments (OSSEs) should be performed to determine the impact to climate research of high vertical resolution global water vapor fields obtained with high-frequency cross-link occultations.
- Jim Anderson will lead the development of a paper, to appear in the Bulletin of the American Meteorological Society, which discusses the role of GPS radio occultation measurements as part of the nation's strategy to identify climate benchmarks and develop credible approaches to climate monitoring.
- We need to demonstrate with technical arguments why the GPS acquired refractivity profiles constitute climate quality data records. With this argument clearly laid out, we need to build strong bridges to the relevant remote sensing communities to explore how integrating the GPS observations will result in more complete and climate records.

In addition to these recommendations, we believe the following course of action is required:

- Continue to develop the Toga class receiver for ocean reflections measurements and compatibility with future GNSS systems such as Galileo.
- Assess the value of the GNSS reflections to oceanography/ice science by performing assimilations of simulated data (with their uncertainties) into models, aimed at testing the impact of the random distribution.
- For atmospheric science, a constellation of 9 satellites is reasonably diverse orbits is enough to satisfy requirements for climate observations. This requirement could either be met by a dedicated constellation similar to COSMIC or by placing GPS receivers on all new NASA satellites. Current projections indicate that there will be 9-12 total NASA/NOAA satellites orbiting in 2012.
- For ionospheric science, our recommendation is to include a GPS receiver on all new solar physics LEO satellites.
- For ocean/ice science, our recommendations are to fly the next generation Toga receiver as soon as possible after 2008 to prove the concept of ocean reflections. If that flight test is successful, a constellation of six GPS receivers could be built up for ocean/ice science.

7. Acknowledgements

Portions of this work were performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. We would like to acknowledge the important contributions of: M. Joan Alexander, Anthea Coster, George Hajj, Stephen Leroy, Ben Santer, Phil Richards (NASA), Paul Straus, Geoff Crowley, and Kyle MacDonald. Materials communicated by Jim Anderson at the December 2005 GPS Workshop were excerpted.

References

Anthes RA, Rocken C, Kuo YH (2000), Applications of COSMIC to meteorology and climate, Terrestrial Atmospheric And Oceanic Sciences **11** (1): 115-156.

Barber, R.T., M.P. Sanderson, S.T. Lindley, F. Chai, J. Newton, C.C. Trees, D.G. Foley, and F.P. Chavez, Primary productivity and its regulation in the equatorial Pacific during and following the 1991-1992 El Niño, Deep-Sea Research II, 43, 933-969, 1996.

Beutler G., G. W. Hein, W. G. Melbourne, G. Seeber, GPS Trends in Precise Terrestrial, Airborne, and Spaceborne Applications, International Association of Geodesy Symposia, Symposium No. 115, Springer , 1996.

Cardellach, E., G. Ruffini, D. Pino, A. Rius, A. Komjathy, and J. Garrison, "Mediterranean balloon experiment: GPS reflection for wind speed retrieval from the stratosphere", Rem. Sens. Env., 2003.

Cardellach, E., C. O. Ao, M. de la Torre Juarez, and G. A. Hajj, Carrier-phase delay altimetry with GPS-reflection/occultation interferometry from low-Earth orbiters, Geophys. Res. Lett., 31, L10402, doi:10.1029/2004GL019775, 2004.

Chelton, D.B., M.G. Schlax, M.H. Freilich, and R.F. Milliff, "Satellite Measurements Reveal Persistent Short-Scale Features in Ocean Winds", *Science, 303*, 5660, 978-983, 2004.

De la Torre Juarez, M., A. Dornbrack, G.A. Hajj, B.A. Iijima, R. Kivi, A.J. Mannucci, and T.M. Schrøder (2006), Observational estimates of air mass with temperatures conducive to arctic polar stratospheric clouds, submitted to Journal of Geophysical Research.

Dunn, C.E. and L.E. Young, Receiver Controlled Phased Array Antenna, NASA New Technology Report NPO-20031, 1996 (patent application underway).

Ern, M., P. Preusse, M.J. Alexander, and C.D. Warner (2004), Absolute values of gravity wave momentum flux derived from satellite data, *Journal of Geophysical Research-Atmospheres*, *109* (D20) Art. No. D20103.

Foster JC, Erickson PJ, Coster AJ, Goldstein J, Rich FJ (2002), Ionospheric signatures of plasmaspheric tails, Geophysical Research Letters **29** (13): Art. No. 1623.

Garrison J.L., A. Komjathy, V. Zavorotny and S.J. Katzberg, " Wind speed measurement using forward scattered GPS signals, IEEE Transactions on Geoscience and Remote Sensing, Vol. 40, No. 1, Jan. 2002.

Garrison, J. L., S. J. Katzberg and M. I. Hill, Effect of sea roughness on bistatically scattered range coded signals from the Global Positioning System, Geophys. Res. Lett., 25, 2257-2260, 1998.

Garrison J. L and S. J Katzberg, The Application of reflected GPS signals to ocean remote sensing, Remote Sens. Environ. Vol 73, pp. 175-187, 2000.

Germain, O., G. Ruffini, F. Soulat, M. Caparrini, B. Chapron, P. Silvestrin,” The Eddy Experiment: GNSS-R speculometry for directional sea-roughness retrieval from low altitude aircraft”, GRL in press.

GLONASS Wikipedia web site, http://en.wikipedia.org/wiki/GLONASS

Hajj GA, Romans LJ (1998), Ionospheric electron density profiles obtained with the global positioning system: Results from the GPS/MET experiment, Radio Science **33** (1): 175-190.

Hajj, G. A., L. C. Lee, X. Pi, L. J. Romans, W. S. Schreiner, P. R. Straus, and C. Wang, COSMIC GPS ionospheric sensing and space weather, Special issue of Terrestrial, Atmospheric and Oceanic Science, 11(1), 235-272, March 2000.

Hajj G. A. and C. Zuffada, " Theoretical Description of a Bistatic System for Ocean Altimetry Using the GPS Signal, " submitted for publication in Radio Science, Sept 2002.

Hajj, G. A., C. O. Ao, B. A. Iijima, D. Kuang, E. R. Kursinski, A. J. Mannucci, T. K. Meehan, L. J. Romans, M. de la Torre Juarez, T. P. Yunck, CHAMP and SAC-C Atmospheric Occultation Results and Intercomparisons, *J. Geophys. Res.*, Vol. 109, D06109, doi:10.1029/2003JD003909, 2004.

Hajj, G. A., C. O. Ao, B. A. Iijima, D. Kuang, E. R. Kursinski, A. J. Mannucci, T. K. Meehan, L. J. Romans, M. D. Juarez, and T. P. Yunck (2004), CHAMP and SAC-C atmospheric occultation results and intercomparisons, Journal of Geophysical Research-Atmospheres, 109, art. no.-D06109.

Healy, S. B., A. M. Jupp, and C. Marquardt (2005), Forecast impact experiment with GPS radio occultation measurements, Geophysical Research Letters, 32L03804, doi:10.1029/2004GL020806.

Ho CM, Mannucci AJ, Lindqwister UJ, Pi X, Tsurutani BT (1996), Global ionosphere perturbations monitored by the worldwide GPS network, Geophysical Research Letters, **23** (22): 3219-3222.

HOT_SWG, Report of the High-Resolution Ocean Topography Science Working Group Meeting, Edited by Dudley B. Chelton, 28 - 29 March 2001. Available at http://www.coas.oregonstate.edu/research/po/research/hotswg/

Huang CY, Kuo YH, Chen SH, Vandenberghe F (2005), Improvements in typhoon forecasts with assimilated GPS occultation refractivity, Weather And Forecasting **20** (6): 931-953.

Kaplan, Elliott D., “Understanding GPS: Principles and Applications,” Artech House, 1996.

Kelley MC, Wong VK, Hajj GA, Mannucci AJ (2005), On measuring the off-equatorial conductivity before and during convective ionospheric storms, Geophysical Research Letters **31** (17): Art. No. L17805.

Komjathy, A., V. Zavorotny, P. Axelrad, G. Born and J. Garrison, “ GPS signal scattering from sea surface: wind speed retrieval using experimental data and theoretical model,” Remote Sensing of Environment, Vol. 73, pp. 162-174, 2000.

Kuo YH, Sokolovskiy SV, Anthes RA, Vandenberghe F (2000), Assimilation of GPS radio occultation data for numerical weather prediction, Terrestrial Atmospheric And Oceanic Sciences, **11** (1): 157-186.

Kursinski, E.R., et al., 1996, “Initial Results of Radio Occultation Observations of Earth's Atmosphere Using the Global Positioning System,” Science, 271, 1107-1110.

Leroy, S. S. (2001), The effects of orbital precession on remote climate monitoring, Journal of Climate, 14, 22, 4330-4337.

Liu H, Zou X, Shao H, Anthes RA, Chang JC, Tseng JH, Wang B (2001), Impact of 837 GPS/MET bending angle profiles on assimilation and forecasts for the period June 20-30, 1995, Journal Of Geophysical Research-Atmospheres, **106** (D23): 31771-31786.

Mendillo, M., C. L. Huang, X. Q. Pi, H. Rishbeth, and R. Meier (2005), The global ionospheric asymmetry in total electron content, J. Atmos. Sol.-Terr. Phys., 67 (15), 1377.

Munjal et al, “A Review of Spaceborne Applications of GPS,“ Proceedings of ION GPS-92, pp 813-823.

Navstar GPS JPO site (http://gps.losangeles.af.mil/jpo/gpsoverview.htm);

Randel, W. J., and F. Wu (2005), Kelvin wave variability near the equatorial tropopause observed in GPS radio occultation measurements, Journal Of Geophysical Research-Atmospheres, 110 (D3).

Smith, R.D., M.E. Maltrud, F.O. Bryan, M.W. Hecht, Numerical simulation of the North Atlantic Ocean at 1/10^o, J. Phys. Oceanogr., 30, 1532-1561, 2000.

Straus, P. R., P. C. Anderson, and J. E. Danaher (2003), GPS occultation sensor observations of ionospheric scintillation, Geophysical Research Letters, 30 (8).

Tsuda, T., and K. Hocke (2004), Application of GPS radio occultation data for studies of atmospheric waves in the middle atmosphere and ionosphere, Journal Of The Meteorological Society Of Japan, 82 (1B), 419-426.

USNO NAVSTAR GPS site (http://tycho.usno.navy.mil/gpsinfo.html);

Zuffada, C., T. Elfouhaily and S.T. Lowe: “Deriving Near-Surface Wind Vector With Ocean Reflected GPS Signals: Simulations And Measurements,” sub. to *Rem. Sens. of the Envir., 2004.*

Appendix 1 – NASA Satellites Used in Analysis of Constellation of Opportunity

Spacecraft	Apogee Alt (km)	Perigee Alt (km)	Semi-major Axis (km)	Inclination (deg.)
ACRIMSAT	719	672	7073	98
AQUA	712	692	7080	98
AURA	695	687	7069	98
CALIPSO	708	690	7077	98
CHIPSAT	582	555	6946	94
CLOUDSAT	710	691	7079	98
EO-1	714	691	7081	98
FUSE	770	748	7137	25
GALEX	711	691	7079	29
GRACE-1	482	464	6851	89
GRAVITY_PROBE-B	636	627	7010	90
HESSI	586	553	6947	38
HETE-2	612	564	6966	2
HUBBLE	579	565	6950	29
ICESAT	603	580	6970	94
ISS-01	362	342	6730	52
JASON-3	1343	1339	7719	66
LANDSAT_07	711	700	7083	98
NOAA_18	874	847	7238	99
ROSSI_XTE	505	491	6876	23
SAMPEX	505	434	6848	82
SORCE	654	603	7007	40
SWAS	629	603	6994	70
SWIFT	605	592	6976	21
TERRA	710	683	7075	98
TIMED	618	604	6989	74
TOMS-EP	754	696	7103	98
TOPEX	1340	1333	7714	66
TRACE	579	554	6944	98
TRMM	406	392	6777	35
UARS	555	374	6842	57

* Note – although some of these satellites are spin-stabilized, for purposes of the coverage analysis we assumed they were 3-axis stabilized.

Appendix 2 – Satellites Used in Analysis of Near-term Constellation

Spacecraft	Apogee Alt (km)	Perigee Alt (km)	Semi-major Axis (km)	Inclination (deg.)
CHAMP	356	340	6726	87
COSMIC-1	800	800	7178	72
COSMIC-2	800	800	7178	72
COSMIC-3	800	800	7178	72
COSMIC-4	800	800	7178	72
COSMIC-5	800	800	7178	72
COSMIC-6	800	800	7178	72
GRACE-1	482	464	6851	89
MetOp1 (July 2006)	825	825	7203	99
SAC-C	701	689	7073	98