Supplementary Information for the GPS System of Systems for Science Study

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1. GNSS Capabilities

1.1. Global Positioning System (GPS)

GPS is a space-based radio navigation and time distribution system managed by the US Air Force. The GPS constellation consists of 24 or more satellites, each circling the Earth twice per day and continuously transmitting navigation signals on two different L-band frequencies, L1 and L2. GPS consists of three main elements, or "segments." In addition to the satellites themselves -- called the "Space" segment --the system includes a worldwide satellite control network -- the "Control" segment -- and GPS receiver units -- called the "User" segment. GPS receivers use the signals from the satellites to compute position and time information for users. The receivers do not send out any signals, or communicate back to the satellites.

The fundamental concept of GPS is to use simultaneous distance measurements from four or more satellites to compute the position and time of a receiver anywhere on Earth at any time. The GPS satellites broadcast signals on two different frequencies so that sophisticated user receivers can correct for distortion effects due to the ionosphere, the ionized region of the atmosphere lying between 50 and 400 km above the Earth. Typical horizontal positioning accuracy for military users is 5 to 10 meters, while for single frequency users it is 10 to 20 meters.

1.1.1. GPS Signal Characteristics

The satellites transmit on two L-band frequencies: L1 = 1575.42 MHz and L2 = 1227.6 MHz. Three pseudo-random noise ranging codes are in use. The coarse/acquisition (C/A) code has a 1.023 MHz chip rate, a period of 1 millisecond and is used primarily to acquire the P-code. The precision (P) code has a 10.23 MHz rate, a period of 7 days and is the principal navigation ranging code. The Y-code is used in place of the P-code whenever the anti-spoofing (A-S) mode of operation is activated. A-S guards against fake transmissions of satellite data by encrypting the P-code to form the Y-code. The C/A code is available on the L1 frequency and the P-code is available on both L1 and L2. The various satellites all transmit on the same frequencies, L1 and L2, but with individual code assignments.

Due to the spread spectrum characteristic of the signals, the system provides a large margin of resistance to interference. Each satellite transmits a navigation message containing its orbital elements, clock behavior, system time and status messages. In addition, an almanac is also provided which gives the approximate data for each active satellite. This allows the user set to find all satellites once the first has been acquired.

GPS provides two levels of service, Standard Positioning Service (SPS) and the Precise Positioning Service (PPS). SPS is a positioning and timing service which is available to all GPS users on a continuous, worldwide basis with no direct charge. SPS is provided on the L1 band, which contains the coarse acquisition (C/A) code and a navigation data message.

PPS is a more accurate positioning, velocity and timing service, which is available on a continuous, worldwide basis to users authorized by the U.S. P(Y) code capable equipment, and provides a predictable positioning accuracy of at least 22 meters (95 percent) horizontally and 27.7 meters vertically and time transfer accuracy to UTC within 200 nanoseconds (95 percent). PPS data is transmitted on the L1 and L2 bands. PPS was designed primarily for U.S. military use, and is denied to unauthorized users by the use of cryptography. PPS is made available to U.S. military and Federal Government users. Limited, non-Federal Government, civil use of PPS, both domestic and foreign, is authorized on a case-by-case basis.

1.1.2. The GPS Space Segment

The SPACE segment consists of at least 24 operational satellites in six orbital planes (four satellites in each plane). The satellites operate in circular 20,350 km (10,988 nm) orbits at an inclination angle of 55 degrees and with a 12-hour period. The position is therefore the same at the same sidereal time each day, i.e. the satellites appear 4 minutes earlier each day

Four generations of GPS satellites have flown in the constellation: the Block I, the Block II, the Block IIA, and the Block IIR. Block I satellites were used to test the principles of space-based navigation, and lessons learned from these 11 satellites were incorporated into later blocks. Block II, IIA and IIR satellites make up the current constellation. The U.S. Air Force Space Command formally declared the GPS satellite constellation as operational in April 1995.

Block IIR satellites, built by Lockheed Martin, began replacing older Boeing Block II/IIAs in July 1997. Block IIR satellites boast dramatic improvements over the previous blocks, having the ability to determine their own position by performing inter-satellite ranging with other IIR vehicles, reprogrammable satellite processors enabling problem fixes and upgrades in flight, and increased satellite autonomy and radiation hardness. They also carry more accurate clocks; each Block II or IIA satellite has two cesium atomic clocks and two rubidium atomic clocks, while each Block IIR has three rubidium atomic clocks. The stability of these clocks is estimated to be approximately 1 second per 300,000 years. Only one clock is in use on each satellite at a time; the others are backups. Additionally, the Block IIR has the ability to be launched into any of the required GPS orbits at any time with a 60-day advanced notice and requires many fewer ground contacts to maintain the constellation.

As of June, 2005, the GPS constellation consisted of 1 Block II and 15 Block IIA satellites, and twelve Block IIR satellites. Eight of the older Block IIR satellites have been modernized to radiate the new military (M-Code) signal on both the L1 and L2 channels as well as the more robust civil signal (L2C) on the L2 channel. The M-Code signal is a more robust and capable signal architecture. The first modernized Block IIR (designated as the IIR-M) was launched on September 26, 2005.

1.1.3. GPS Time Transfer

GPS is at the present time the most competent system for time transfer, the distribution of Precise Time and Time Interval (PTTI). The system uses time of arrival (TOA) measurements for the determination of user position. A precisely timed clock is not essential for the user because time is obtained in addition to position by the measurement of TOA of four satellites simultaneously in view. If the altitude of the receiver is known, (i.e. for a surface user), then three satellites are sufficient to determine position. If time is being kept by a stable clock (say, since the last complete coverage), then two satellites in view are sufficient for a fix at known altitude. If the user is, in addition, stationary or has a known speed then, in principle, the position can be obtained by the observation of a complete pass of a single satellite. This could be called the "transit" mode, because the old transit system uses this method. In the case of GPS, however, the apparent motion of the satellite is much slower, requiring much more stability of the user clock.

1.1.4. GPS System Future Developments

The future Block IIF GPS includes increased power and accuracy, as well as increased civil navigation safety with the addition of a new civil-only signal on a new link, L5, to be broadcast at 1176.45 MHz. Additional improvements include an extended design life of 12 years, faster processors with more memory. The first Block IIF satellite is scheduled to launch in 2007. A new military-only signal (M-code) on the L1 and L2 links is programmable for completion in 2010. It will have increased power and reduced vulnerability to signal jamming. In addition to the improved signals, the reliability of the GPS navigation message will be improved by adding more monitor stations. These additional monitor stations will ensure that each satellite is simultaneously monitored by no less than two monitor stations. The data collected by these additional monitor stations will be combined with the data from the existing monitoring stations, and sent to the GPS control center for processing. The result is improved accuracy of the navigation message broadcast by the satellite.

1.2. GLONASS – The Russian GNSS

GLONASS is a radio satellite navigation system, the Russian counterpart to the United States' GPS system. It is operated for the Russian government by the Russian Space Forces. At peak efficiency the system offered a standard (C/a) positioning and timing service giving horizontal positioning accuracy within 55 meters, vertical positioning within 70 meters, velocity vector measuring within 15 cm/s and timing within 1 µs, all based on measurements from four satellite signals simultaneously. A more accurate signal (P) was available for Russian military use.

Like GPS, the complete nominal GLONASS constellation consists of 24 satellites, 21 operating and three on-orbit 'spares' placed in three orbital planes. Each plane contains eight satellites identified by "slot" number, which defines the corresponding orbital plane and the location within the plane: 1-8, 9-16, 17-24. The three orbital planes are separated by 120°, and the satellites equally spaced within the same orbital plane, 45° apart. The GLONASS orbits are roughly circular, with an inclination of about 64.8° and a semimajor axis of 25,440 km. The planes themselves have 15° argument of latitude displacement. GLONASS constellation orbits the Earth at an altitude of 19,100 km (slightly lower than that of the GPS satellites). Each satellite completes an orbit in approximately 11 hours, 15 minutes. The spacing of the satellites in orbits is arranged so that a minimum of 5 satellites are in view at any given time.

GLONASS satellite transmits two types of signal: standard precision (SP) and high precision (HP). SP signal L1 have a frequency division multiple access in L-band: L1= 1602MHz + n0.5625MHz, where "n" is frequency channel number (n=0,1.2...).

A characteristic of the GLONASS constellation is that the satellite orbits repeat after 8 days. As each orbit plane contains 8 satellites, there is a non-identical repeat (i.e., another satellite will occupy the same place in the sky) after one sidereal day. This differs from the GPS identical repeat period of one sidereal day.

Due to the economic situation in Russia there were only eight satellites in operation in April 2002, rendering it almost useless as a navigation aid. Since the economic situation in Russia has improved, 11 satellites were in operation by March 2004. Additionally, an advanced GLONASS satellite, the GLONASS-M, with an operational lifetime of 7 years, has been developed. A 3-satellite block of this new version was launched in December 2005. A further improved GLONASS-K satellite, with a reduced weight and an increased operational lifetime of 10-12 years, is due to enter service in 2008. Following a joint venture deal with the Indian Government, which will launch two GLONASS-M satellites on its PSLV rocket, it is proposed to have the system fully operational again by 2008 with 18 satellites and by 2010 with all 24 satellites. As of February 2006, there are 17 GLONASS satellites in orbit with 12 currently operational.

1.3. Galileo – The ESA GNSS

The Galileo positioning system is a proposed satellite navigation system, to be built by the European Union as an alternative to the US military-controlled Global Positioning System and the Russian GLONASS. The system should be operational by 2013. The following are the characteristics of the Galileo satellite constellation:

- 30 spacecraft
- Orbital altitude: 23222 km
- 3 orbital planes, 56° inclination (9 operational satellites and one active spare per orbital plane)
- Satellite lifetime: >12 years

There will be four different navigation services available:

- The Open Service (OS) will be free for anyone to access. The OS signals will be broadcast in two bands, at 1164–1214 MHz and at 1563–1591 MHz. Receivers will achieve an accuracy of <4 m horizontally and <8 m vertically if they use both OS bands. Receivers that use only a single band will still achieve <15 m horizontally and <35 m vertically, comparable what the civilian GPS C/A service provides today. It is expected that most future mass market receivers will process both the GPS C/A and the Galileo OS signals, for maximum coverage.

- The encrypted Commercial Service (CS) will be available for a fee and will offer an accuracy of better than 1 m. The CS can also be complemented by ground stations to bring the accuracy down to less than 10 cm. This signal will be broadcast in three frequency bands, the two used for the OS signals, as well as at 1260–1300 MHz.

- The encrypted Public Regulated Service (PRS) and Safety of Life Service (SoL) will both provide accuracy comparable to the Open Service. Their main aim is robustness against jamming and the reliable detection of problems within 10 seconds. They will be targeted at security authorities (police, military, etc.) and safety-critical transport applications (air-traffic control, automated aircraft landing, etc.), respectively.

- In addition, the Galileo satellites will be able to detect and report signals from COSPAS-SARSAT search-and-rescue beacons in the 406.0–406.1 MHz band, which makes them a part of the Global Maritime Distress Safety System.

Figure 1 contains a summary of all current and future GNSS systems capabilities for the next 15 years.

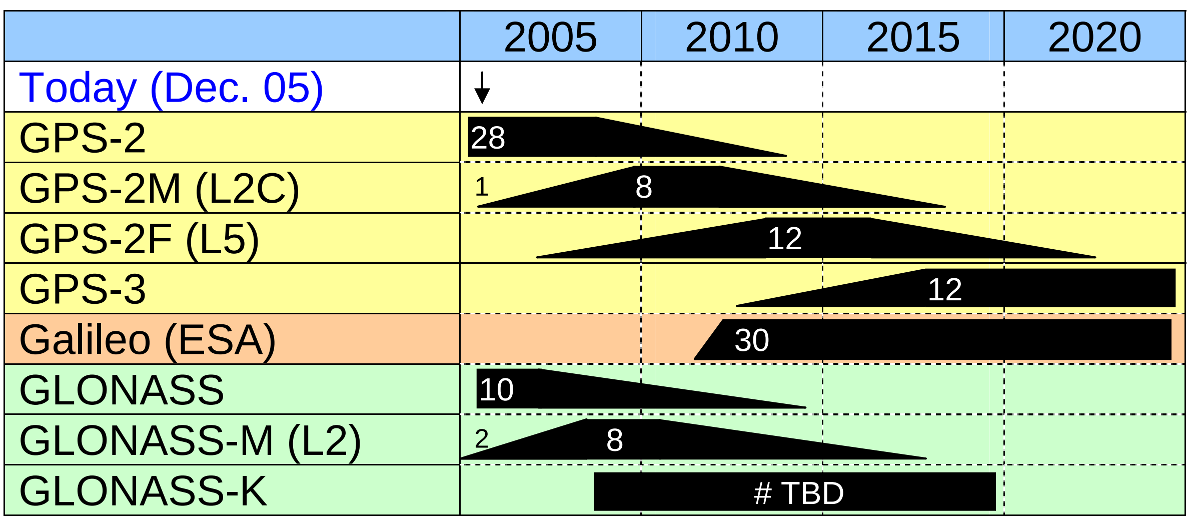

Figure 1 – Summary of GNSS Systems. The numbers in each bar denote the number of satellites operating in that year. All data based on current estimates. GPS-4 is not yet in the planning cycle but will likely start launching around 2017.

2. GPS Receiver Capabilities

2.1. Receiver Discussion

The differences among space borne GPS receivers are primarily a function of the frequencies they are designed to receive and the sensitivity of the receiver/antenna combination to the band of interest. The original GPS band, known as L1, centered on 1575.42 MHz, comes in 2 flavors: civilian and military. Prior to the discovery of atmospheric profiling with GPS occultation, GPS receivers were predominantly used for Precision Orbit Determination (POD), and related engineering applications such as relative positioning, attitude determination and clock synchronization. The TANS-Vector, AST-V and GPS-DR are representative of this class of GPS receivers.

JPL has developed the BlackJack flight GPS receiver, designed to provide very high accuracy with a flexible architecture. The software controlling tracking loops as well as science data collection is designed to be modified in orbit. The Black Jack receiver was developed by NASA to fill future needs for orbit-based GPS science. These range from a receiver to determine precise (1-cm radial accuracy goal for JASON-1) orbits, to missions using the GPS signals for remote sensing of the Earth's atmosphere. The Blackjack follows the TurboRogue space receiver, which was successfully used in collaboration with engineers and scientists at JPL on five satellite missions. While the TurboRogue was initially designed as a high-accuracy ground receiver, the BJ was designed from the start as an instrument for use from orbit. The BJ contains many innovations to better suit it to this application. In order to simplify the analog electronics, it directly samples the amplified and filtered RF (radio-frequency) signal. This sampling produces two sample streams in quadrature for improved SNR (signal-to-noise ratio). The BJ semicustom Application Specific Integrated Circuit (ASIC) uses a full matrix switch so that inputs from multiple antennas can be directed to any of 48 tracking channels. Other ASIC capabilities are telemetry reception, tone tracking, and precise time tagging of external events.

Although the Blackjack is designed as a science instrument rather than for mission-critical operation, it does contain innovative features such as the capability to operate in a bit-grab mode. In the event the highly-redundant digital processing fails, the main processor stops, or the spacecraft can no longer power the GPS receiver, the BJ can turn on for less than a second every hour, and still transmit data to the ground allowing sub-100-m orbit determination. The BJ receiver is designed with excess processor capacity to allow it to perform non-GPS functions; for example, on the GRACE mission, the BJ controls an intersatellite K-band link and also processes the output of a star camera to determine spacecraft attitude. This excess processor capacity can also be used to upgrade the receiver to operate with the latest GPS signals. For example, several Blackjack receivers in orbit are being upgraded to process the new L2C signal from the recently launched GPS-2M satellite. The BlackJack receiver has successfully flown on SRTM (2000), SAC-C (2000), CHAMP (2000), JASON-1 (2001), and GRACE (2002). Several future missions will be using the Blackjack as well.

2.2. Current Missions – CHAMP, SAC-C, GRACE

All of the science objectives listed in Section 4 require a constellation of low-Earth orbiting GPSRO satellites. Currently this constellation is being pursued in two ways: 1) as a dedicated constellation of instruments and 2) as constellations of opportunity. The COSMIC constellation is an example of the “dedicated” approach and is discussed in section 5.4. Currently, GPS science is being conducted using a “constellation of opportunity” consisting of diverse missions that share a common instrument: an advanced “Blackjack” receiver designed and built at JPL. The constellation is comprised of the following satellites: CHAMP, SAC-C, and GRACE. The SAC-C mission is conducted jointly with the Argentine space agency, CONAE. The GRACE and CHAMP missions are conducted jointly with the GeoForschungsZentrum in Potsdam, Germany. NASA funds the multi-mission GPS Atmospheric Limb-Sounding data analysis center at JPL.

The GPS science community has demonstrated that the opportunistic approach is effective, and GPS science analysis centers have successfully processed data from several missions at a single center. This multi-mission approach is possible because of the “system-of-systems” approach to the GPS in general, that leverages standard data formats and precise measurements throughout the system, including precise high cadence clock solutions (GPS satellite and ground receiver network), precise orbital positions of the GPS transmitter constellation, precise station locations and the consequent precise orbits of the low-Earth orbiting receiver constellation. The continuously available calibration of the GPS system-of-systems is a unique feature that is not shared by other Earth observing systems and is one of the reasons that GPS observations can be reliably drift-free and compared over decades. The absence of inter-satellite bias in the observations has been established recently for a limited data set [Hajj et al., 2004].

The Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) is a collaborative science project between the United States (NASA, NSF, and NOAA) and Taiwan. COSMIC includes a constellation of six small satellites launched in April 2006, each carrying Blackjack receiver. NASA supplyed the GPS receiver technology (through JPL) and NSF is funded the COSMIC Data Analysis and Archiving Center (CDAAC). COSMIC will produce approximately 3,000 radio occultation soundings per day, uniformly distributed around the globe. The objective is to demonstrate quasi-operational GPS limb sounding with global coverage in near-real time to provide data used primarily for weather (including space weather and ionospheric scintillation) forecasting. In addition, COSMIC will provide nearly 5600 globally distributed occultations per day suitable for ionospheric sensing. [Hajj, 3/2000]. Occultations can be processed individually to obtain vertical profiles of electron density, with vertical resolution of ~1km, or collectively by means of tomography or data assimilation to obtain 3-D images of electron density or irregularity structure.

2.3. Future Missions

The Department of Defense has funded GPS occultation receivers for space science on the C/NOFS mission, as part of a system to predict ionospheric conditions that affect navigation and radar at low latitudes. C/NOFS is a satellite mission dedicated to forecasting ionospheric densities, irregularities and scintillation. It will be launched in July 2006, in a 13 degrees inclination, 710 x 375 km orbit. The C/NOFS Occultation Receiver for Ionospheric Sensing and Specification (CORISS) is a GPS receiver derived from the Jason Mission. CORISS was built by General Dynamics with software modified by the Aerospace Corporation to perform occultations and incorporate special processing for ionospheric scintillation science. CORISS will measure total electron content (TEC) along the lines-of-sight between C/NOFS and GPS satellites. It will thus provide a remote sensing capability for extracting vertical profile information during occultations. Limb profiles of TEC can be inverted to produce vertical profiles of electron density. CORISS measurements of TEC from occulting and non-occulting GPS satellites at various bearings relative to the satellite track can constrain C/NOFS ionospheric models. It may also be possible to measure L-band scintillations caused by electron density irregularities along lines-of-sight between C/NOFS and GPS satellites.

MetOp1, launching in July 2006, will be Europe's first polar-orbiting satellite dedicated to operational meteorology. It represents the European contribution to a new cooperative venture with the United States providing data that will be used to monitor our climate and improve weather forecasting. The Global Navigation Satellite Systems Radio Occultation Receiver for Atmospheric Sounding, known as GRAS, will use the radio-frequency signals generated by the GPS satellites. GRAS measurements will provide atmospheric temperature and humidity profiles, which are intended to be assimilated into Numerical Weather Prediction (NWP) models. Two additional MetOps satellites will be launched in 2011 and 2016.

The International Living With a Star (LWS) program is planning the Ionosphere Thermosphere Storm Probes (ITSP) mission due for launch in 2014 that will use a GPS receiver along with in-situ sensors placed on 2-4 satellites in polar orbit at ~450 km altitude. Any future GPS constellation for space science must be viewed in the context of ITSP, which will measure in-situ properties of the ionosphere as well as carrying remote-sensing instruments to provide information on electron density structure away from the satellite (e.g. GPS receivers, active sounders, and ultraviolet imagers).

Figure 2 contains a chart of the total number of GPS science receivers in operation by year from 2000 to 2016.

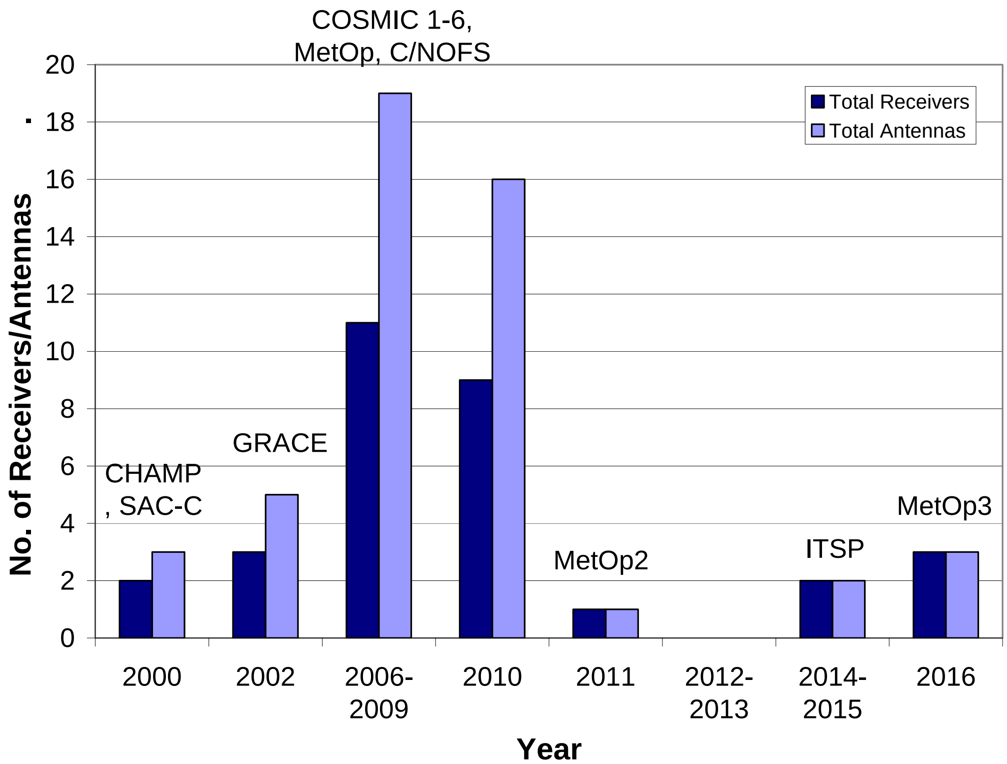

Figure 2 – Total number of GPS science receivers and corresponding antennas in orbit. This data assumes a 10-year life for CHAMP, SAC-C, and GRACE, and a 5-year life for all other satellites. These are all Blackjack-class receivers.

3. Future GPS Receiver Capabilities

JPL is currently developing the Toga next generation instrument. An engineering model of this instrument will be fully tested and ready in September 2008. The follow-on costs for a flight instrument are estimated to be around $9M. This instrument will uniquely perform:

- All GNSS remote sensing measurements such as GNSS occultations or ocean/ice altimetry
- High-accuracy POD measurements, such as repeat-pass or long-baseline interferometric SAR missions
- Navigation and timing above the GPS constellation, such as geostationary or lunar missions
- New ionospheric measurements, such as measurements of small-scale ionospheric density irregularities or global-scale electron density

The instrument capabilities take advantage of future GNSS capabilities to include the use of the several new and stronger signals, such as GPS L2-Civil, GPS L5, and Galileo's Open Signals (OS). With the current GPS space receivers, one LEO with fore and aft viewing antennas provides ~500 daily occultations. The addition of the Galileo constellation and the building of an instrument capable of tracking both GPS and Galileo will double the occultation coverage providing 1000 daily occultations. The Toga instrument will not be able to track the Russian GLONASS signals.

The Toga instrument is comprised of two major components: an FPGA-based GNSS radio/receiver (GRR), followed by a reconfigurable digital processor (RDP). The radio/receiver will function similarly to a BlackJack GPS science receiver, but with a number of enhancements. The basic GRR functions will be implemented with FPGA circuits (compared to the BlackJack's ASIC chips) so the low-level cross-correlation functions can be reconfigured or copied extensively, even on-orbit. This allows the GRR to flexibly process all the GNSS signals of interest, easily grow with GNSS upgrades, and service several different missions with minimal modifications. The GRR will also perform basic receiver functions, drawing heavily from existing and mature BlackJack technology and software. Thus, the GRR is a powerful, flexible GNSS signal pre-processor that also performs basic navigation and tracking functions. The second component, the RDP, uses the navigation and geometry information from the GRR, along with low-level GNSS signal parameters to perform extensive and complex remote-sensing computations.

The Toga receiver has the capability to perform ocean science by receiving and processing GPS ocean reflections. To acquire and process reflections effectively two features are required: 1) Antenna array phasing and 2) Multi-lag processing. The ability to process upcoming GPS and Galileo signals represents a huge opportunity; much of the needed work will be in front-end electronics design.

3.1. Antenna Array Phasing

Several GNSS applications require high-gain signals. Using phased arrays of antenna elements is one way to obtain high-gain observations. Using phased arrays to steer a single beam are common, but the simultaneous steering of several high-gain beams is not. Array phasing technology has been demonstrated on a Champ engineering model.

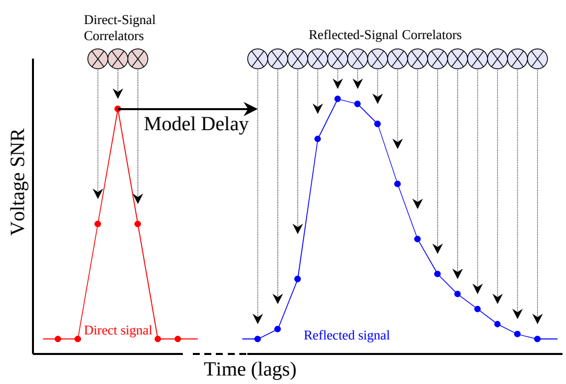

Figure 3 – Each direct signal requires 3 correlators (red) to implement delay and phase tracking loops. A geometric model calculation gives the expected delay between the direct and reflected signal used to window about 20 reflected-signal correlators (blue).

3.2. Multi-Lag Processing

Multi-lag processing is used to capture a reflected GNSS signal for remote-sensing purposes. For example, ocean or ice altimetry are concerned about the timing of the rising edge of the reflected signal while scatterometric measurements use the signal tail to give information about the statistical properties of the surface. Figure 3 illustrates multi-lag processing; the usual 3 lags present in a typical receiver are shown in red, while the multiple lags needed for the reflected signal are shown in blue. A geometric model of the instrument and satellite positions and the Earth's surface are used to compute the expected delay between the direct and reflected signals.

3.3. Adding a GNSS Science Receiver to a Mission of Opportunity

3.3.1. Integration with a Host Spacecraft

One of the most attractive aspects of implementing a GNSS Science constellation is the ability to attach a receiver system to a selected mission concept, as a piggyback payload, with a relatively low level of interference in the design of the host spacecraft. This section will address some of the technical considerations to be addressed in the design and integration of such a system with the host mission, and provide a rough estimate of the costs to be expected in mounting such a project.

The first considerations in determining the feasibility of a piggyback payload are the fundamental mission constraints of mass, size, power and data rate. Assuming a mission is willing to consider adding an instrument of opportunity, there will be very few candidates that cannot afford to support the mass, power and data requirements of a GNSS receiver system. A typical BlackJack receiver system has a mass of less than six kilograms, average power consumption of 10 – 15 W, and data downlink requirements on the order of 20 kbps or less. A TOGA – class receiver is expected to have similar requirements; although a flight-ready instrument has not yet been designed, its mass, power and data rate are not expected to exceed those of the BlackJack by more 50%. Similarly, the size of the receiver should not be an issue with most host missions; the Blackjacks on CHAMP and SAC-C measured 20x24x9 cm. The most likely concern with a space-borne GNSS system will be the size and location of the antennas, particularly if the system will be receiving ocean/ice reflections.

Figure 4 and Figure 5 are graphic illustrations of the BlackJack antenna placement on the CHAMP spacecraft, and Figure 6 is a close-up photo of the aft-mounted antenna installation. As the figures show, the GPS Precision Orbit Determination (POD) antenna is a small omni-directional patch antenna, mounted in a ring structure roughly 30 cm in diameter, which can be mounted in any unobstructed location on the zenith face. The GPS altimeter antenna (referenced but not shown in Figure 6) is a small helix antenna, roughly 10 cm in diameter, located on the nadir face. Neither of these antennas is likely to pose a placement problem on a moderately sized science spacecraft. The limb-sounding antenna array is also fairly small, comprising a 20 cm diameter horn and a 12 cm patch on the aft-facing end of the spacecraft, facing 20 degrees off of the anti-velocity vector. However, an ideal host will permit this array to be mounted on both the fore and aft faces of the spacecraft, allowing occultations to be viewed along both the velocity and anti-velocity directions. Depending on the configuration and available surface area on the host spacecraft, this may not be possible, as was the case with CHAMP. Nevertheless, it is reasonable to assume that a large number of missions will be able to accommodate this requirement, enabling a large constellation of limb-sounding receivers to be placed in orbit for relatively little investment other than the cost of the receiver, integration and calibration.

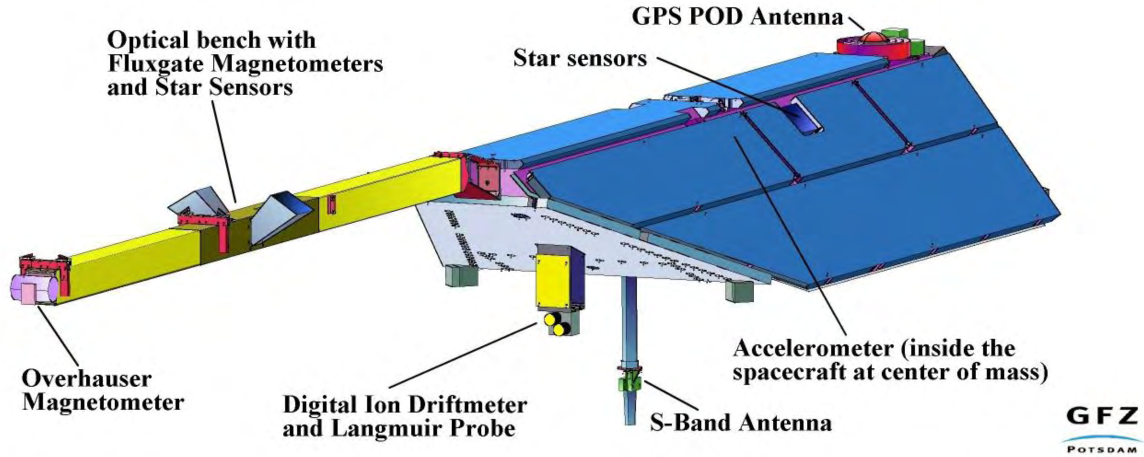

Figure 4 – CHAMP Spacecraft, Front View

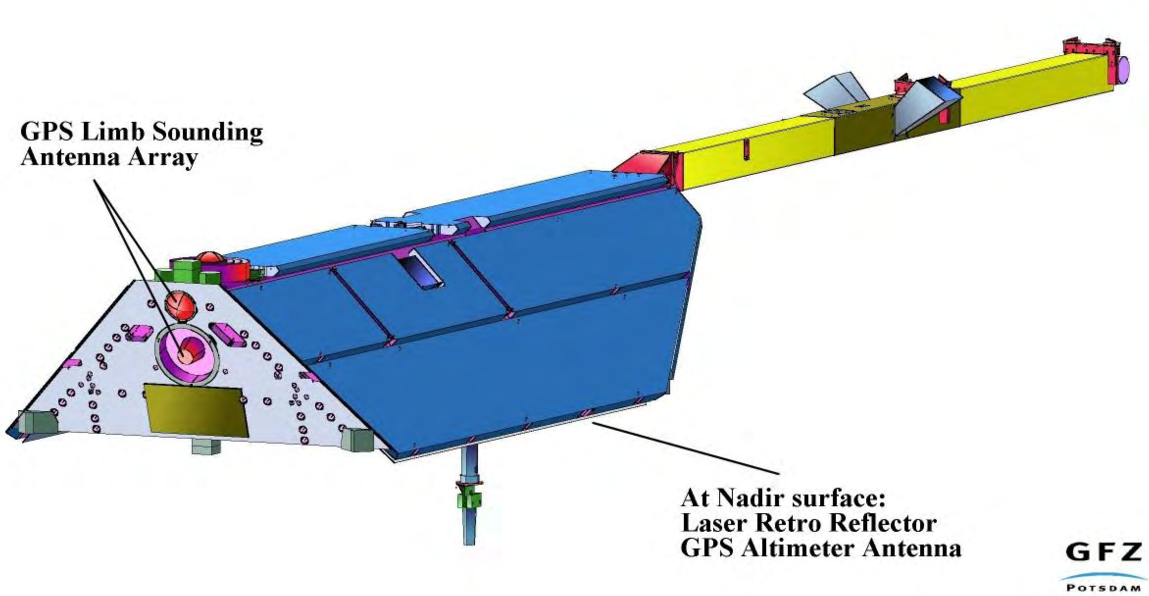

Figure 5 – CHAMP Spacecraft, Rear View

The measurement of ocean reflections presents somewhat more of a challenge, due to the size and orientation of the required antenna. In order to simultaneously receive GNSS signals from several satellites over a broad field of view, a multi-lag, electronically steerable antenna will be needed. NASA's Instrument Incubator Program is currently funding the development of such an antenna, a two dimensional phased array that can support multi-beam bi-static reflections over a nearly hemispherical field of view. This antenna will require 1-2 m of surface area on the nadir face of the spacecraft, in order to receive and amplify the faint GNSS signals reflected off the water to a minimum of 20 dB. Such an antenna will be more expensive and complex to integrate than the simple limb-sounding antenna system described above, and it is doubtful that many host spacecraft will be able to spare one square meter or more of real estate on their nadir-facing side. It is reasonable to assume that a greater percentage of potential hosts will be able to accommodate a GPS science package for limb-sounding and POD than one that combines these functions with tracking of ocean and ice reflections. Accordingly, it may not be practical to consider launching a substantial constellation of these combined, TOGA-class systems, based solely on missions of opportunity.

3.3.2. Cost of Installation

The existing BlackJack receiver is a thoroughly tested and flight proven design. It is commercially distributed as the Integrated GPS Occultation Receiver (IGOR) from Broadreach Electronics Company. (See Figure 7.) The IGOR is sold with a full compliment of antennas (fore and aft limb sounding antennas, altitude and POD) for less than $300K. However, the cost of setting up this receiver, making mission-specific software modifications, integrating it with a mission of opportunity and calibrating it in flight far exceeds the hardware cost. At this time, the estimated cost per mission, through calibration, is believed to be in the range of $3M-5M.

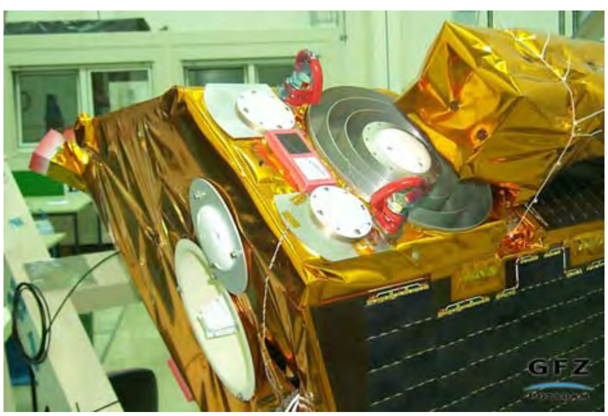

Figure 6 – CHAMP Antenna, rear face

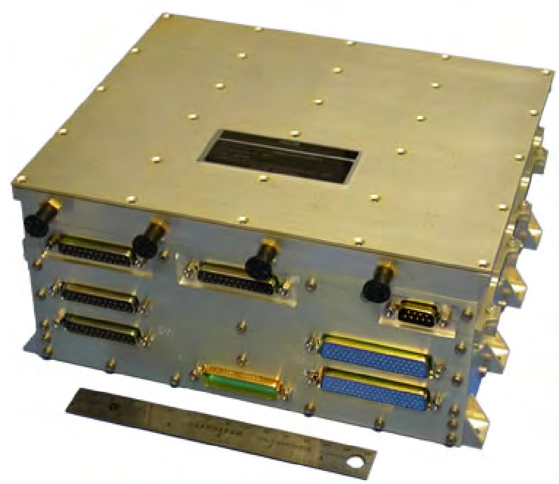

Figure 7 – IGOR Receiver (Broadreach Engineering)

The TOGA receiver is still in development under the Instrument Incubator Program, and is expected to be completed by 2008. The follow-on costs to a flight instrument are estimated to be $9M over 3 years. Once the design has been completed and a flight-ready model has been built, it is believed that it will be offered for sale by a private sector electronics distributor. The per unit cost for the receiver is unknown at this time. The cost of setting up this receiver for limb-sounding is expected to be in the same range as the BlackJack, and this may be worthwhile in order to take advantage of

TOGA's expanded capabilities. However, the cost of the phased-array antenna that will be needed to receive ocean and ice reflections is harder to estimate. In addition to the fact that the hardware cost is uncertain, as it is still being developed, we do not know how much work will be required for setup, integration and calibration, as there is no comparable phased-array antenna design that has been flown to date.

Appendix 1 (Web Document) – Detectable Wave Scales

The derivation of Figure 8, the wavelengths and periods that can be detected with the full constellation, required several assumptions that are described here. The conceptual basis for this plot is that it is desirable to measure horizontal as well as vertical wavelengths to characterize the important quantity of wave momentum flux (Alexander, 1998). Previous studies using radio occultations have concentrated on vertical wavelengths of gravity waves, since GPS profiles have sufficient resolution to resolve small vertical wavelengths. Estimating horizontal wavelengths requires measuring pairs of profiles that sample the same wave (See Ern et al., 2004 for a discussion). Therefore, for all simulated occultation locations in the "full constellation", we computed the distance between every pair of occultations. An example is shown in Figure A1.1. This plots the number of occultation pairs (y-axis) that are within a given distance range bin (x-axis) for times 0100-0200 UT assuming a simulated constellation of six satellites similar to COSMIC. The calculation was repeated several times, for data sets spanning particular time intervals (1, 2 and 6 hours). The longer the time period considered, the more occultations are available to form pairs at a given separation. On the other hand, including longer time periods to increase the number of pairs implies that the measurement pairs might be separated by longer times. This has implications for what wave periods can be detected by a measurement pair.

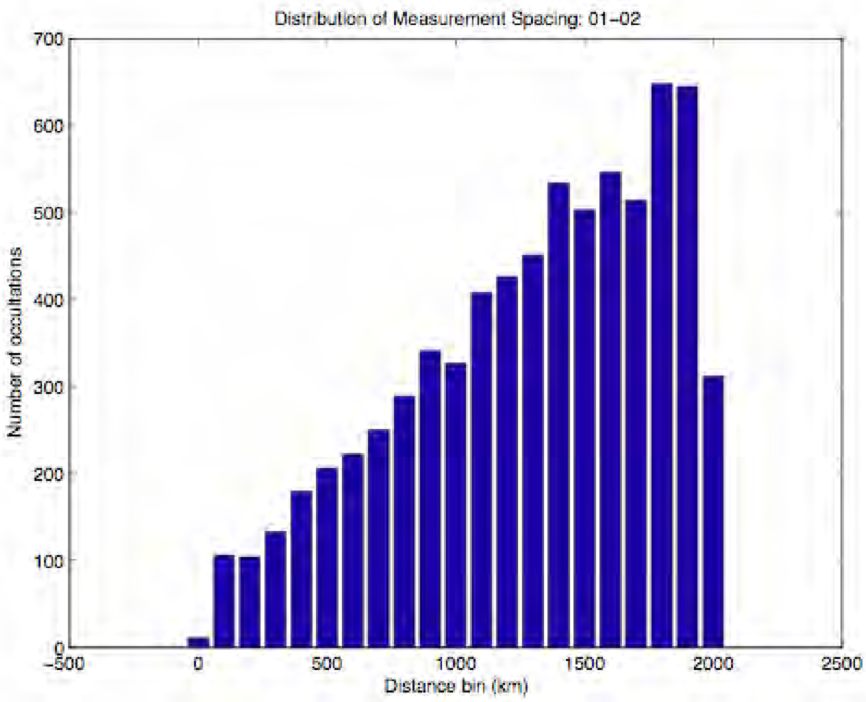

Figure A1.1: Histogram of distances between pairs of occulations occurring between 0100-0200 UT.

We assume here that measurement pairs separated in time by T (e.g. up to one hour) can detect a wave with period of 4*T or longer. Waves with shorter periods will have oscillated within the separation time of the measurements, so that correlating the wave crests and troughs between the two profiles becomes more difficult. Therefore, we associate a detectable wave period based on the maximum time separation considered for the measurement pairs.

We also associate a wavelength with the distance between a measurement pair. The distance between two measurements can provide information on wavelengths longer than that distance, but not shorter. Similarly to the time case, we assume that measurements separated by a distance D can sample wavelengths 4*D or longer. The algorithm mentioned earlier for deriving horizontal wavelengths from profile pairs determines the appropriate wavelenth from the phase differences between the two measurements in a pair.

Deriving Figure 8, the wavescales plot, relies on the two assumptions above regarding the time and spatial separation of pairs of measurements. The procedure for deriving the plot can be described as follows:

1) Compute the histogram of pair distances within a given time period (e.g. 1 hour). See Figure A1.1.
2) Assuming that 400 measurements globally in one day are required for a sufficient sample of a given wave scale, find the minimum pair distance that occurs at least 400 times per day. As an example, referring to Figure A1.1, we note that measurement pair distances of 1200 km or greater occur 400 or more times. For

the measurement distances less than 1200 km, there were fewer than 400 pairs, so these shorter wave scales were not sufficiently "detectable" by our criterion.

3) The time period used in step 1 and the distance determined in step 2 define a minimum detectable wave scale, using the multiplicative factor of 4 mentioned previously. As an example, using Figure A1.1, we determine that wavelengths of 4800 km (=4*1200 km) and wave periods of 4 hours (=4*1 hour) are "detectable" based on our criteria.

Each point in Figure 8 is based on the analysis followed in Steps 1-3 above. Three time periods were examined: 1, 2 and 6 hours. Obviously, the longer the period in which to form measurement pairs, the shorter the wavelength that can be detected and resolved because there are more measurement pairs at closer distances. Conversely, insisting that measurements be close enough in time to capture short-period waves restricts one to observing longer wavelengths.

Unfortunately, the real atmosphere follows a different trend between temporal and spatial scales than our observing system. Because wave speeds tend toward an upper limit, for atmospheric waves spatial and temporal scales generally track each other (speed is the ratio of wavelength to period). Short period waves tend to have shorter wavelengths, and longer period waves tend to have longer wavelengths. In contrast, our observing system tracks only short-period waves associated with longer wavelengths.

On Figure 8 we have plotted the speed corresponding to the minimum detectable wavelength derived for the 1, 2 and 6-hour cases. An upper limit to gravity wave speeds is in the range ~170 m/sec, shown in Figure 8 as the green line. This suggests that for the full constellation, wave periods shorter than 6 hours could not be resolved adequately because the long detectable wavelength implies a speed exceeding the maximum expected.

We conclude with some caveats about this analysis. We acknowledge it is coarse, in the sense that we have used time bins to characterize waves of different periods. It would have been more precise to compute the detectable wave scale for each pair of simulated GPS observations, separated by a time t and distance d. For a given such pair, the detectable period would be $4*t$, and the detectable wavelength $4*d$. Other caveats are mentioned in the main text. Our goal here was to perform a preliminary analysis that provides a rough measure of horizontal wavelength scales that can be characterized using GPS occultation constellations.