GEODETIC REFERENCE ANTENNA IN SPACE (GRASP) – A MISSION TO ENHANCE SPACE-BASED GEODESY

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ABSTRACT

The Geodetic Reference Antenna in Space (GRASP) is a micro satellite mission concept dedicated to the enhancement of all the space geodetic techniques, and promising revolutionary improvements to the definition of the Terrestrial Reference Frame (TRF), its densification, and accessibility. GRASP collocates GPS, SLR, VLBI, and DORIS sensors on a supremely calibrated and modelable spacecraft, offering an innovative space-based approach to a heretofore intractable problem: establishing precise and stable ties between the key geodetic techniques used to define and disseminate the TRF. GRASP also offers a solution to another difficult problem, namely, the consistent calibration of the myriad antennas used to transmit and receive the ubiquitous signals of the present and future Global Navigation Satellite Systems (GNSS). The space-based GNSS reference antenna concept has already been prototyped with the GRACE mission, and GRASP is designed to compensate for the various shortcomings of the GRACE spacecraft, which were never designed or intended to serve as a reference antenna. The resulting improvement in GNSS signal modeling will benefit all precision applications of these systems, which are the cornerstone of many Earth science missions.

1. OVERVIEW

The Geodetic Reference Antenna in Space (GRASP) is a proposed mission concept. The spacecraft itself is a science instrument, as the whole system must be designed for ultra-precise positioning of its set of geodetic sensors, both relative to each other, and absolutely in the Terrestrial Reference Frame (TRF). GRASP will carry precise sensors systems for all the key geodetic techniques used to define and monitor the TRF: a Global Navigation Satellite Systems (GNSS) receiver, a Satellite Laser Ranging (SLR) retroreflector, a Very Large Baseline Interferometry (VLBI) transceiver, and a Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS) receiver. The baselines between RF/Optical phase centers of all sensors on the supremely-calibrated GRASP spacecraft will be known to 1 mm accuracy and stable to 0.1 mm/year, and the spacecraft will lend itself to absolute positioning of its center of mass with an unprecedented accuracy of 1 mm RMS, and stability of 0.1 mm/year.

The primary driver for the GRASP spacecraft design is the demanding requirement for 1 mm absolute positioning and 0.1 mm/year stability. Only an extremely simple spacecraft can support such requirements: no moving parts, no sloshing fuel, unchanging center of mass.

The broad and profound benefits from an operational GRASP mission include:
• Enable the determination of ties (relative offsets) between the different geodetic techniques in a consistent reference frame
• Enable consistent joint processing of data from all techniques for optimal TRF realization
• Enhance the long-term stability of the TRF
• Enhance the accurate dissemination and densification of the TRF by the ubiquitous GNSS
• Enhance accuracy for all precise GPS applications
• Enable improved science accuracy from missions that depend on GNSS for precise positioning, such as OSTM, and the Decadal Survey recommended missions of DesDynI, ICESAT-II, SWOT, GRACE-II,…
• Enable the consistent measurement of climatological data records of sea surface height, ice elevations, gravity field variations,…
• Enable the calibration and consistent data processing from the growing diversity of Global Navigation Satellite Systems

2. SCIENCE DRIVERS

2.1. The Terrestrial Reference Frame (TRF)

The National Research Council (NRC) Decadal Survey states that the TRF "*provides the foundation for virtually all space-based and ground-based observations in Earth science and global change, including remote monitoring of sea level, sea surface topography, plate motions, crustal deformation, the geoid, and time-varying gravity from space. It is through this reference frame that all measurements can be inter-related for robust, long-term monitoring of global change. A precise reference frame is also essential to interplanetary navigation and diverse national strategic needs.*" [Space Studies Board, 2007]

The Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) has recently reviewed the scientific rationale and requisite specifications for a global geodetic observing system in terms of concepts, conventions, infrastructure and services, that are needed to meet the future requirements of a global society facing increasing challenges on a changing planet (Plag and Pearlman, 2009). Improvements of the terrestrial reference frame and the availability of geodetic observations over the last few decades have been major drivers of scientific discovery and further improvement can be expected to lead to more exciting discoveries. Following a review of the requirements of the diverse set of scientific and societal users, the IAG made the following recommendations concerning the accuracy and stability of the terrestrial reference frame (Gross et al., 2009):

"... accurate to 1 mm, stable to 0.1 mm/yr, including geocenter; scale accurate to 0.1 ppb, stable to 0.01 ppb/yr ..."

At present the TRF is defined through the loosely coordinated networks of four independent space geodetic techniques: Satellite Laser Ranging (SLR), in which ground-based lasers range to Earth satellites carrying suitable reflectors; Very Long Baseline Interferometry (VLBI), in which ground-based radio telescopes make precise angle (or differential range) measurements to distant radio sources; and Global Positioning System (GPS) geodesy, in which ground-based (and some low orbiting) GPS receivers make precise one-way range and range rate measurements from orbiting GPS sources, and DORIS, in which ground-based beacons broadcast to receivers on Earth orbiting satellites.

The current ITRF2005 reference frame has contributions from all four techniques [Altamimi et al., 2007]. For ITRF2005 SLR provides the most accurate determination of the origin (geocenter), while the TRF scale is determined from VLBI data. VLBI also determines the absolute orientation of Earth with respect to distant quasars, thus providing the important connection between the TRF and the celestial reference frame (CRF) (in which deep space spacecraft orbits are integrated). Though GPS performs comparably in many individual TRF parameters [Heflin et al., 2002], uncertainties in the phase-center models for GPS satellites and ground tracking stations at the decimeter level, prevent this technique from significantly contributing to the TRF geocenter and scale determination. However, GPS is unchallenged in efficiently densifying the frame (spatially as well as temporally), transferring its precision to virtually any point on the globe or in near space through ubiquitous GPS receivers on the ground or on satellites.

To propagate and densify the TRF the GPS tracking network must be tied to the SLR, DORIS and VLBI tracking networks. These ties are realized through collocations of the geodetic techniques at key ground sites and the application of tie vectors that have been measured in-situ with sufficient accuracy [Altamimi et al., 2007]. The accurate measurement of these ground ties has proven extremely difficult due to the expensive logistics involved in doing repeated ground surveys, and is fundamentally suspect due to the above-mentioned challenge of physically determining the radio frequency phase center of the GPS antennas (and to some extent of the VLBI antennas). Hence, the ability of GNSS to contribute and densify the TRF, or to propagate the TRF, is compromised by the difficulty of tying together the different geodetic techniques.

Stability of the frame is critical for many global change measurements. For example, Morel and Willis [2005] looked at the errors in mean sea level arising from errors in the geocenter or scale determinations of the ITRF. They found that a 10 mm error in the Z component of the reference frame can lead to an error of –1.2 mm in the determination of mean sea level, with a strong regional systematic error signal at the high latitudes. Beckley et al. [2007] reprocessed all the TOPEX/Poseidon and Jason-1 SLR & DORIS data within the ITRF2005 reference frame, and found that the differences in the older CSR95 and ITRF2000 realizations and ITRF2005 caused differences of up to 1.5 mm/yr in regional rates of mean sea level rise. The overall differences reach ± 0.44 mm/yr between 1993 and 2007 - larger than the Greenland contribution to sea-level change as measured by GRACE [Luthcke et al., 2006]. Comparisons of ITRF2005 with ITRF2000 indicate drift rates of 0.2 mm/yr, 0.1 mm/yr, and 1.8 mm/yr for the xyz geocenter coordinates, and 0.08 ppb/yr for the scale. Comparisons of ITRF2005 with independent GPS measurements indicate drift rates of -0.6 mm/yr X, -0.6 mm/yr Y, and 1.1 mm/yr Z for the geocenter and -0.05 parts per billion per year for the scale [Heflin et al., private communications].

Thus, we assess that current state of the art reference frame errors are at roughly the mm/yr level, making observation of global signals of this size very difficult to detect and interpret. This level of error contaminates climatological data records, such as measurements of sea level height from altimetry missions, and was appropriately recognized as a limiting error source by the NRC Decadal Report and by GGOS. It is worth noting that tide gauge records contain evidence of decadal basin-scale gyre variations [Miller and Douglas, 2004], and that the elucidation of these signals in a time series from satellite altimeter data may also be compromised if the TRF realization is not sufficiently

stable.

2.2. GNSS Antenna Calibration and Precise Orbit Determination

Precise orbit determination (POD) is a critical component of an increasing number of Earth science missions. Examples of past and extant missions include TOPEX/Poseidon, Jason-1, and GRACE, to name just a few. Many future missions, such as OSTM (Ocean Surface Topography Mission) and several advocated by the Decadal Survey (DESDynI, ICESAT-II, SWOT, and GRACE-II) will also rely significantly on POD. For many of these missions, the quality of the science product is directly dependent on the accuracy of the orbit determination. For missions providing long-term climatological data records, such as OSTM (Jason-2), ICESAT-II, and SWOT, it is essential that the orbit determination be carried out in a consistent reference frame across many years and different spacecraft.

Conventionally, orbit determination of an Earth science spacecraft refers to the positioning of its center-of-mass (CM) in a specific TRF. The location of the spacecraft CM within the spacecraft's local reference frame can be accurately measured prior to launch. (For GRACE the CM location knowledge was required with 0.5 mm accuracy, and was shown using an in-orbit calibration procedure to be accurate to 0.25 mm.) Also measured pre-launch are the vectors (or relative offsets) between the various positioning (POD) sensors and the CM. Many of these missions employ multiple independent positioning (POD) payloads for robustness and to enable cross calibration. GRACE carries GPS and SLR sensors. TOPEX, Jason, and OSTM carry a DORIS receiver as well.

Beginning with the success of the precise GPS-based orbit determination demonstration on TOPEX [Bertiger et al., 1994], GPS has emerged as the positioning sensor of choice for science missions requiring high accuracy orbit determination. This can be attributed to its unbeatable combination of accuracy, availability, and economy. GPS-based orbit determination has met and exceeded the most stringent science requirements for missions such as Jason [Haines et al., 2004], and GRACE [Bertiger et al., 2002]. Accuracies of better than 1 cm (RMS, Radial) are now being achieved for the OSTM/Jason-2 mission [Bertiger et al., 2009], and represent the state-of-the-art for POD. For the GRACE tandem mission, GPS is being used to determine the intersatellite distance (~200 km) to better than 1 mm [Kroes et al., 2005, Wu and Bar-Sever, 2006].

However, pushing GPS to the limit on missions such as Jason and GRACE, as well as for geodesy and TRF determination, has uncovered certain challenges. Primary among them is the difficulty in calibrating variations in the electromagnetic reference points of the antennas of the GPS space vehicles (GPS-SVs). The location of this point varies in both time and space, depending in large measure on the direction (azimuth/elevation) of signal transmission. This is due not only to the gain pattern of the transmitting antennas [Aparicio et al., 1996], but also to the particulars of the spacecraft structure in the near-field environment. Signal multipath off neighboring components of the vehicle can systematically influence the effective phase center location [Young et al., 1985]. Antenna range measurements taken on the ground are usually performed using only the antenna fixture, and thus do not reflect the potentially significant influence of the real spacecraft environment, or of the ground environment for GPS ground antennas.

These antenna phase variations (APV) can be approximated by a single reference point, the "antenna phase center" (APC), defined as the center of the sphere that best fits the APV. Since the GPS observations actually provide the distance between the electromagnetic reference points of the transmitting and receiving antennas, it is essential for practical applications to measure the vector between the APC/APV and a physical reference point. For orbit determination applications this physical reference point is the center of mass of the spacecraft. For geodetic applications the reference point is often a permanent marker on the ground. The challenge stems from the virtual nature of the APC/APV, and its susceptibility to the environment surrounding the antenna.

Major campaigns have taken place in recent years to calibrate the APC/APV of key GPS antennas. These key antennas include not only the transmit antennas of the GPS satellites [Bar-Sever, 1998, Mader and Czopek, 2001; Schmid and Rothacher, 2003; Haines et al., 2004; Ge and Gendt, 2005; Schmid et al., 2005], but also the receive antennas represented in the ground tracking network [Bar-Sever, 1998; Mader, 1999], and the receive antennas on science spacecraft [Haines et al., 2004]. Two different approaches are used for these calibrations. The majority of campaigns have used anechoic chamber-calibrated antennas (or their equivalent, e.g. 'robot' calibrations by Geo++ [Wubenna et al., 2006]) to model the receive antennas in the global ground network. These antennas are in turn treated as reference for calibrating other (i.e, transmit) antennas in the system. It should be noted, however, that the intrinsic APV pattern provided for the ground antennas by anechoic and/or robot measurements can be significantly altered by near-field effects (multipath, scattering) unique to each terrestrial tracking site. As highlighted by Elosegui et al. [1995], the permanent structures (e.g., pillars) to which the antennas are typically mounted become electromagnetically coupled to the antennas themselves. Natural changes in the

environment, such as foliage, can also affect the receiver phase center patterns.

Another point of contention, which is critical to our discussion, revolves around the determination of scale. It stems from the fact that the change in measured range by a ground GPS antenna would be the same whether the phase center shifts vertically by a fixed amount, or whether the antenna is physically moved vertically by the same amount. Consequently, system-wide biases would result if all the ground GPS antenna would physically move up or down by an equal amount – the consequence of a change in the TRF scale. This problem underlies our reservations about using the ground GPS network to calibrate the transmit antenna on the GPS satellite. The ground antennas must be referenced to the TRF, with scale determined by VLBI and SLR. However, the ties (or vectors) that connect the SLR or VLBI telescopes and the GPS sites are of insufficient accuracy and abundance. Indeed, decimeter-level discrepancy between the various approaches in determining the phase center of the transmit antennas attest to the difficulty of accurately calibrating the GPS-SV antennas.

Our approach to recovering the APV of the GPS transmitters addresses these deficiencies by using data from geodetic-quality GPS receivers in low orbit. This approach offers a number of substantial advantages. Most important, POD techniques can be invoked to fix the average estimated height of the low-Earth orbiter (LEO) CM at the cm level (to be improved to mm level with GRASP), with little sensitivity to the scale of the underlying TRF defined by locations of tracking stations on the Earth's surface. The Earth gravitational constant, GM, constricts the inferred semi-major axis of the LEO orbit in much the same way it controls the estimated height of the GPS constellation. Linking the scale of system to GM is attractive because this fundamental constant represents the combined mass of the Earth system, and as such is nearly immutable. APV solutions that rely on terrestrial GPS tracking data cannot directly access the accuracy and stability of GM, because ground station positions are modeled using kinematic rather than dynamic techniques.

Another advantage of using orbiting antennas is that there is no troposphere refraction to confound interpretation of the measurements. The only significant atmospheric refraction arises from the presence of free electrons in the ionosphere above the low orbiter carrying the GPS antenna. Since the ionosphere is a dispersive medium, the resulting signal delay is corrected to first order using the two GPS frequencies. Thus, in contrast to terrestrial GPS applications, no additional modeling or estimation of atmospheric delays are needed.

Following this approach, we have recently used data from JPL's Trig GPS receivers onboard the GRACE satellites (2002–) to develop new estimates of GPS satellite APV [Haines et al., 2006]. The GRACE satellites offer at present the best available reference antenna in space, despite several shortcomings that we expect to remedy with GRASP. The APV estimates are expressed as tracking observable (distance) corrections mapped in two dimensions (nadir angle and azimuth). We have developed maps for both ionosphere-free carrier phase (LC) and pseudorange (PC), and for all individual GPS satellites flying in the 2002–2004 time frame. Examples are shown in Figure 1.
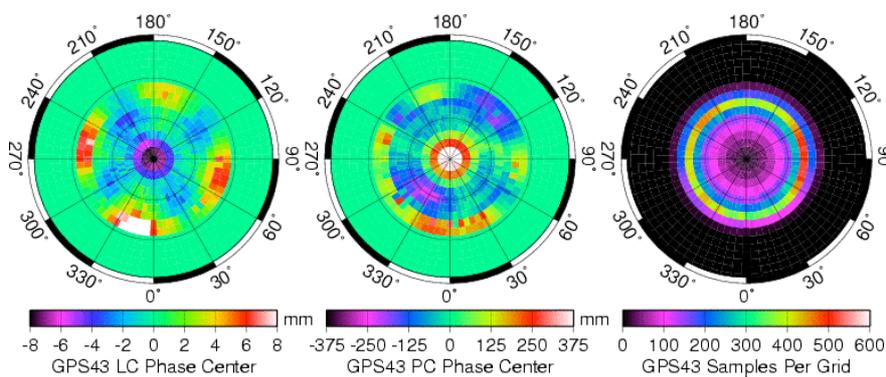

Figure 1: Estimated GPS phase-center variation (PCV) maps for space vehicle (SV) number 43 (PRN 13). The concentric circles are 10° bands of nadir angle as measured from the GPS transmit antenna boresite (The center of the plot is 0° off nadir.) Azimuth is angle is measured counterclockwise. The left and center panels depict the variations for the ionosphere-free carrier phase (LC) and pseudorange (PC) respectively. The right panel shows the number of observations used in generating the maps. 90% of the GPS power is transmitted from a circle of 4 conical antenna elements—these elements are clearly seen in the LC map. The PC map is dominated by multipath [from Haines et al., 2004].

We have undertaken independent evaluations of these APV estimates using data from the TOPEX/Poseidon (1992–2005) and Jason-1 missions (2001–), both of which carry precision GPS receivers (Figure 2). An apparent vertical offset of ~4–5 cm in the daily solved-for positions of the Jason-1 antenna is reduced to –2 cm by applying the GRACE-based GPS APV maps (The remaining signal in the Jason-1 antenna offset estimates is likely due to local multipath on the spacecraft.). Equally important, a spurious long-term (4-yr) drift in these daily estimated offsets is reduced from +3.7 to +0.1 mm/yr. This antenna offset parameter is a proxy for TRF scale, since the antenna height is determined from the observation geometry, while the vehicle CM is fixed—in a dynamical solution—by the laws of physics. The conspicuous improvement in scale is due to improved modeling of the GPS APV. This is especially relevant for the newer Block IIR satellites, which comprise an increasing fraction of the overall GPS population [Ge et al., 2005]. The scale realized with historical data, however, also strongly benefit from the GRACE-based APV maps. This is illustrated by the dramatic reduction in the solved-for position of the T/P antenna, circa 1995 (Figure 2). The apparent 5–6 cm bias in the T/P antenna offset estimates has eluded explanation for over a decade. The adoption of the GRACE-based APV maps reduces the bias to

insignificance. Unlike its counterpart on Jason-1, the T/P GPS antenna is placed on a 4-m boom to reduce multipath reflection, so the estimated offset should be negligible once the GPS spacecraft effects are properly modeled. These results hint at the enormous potential of these new GPS antenna APV maps for wide-ranging geodetic applications wherein scale and long-term stability are important. Were it not for the compensating role of dynamic models, these scale and scale-rate errors would have been fully expressed in the estimates of global sea-level change derived from T/P and Jason-1 altimeter and GPS ephemeris data.

Despite the important advances enabled by the GRACE-based approach, this tandem mission has proved inadequate in removing potential biases at the mm level. The deficiencies are due in part to the lack of a rigorous calibration of the GRACE antennas on the ground prior to launch. In particular, the antennas were not calibrated on the spacecraft. While GRACE offers a relatively clean geometry, simulation analysis show significant levels of both phase and pseudorange multipath. These effects could bias the effective antenna phase center by an unknown amount. Equally important, GRACE's orbit is strongly impacted by the unpredictable, and difficult to model atmospheric drag. As a result the orbit determination of GRACE depends too much of the GPS
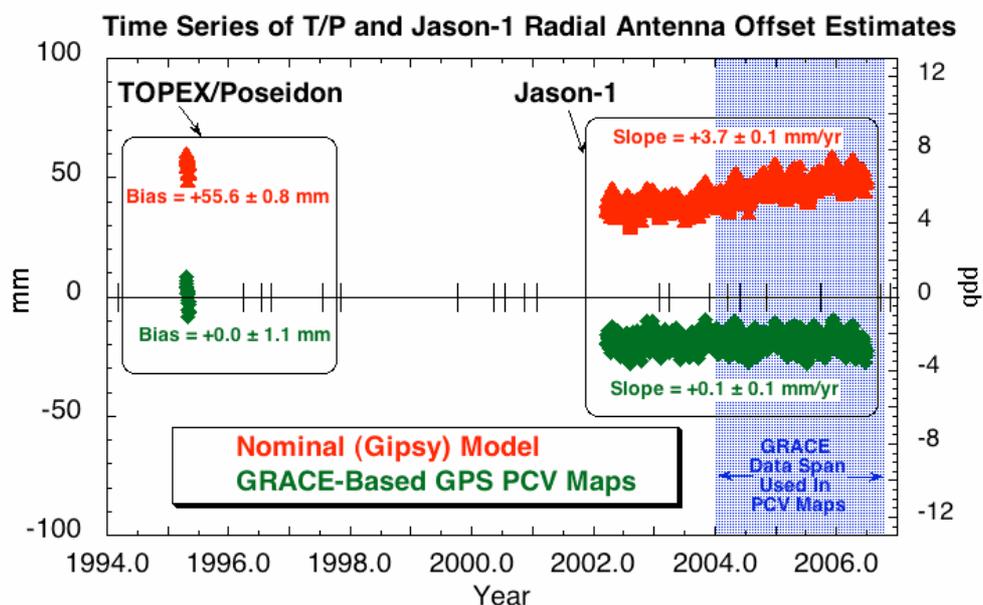

Figure 2: Time series of the daily estimated T/P and Jason-1 radial antenna offset with and without the new GRACE-based GPS APV maps. The radial antenna offset is estimated in flight relative to its known (pre-launch) measured value, with the s/c center of mass providing a constraint on the s/c trajectory via the laws of motion. The apparent (estimated) location of the antenna can move freely and independently based on the GPS tracking data used in the POD process, and is thus a proxy for systematic GPS measurement-system errors. Implementation of the maps significantly decreases the spurious 5-cm bias in the the T/P and Jason-1 antenna offsets, and reduces the long-term drift to insignificance. It is important to note that the T/P and Jason-1 data were not used in generating the APV maps, so this can be considered a strong, independent test of the GPS APV maps referenced to GRACE.

measurements, and is susceptible to biases in the phase center of the antennas, which represent the calibration target. Finally, GRACE flies too low to sample the full GNSS APV angles that are observe with the ocean altimetry platforms flying at 1300 km and, consequently, it cannot provide full calibration for these missions.

GRASP is intended to overcome the limitations of GRACE by ensuring that the GPS antenna and the spacecraft are carefully calibrated as a single instrument. The objective it to model the spacecraft dynamics with sufficiently high fidelity so as to be insensitive to biases in the GPS measurements. This can be achieved by constructing a uniquely simple spacecraft, which in turn enables high fidelity modeling of the non-conservative forces, and placing it in a much higher orbit so as to minimize impact of the difficult to model forces of atmospheric drag and gravity field.

2.3. Benefits to Future Earth Science Missions

The ability to cross calibrate and tie the disparate geodetic techniques, enabled by the GRASP technology and mission concept, and the resulting improvement to the TRF will benefit all the missions studied by the Decadal Survey, which stated: "improvement and the continued operation of this geodetic infrastructure is a requirement of virtually all the missions for every Panel in this study".

The following missions, recommended by the Decadal Survey, strongly depend on accurate GPS-based positioning, and will directly benefit from the system-wide improvement in GPS accuracy derived with the GRASP technology:
- DESDynI – requires precise positioning to detect surface change. Error in spacecraft positioning directly translates to in error in the science interferograms
- SWOT – like all altimetry missions, vertical positioning errors directly translate to error in sea surface height measurements
- ICESAT-II - like all altimetry missions, vertical positioning errors directly translate to error in ice sheet elevation measurements
- GRACE II – requires primarily precise timing, which is a by-product of GPS positioning. Will also benefit from improvement in the measurements of the geocenter of the TRF promised by GRASP

The last three missions above, plus OSTM, aim to provide long-term climatological records of Earth change. Any bias due to TRF inconsistencies, including to the scale and geocenter, will translate into spurious trends. This has been demonstrated on Jason, where the potential for uncalibrated antennas on the GPS satellites to cause spurious trends in sea surface height was

shown [Haines et al. 2006]. GRASP will ensure that the ever-changing GNSS constellations are continuously and consistently calibrated, so as to avoid aliasing antenna biases and TRF biases into spurious climatological signals.

3. AN IMPLEMENTATION APPROACH

The GRASP instrument system combines sensors and spacecraft to facilitate the unprecedented goal of achieving mm-level positioning in space. We identify three key subsystems of the GRASP system:
- Tracking sensors for GPS, SLR, VLBI, and DORIS
- Spacecraft structure
- Spacecraft services: power, propulsion (if any), attitude sensing and control (if any), command and data handling, communications

3.1. The Positioning Sensors Subsystems

The tracking sensors vary in their maturity levels. The GNSS, DORIS, and SLR sensors are relatively mature technologies, some with significant flight heritage. The VLBI sensor is less mature. For integration, calibration, and testing we baseline the following sensors:
- JPL's BlackJack GPS receiver with a choke ring antenna. This is the only flight receiver with a track record of sub-centimeter POD. Additional GNSS receive capabilities are being added.
- SLR retroreflector array, nominally of the type deployed on CHAMP, GRACE, and TerraSAR-X [http://ilrs.gsfc.nasa.gov/satellite_missions/list_of_sa tellites/tsar_reflector.html], but more advanced models are available.
- Two options exits for the VLBI sensor, which must still be evaluated and traded. One is a beacon transmitting ranging signal synchronized to the GPS-based timing. The transmission will be in S- and X-band to allow for ionospheric-free combination of the signals. The two frequencies are those used by the VLBI sites responsible for the determination of the TRF scale, and will require no changes at these stations. The second option is a dual one-way ranging system, based on JPL's flight proven GRACE inter-spacecraft ranging instrument, which has demonstrated micron-level precision. This instrument, which has already been integrated into the BlackJack receiver, will be shifted from K/Ku to S/X frequencies and will include a ranging code as demonstrated with JPL's Automated Formation Flyer testbed. Equivalent devices will be installed at ground VLBI sites to support the second option.
- We hope that the French Space Agency (CNES) will provide a DORIS receiver of the type that is carried on OSTM.

3.2. The Spacecraft Subsystem

The GRASP spacecraft is required to provide stable,

mm-level collocation of the phase centers of its multiple positioning sensors relative to the spacecraft center of mass, as well as absolute positioning of the center of mass in inertial space that is free of biases at the mm level or better. To achieve this unprecedented relative and absolute positioning accuracy the spacecraft has to be designed from the ground up for precise orbit determination, and metric stability. To facilitate that the GRASP spacecraft must have the following unique design attributes:

- Have no major moving parts. Moving parts, such as pitching solar arrays, shift the center of mass, and complicate the modeling of the spacecraft dynamics. Moving parts also tend to reduce mission lifetime.
- Have no expendable fuel. Fuel may shift the center of mass as it sloshes in its tank or as it is being depleted. Some fuel (cold gas) may be necessary at the beginning and end of life for orbit insertion and disposition of the spacecraft.
- Have a very simple shape (box or cylinder), with nearly uniform external panels in order to facilitate high fidelity modeling of the non-conservative forces (primarily solar pressure and Earth radiation, but potentially also atmospheric drag)
- Have a low ballistic coefficient value (area to mass ratio) to minimize the impact of mis-modeled non-conservative forces.
- Orbit at sufficiently high altitude (above 1000 km) so as to minimize or eliminate the impact of the hard to model atmospheric drag, and also to minimize the susceptibility to other poorly determined models such as Earth radiation and high degree and order gravity field harmonics. This requirement has important radiation tolerance implications.
- Very low thermal expansion coefficient to ensure 0.1 mm/year stability of the sensors relative to the center of mass.

To facilitate the precise calibration of the phase centers of the GRASP RF and optical positioning sensors, recognizing that the sensors interact with the totality of the spacecraft environment, we must be able to enter the whole spacecraft into an anechoic chamber, and to determine the spacecraft center of mass with sub-mm precision. Consequently we require GRASP to be a microsat-class spacecraft, of a size that could be readily accommodated in available anechoic chambers

The following is a potential concept for the GRASP spacecraft and its mission profile (see Figure 3):

- Gravity gradient spacecraft. The only active attitude control system consists of magneto torquers that can prevent the spacecraft form turning upside-down, and can slow down high rate of spin if necessary
- Sun-synchronous orbit at 2500 km altitude ensures no eclipse seasons, eliminating the complexity and attendant uncertainty of modeling the discontinuous solar radiation pressure during eclipse seasons, and

eliminates atmospheric drag as an error source.
- No propellant system, and no fuel; 2500 km qualifies as a disposal orbit.
- The area to mass ratio is roughly 1/500 m2/kg (5 times lower than a typical spacecraft)

Flying at 2500 km altitude also enables X/S band interferometry measurements across continental baselines, encompassing, for example, the whole of the Very Large Baseline Array (VLBA), and facilitates improved measurements of baseline lengths and the TRF scale from GRASP. However, this altitude exposes GRASP to a severe radiation environment. While the near polar orbit minimizes the exposure to radiation, the expected total radiation dose is ~11K Rad/year (behind 11.6 mm of shielding), and requires special consideration. For example, extra shielding may be necessary. The baseline design mitigates the high radiation dose with massive shielding (more mass also achieve the desirable outcome of reducing the ballistic coefficient), and with redundant electronics designed to tolerate single even upsets.

4. PERFORMANCE ANALYSIS

We performed a number of simulation and covariance analyses designed to assess the performance of GRASP under realistic scenarios. For the purpose of quantifying reference frame transfer and collocation accuracy we focused on GPS and SLR. The latter can serve as a proxy for either DORIS or VLBI. The following assumptions were made:

GPS constellations: 29 satellites
GRASP orbit: 2500-km altitude polar orbit
SLR stations: 11 stations (see Figure 3).
GPS tracking network: 66 stations
Data types/noise:
- 0.4 m for GPS iono-free pseudorange combination at GPS ground sites. Simulated multipath obtained with actual measured multipath at GPS ground sites. Maximal multipath amplitude is ~1 m.
- 0.005 m for GPS iono-free carrier phase combination at GPS ground sites. Simulated multipath obtained with actual measured multipath at GPS ground sites. Maximal multipath amplitude is ~0.01 m
- 0.1 m for GPS iono-free pseudorange combination at GRASP
- 0.0025 m for GPS iono-free carrier phase combination at GRASP
- 0.01 m for the two-way SLR ranges to GRASP
Data Span: 7 days
Data Sampling: once every 5 minutes

The above-specified measurement noise for the GPS receiver on GRASP is being observed on GRACE, and is, therefore, a conservative value.
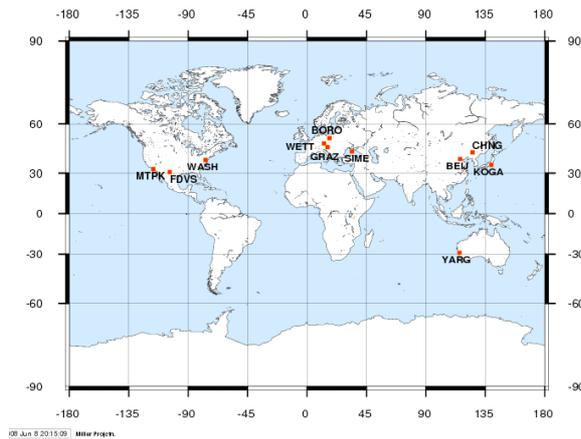
Figure. 3. Locations of SLR sites used in the simulations

We analyzed three scenarios:

Scenario 0: Conventional ground-based GPS orbit determination. The following parameters are modeled and estimated:
- GPS transmitting antenna phase centers
- X & Y polar motion
- X & Y polar motion rate
- UT1–UTC rate
- GPS ground site location, or
- Geocenter (and site locations are held fixed)
- GPS epoch states
- GPS X & Z solar scales as process noise (at 1%)
- GPS Y force as process noise (0.01nm/sec2)
- GPS satellites and ground clocks as white noise
- GPS tracking site zenith troposphere delays as random walk
- Phase biases

Scenario 1: Reference frame enhancements and GPS performance enhancements with GRASP using only GPS data (received on the ground and on GRASP). The following parameters are modeled and estimated in addition to these mentioned in Scenario 0:
- GRASP epoch states
- GRASP empirical forces in each coordinate as white noise process with nm/sec^2 steady state sigma, updated every 4 hours

Scenario 2: Reference frame transfer from SLR to GPS. In this scenario GRASP orbit determination is carried out by SLR, and GRASP serves to transfer the SLR frame to GPS through a network solution in which the GPS satellite orbits and ground sites positions are determined in a grand estimation scheme. The accuracy with which the GPS ground sites are determined in this scheme is a measure of the reference frame transfer from SLR to GPS. It is evaluated with a 7 parameter Helmert Transformation.

Scenario 3 is the reverse of Scenario 2. Here GRASP orbit is determined as in Scenario 1, and the SLR sites locations are estimated in point-positioning mode from ranges to GRASP. The accuracy with which the GPS ground sites are determined in this scheme is a measure of the reference frame transfer from SLR to GPS. It is evaluated with 7 parameter Helmert Transformation.

The results are summarized in Table 1.

From Table 1 we can draw the following key conclusions about benefits that can be attributed to GRASP:

- With a factor of 3.5 improvement is determination of GPS antenna radial offset with GPS data alone, and a factor of 8 improvement when SLR data is also used through GRASP, GRASP is ideally suited to serve as absolute reference antenna for consistent calibration of all GNSS antennas, ground and space. At 2500 km altitude, GRASP provides for GNSS satellite APV sampling fully consistent with high LEO missions, such as OSTM.

- GRASP directly improves GNSS orbit determination by a factor of 3 due to exquisite dynamics (10 times better than Jason) and outstanding observation geometry.

- GRASP enhances GNSS contributions to the TRF through geocenter and scale, with a Factor of 10 improvement in Geocenter determination with GPS data alone.

- GRASP enables phase-center to phase-center reference frame transfer between the key geodetic techniques with a few mm accuracy in just 7 days. This reduces or eliminates the need for ground-based collocation, and for local tie surveys, and it enables unlimited densification of the TRF through GNSS

Finally, GRASP offers a fresh approach to geodesy will bring together the disparate geodetic communities as never before, and energize the unified modeling campaign, consistent with GGOS goals.

5. REFERENCES

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Table 1. Scenario simulation results, combining in quadrature the random (from covariance analysis) and systematic (from simulation) errors. H C, and L stand for Height, Cross-track, and aLong-track component of the orbital error.

Performance Metrics / Scenarios	GPS Orbit mm	GPS Ant Z Offset mm	GRASP Orbit mm	Geo-center mm	GPS Site Position mm	SLR Site Position mm	Helmert Trans. mm
0) Ground GPS Data Only (No GRASP): Fixed ground sites, estimate GPS orbits, phase offsets, geocenter	20.7 H 13.5 C 22.2 L	113.6	N/A	2.9 X 2.6 Y 59.4 Z	N/A	N/A	N/A
1) GPS Data Only from Ground and GRASP: Fixed ground sites, estimate GPS orbits, phase offsets, geocenter	7.4 H 7.2 C 7.4 L	30.9	0.9 H 0.6 C 2.4 L	2.2 X 0.9 Y 5.6 Z	N/A	N/A	N/A
2) SLR -> GPS Ref. Transfer: GPS and SLR Data, fixed SLR sites, estimate GPS orbits, phase offsets, and GPS sites	8.4 H 8.7 C 7.9 L	14.1	0.7 H 0.7 C 1.9 L	2.7 X 1.3 Y 1.4 Z	2.9 X 3.7 Y 0.9 Z	N/A	0.4 Ry 2.0 Tz 4.5 Sc
3) GPS -> SLR Ref. Transfer: GPS and SLR Data, fixed GPS sites, estimate GPS orbits, and SLR sites	8.3 H 7.1 C 7.4 L	N/A	0.7 H 0.6 C 2.0 L	0.8 X 0.8 Y 0.7 Z	N/A	0.1 X 0.2 Y 0.1 Z	0.4 Ry 0.4 Tz 0.3 Sc

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6. ACKNOWLEDGEMENT