Geodetic Observations and Global Reference Frame Contributions to Understanding Sea Level Rise and Variability

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1 Introduction

1.1 Purpose and Scope

Climate models that are used to study the effects of atmospheric greenhouse gases predict an overall increase in the global temperature over the next century of from 1.4 – to 5.8 °C degrees centigrade [Houghton et al., 1996, 2001]. An increase of this magnitude could have numerous catastrophic effects, not the least of which might be a global rise in sea level due to a combination of melting polar ice caps and glaciers and the thermal expansion of sea water. The global rate of sea level rise during the last century has apparently been estimated to be about 1.7–1.8 mm/ [Douglas et al., 2001; Church et al., 2004; Kuo, 2006] with a recent acceleration being reported [Church and White, 2006]. One of the important goals of all national and international global change programs is to improve our understanding of the mechanisms and implications of observed sea level changes.

Geodetic observations can characterize highly precise spatial and temporal changes of the Earth system that relate to sea level changes. The challenge for quantifying long-term change in sea level imposes most stringent observation requirements, and can only be addressed within the context of a stable, global reference system, such that sea level measurements today can be meaningfully compared with measurements 10 years later with sub-millimeter accuracy. Only geodetic observations can provide the basis for a global reference frame with sufficient accuracy. Significantly, this reference frame is extensible to all regional and local studies in order to link multi-disciplinary observations and ensure long-term consistency, precision and accuracy. The reference frame becomes the foundation to connect observations in space and time and defines the framework in which global and regional observations of sea level change can be understood and properly interpreted. Geodetic observations from *in situ,* airborne and spaceborne platforms measure a variety of quantities with increasing accuracy and resolution and address interdisciplinary science problems, including global sea level change. For this workshop, we will address topics that will help to identify geodetic requirements to meet the rigorous scientific demands for understanding sea level rise and its variability, towards improving its prediction. In particular, we stress the need for the continuity of the geodetic observational series that serves basic research, applications and operational needs.

1.2 Geodesy – Science and Technology

Geodesy is concerned with the measurement of:

- changes of the surface geometry of the Earth i.e., the variations in time and space of ocean surfaces and ice covers, and of horizontal and vertical deformations of land surfaces (geometry part), unfortunately, geodesy currently is not able to measure the vertical deformations of roughly 71% of the Earth's surface, i.e. the ocean floor;
- fluctuations in the orientation of our rotating planet relative to the stars commonly divided into precession, nutation, polar motion and changes in spin rate (Earth orientation part), and,
- variations in space and time of the Earth's gravitational field usually expressed as anomalies of gravity and of the geoid or in the form of gravity gradient tensor (gravity and geoid part).

All three of these "pillars of geodesy" are associated with sea level, and so sea level has always been a traditionally strong aspect of geodetic theory and practice. The surface geometry of the solid Earth defines the ocean bottom surface, which can provide a reference for measuring relative sea level (e.g., tide gauges), and is essential to understanding the impacts of sea level change (e.g., ground subsidence at Venice or Lagos). Sea level changes associated with mass redistribution (e.g., melting polar ice caps) will affect Earth rotation and polar motion. In static equilibrium, the sea surface follows the shape of the time-varying geoid. Moreover, mass redistribution associated with sea level change will also change the shape of the geoid and ocean bottom surface, and hence sea level (Figure 1). Thus geodesy is fundamental to a comprehensive understanding of sea level variation; in fact, *sea level variation cannot be understood outside the context of geodesy*.

Geodesists specialize in acquiring, analyzing, and interpreting space-based, ground-based and airborne geodetic measurements that are significantly important for understanding sea level changes. Related processes that geodetic observations and analysis can contribute to understanding the Earth include:

- changes in sea level;
- hydrology and continental water storage;
- mass fluctuations and motions of glaciers and ice complexes;
- postglacial rebound;
- tides of the solid Earth and the oceans, and to a lesser extent, poles and atmosphere;
- ocean circulation;
- atmospheric circulation and water vapor;
- crustal motion associated with plate tectonics, earthquakes, and volcanoes, including coastal deformations and anthropogenic subsidence;
- weather and climate, atmospheric structure and dynamics, space weather.

Fundamental to understanding these processes is the creation and maintenance of a terrestrial reference frame (TRF) and its tie to inertial space, the celestial reference frame (CRF). The TRF/CRF provides the universal standard against which the Earth is measured; it is the foundation on which solid Earth science rests. Deficiencies in the accuracy or continuity of the TRF/CRF system limit the quality of science it can support. Observable variations in the TRF/CRF – geocenter motion and rotation irregularities – are themselves primary signals in the science of Earth change. Within the context of this focused workshop, control of the reference frame over long periods of time may be a primary limiting factor for understanding sea level change, land subsidence, crustal deformation, and ice sheet dynamics.

1.3 Global Geodetic Observing System – GGOS

In the past, geophysical research concerned with the three geodetic components, i.e., geometry, Earth orientation and gravity/geoid, concentrated on individual techniques and processes, and not so much on the added-value that can be drawn from their integration. The Global Geodetic Observing System (GGOS) [Drewes 2005] intends to give to these fundamental components of geodesy a new quality and dimension in the context of Earth system research by integrating them to one collective observing system with utmost precision and in a well-defined and reproducible global terrestrial frame. This observing system, in order to meet its objectives, must combine the greatest measurement precision (a relative precision of 0.01 part-per-billion, where 0.01 ppb = 10^{-11}) with utmost consistency in space, time and in the applied data modeling and with stability over decades.

Advances in the measurement of the gravity with modern free-fall methods have reached accuracies of 10^{-9} g (1 μGal or 10 nm/s^2), allowing the measurement of effects of mass changes in the Earth interior or the geophysical fluids (ocean and atmosphere loading), as well as the measurement of height changes at ~3 mm relative to the Earth center of mass [Forsberg et al., 2003]. Satellite altimetry (laser and radar) measures the changes of the sea level, ice elevations, lake/river level with an accuracy of 1 part in a billion and with respect to the center of mass of the Earth. Measurements of temporal gravity field from space [Tapley et al., 2004] and *in situ* terrestrial measurements (absolute and superconducting gravimeters) provide one with a new global instrument for measuring mass changes of the fluid envelops of the Earth system as well as viscoelastic response of the Earth's mantle to deglaciation, which are directly relevant to the measurement of the global sea level change. Synthetic Aperture Radar Interferometry (InSAR) measures 2-D glacier or ice stream flow rates directly related to thbe computation of ice mass balance which is one of the major uncertainties of sea level change. InSAR can contribute to the measurement and modeling of vertical land motion critical for accurate sea level observations from coastal tide gauges. Finally, the accurate exploitation of almost all space measurements require precise orbit determination, an achievement of 1 ppb observational technology, integrating multiple disciplines including physics, engineering, astronomy, geophysics, geodesy, atmospheric sciences. This is a key focus of GGOS.

1.4 Geodetic Observations as a Foundation for Assessing and Inter-relating Sea Level Measurements and Uncertainties

Altimetry measurements by TOPEX/Poseidon and its follow-on, Jason-1, allow the determination of the sea surface height (Figure 2) which varies due to both thermal expansion of sea water and changes in ocean water mass arising from changes in polar ice cap, mountain glacier mass, and groundwater storage. Longer-term altimeter observations from multiple missions are clearly needed in the future and with sufficient overlap (Figure 3). Since gravitational field observations, such as those from GRACE, are sensitive to processes that change the Earth's mass distribution, they can be used to investigate sea level rise and ice sheet volume changes.

Moreover, since the Earth's gravitational field is not sensitive to the thermal expansion of sea water, observations of the gravitational field can be used in concert with sea level change observations to separate the change due to thermal expansion or contraction from that due to oceanic mass changes, thereby helping to quantify the extent to which greenhouse warming is sequestered in the oceans [cf. Watts and Morantine, 1991].

The rotation vector of the solid Earth exhibits minute but complicated changes of up to several parts in 10^8 in speed (corresponding to a variation of several milliseconds (ms) in the length of the day), and about one part in 10^6 in the orientation of the rotation axis relative to the solid Earth's axis of figure (corresponding to a variation of several hundred milli-arcseconds (mas) in polar motion). The principle of conservation of angular momentum requires that changes in the rotation vector of the solid Earth must be manifestations of (a) torques acting on the solid Earth or (b) changes in the mass distribution within the solid Earth, which alter its inertia tensor. Angular momentum transfers occur between the solid Earth and the fluid regions (the underlying liquid metallic core and the overlying hydrosphere and atmosphere) with which it is in contact; concomitant torques are due to hydrodynamic or magneto hydrodynamic stresses acting at the fluid / solid Earth interfaces. Thus, as the angular momentum of the hydrosphere changes because of sea level rise and ice sheet volume variations, the angular momentum of the solid Earth will change thereby giving rise to changes in the solid Earth's rotation vector. Such variations are detectable from space-geodetic observations.

Satellite altimetry provides measurements of the time-varying sea level which, when assimilated into oceanic general circulation models along with other remotely sensed and in situ measurements, provide improved estimates of the three-dimensional oceanic temperature, salinity, and velocity fields. The Earth's gravitational field will change as the ocean-bottom pressure changes, and, under the principle of the conservation of angular momentum, the Earth's rotation will change as the oceanic angular momentum varies due to fluctuations in the ocean-bottom pressure and velocity fields. These three data sets (satellite altimetry, gravity, and Earth rotation) therefore provide a powerful means of investigating the causes and consequences of sea level change.

In addition, geometrical geodesy (which today primarily implies GPS) can directly measure displacements of the Earth's surface with a precision < 1 mm/yr, and thus can characterize change in Earth's shape, and thus the land component of relative sea level change as measured by tide gauges. Changes in the Earth's shape can also be inverted for surface mass redistribution [*Blewitt and Clarke*, 2003] and thus can infer time variations in the shape of the geoid that defines the sea surface in static equilibrium. Blewitt and Clarke [2003] demonstrated this technique to infer the seasonal variation in the mass component of sea level change with no direct measurements of the ocean, thus independently confirming published results from Topex/Poseidon (corrected for steric effects), and results inferred from terrestrial hydrology (Figure 3). GPS is also used to position satellite altimeters in space relative to GPS stations on land, thus the reference frame of Earth surface measurements can be made compatible with the frame of sea surface measurements.

2 Global and Regional Reference Systems

2.1 Introduction

One of the largest sources of error today in the global characterization of long-term sea level variation is uncertainty in the terrestrial reference frame (TRF). For example, a 2 mm/yr error in relative velocity between the mean surface of the Earth and the Earth system's center of mass can result in an error as large as 0.4 mm/yr in mean global sea level variation as determined by satellite altimetry. The effect on local sea level can be even larger and of opposite sign (Figure 4). A scale rate error of 0.1 ppb/yr would map into a sea level rate of 0.6 mm/yr. These frame biases are comparable to or larger than the contributions to secular sea level change of thermal expansion, and mass exchange with the Greenland and Antarctic ice sheets. Therefore it cannot be understated how important it is to make further progress in improving the terrestrial reference frame for studies of global change in sea level.

Yet reference frames (apart from the importance of the vertical motions of the ocean bottom) are perhaps the least understood or appreciated component of the models that connect observations to global measures of sea level change.

In this section, we therefore focus on two main points. Firstly, it is important to educate the scientific community about reference frames and their importance in the study of sea level change. This requires careful definition of terms with this exacting application in mind. Secondly, there is a complex interaction through models between the reference frame and observations that can be used to assess sea level variation. We explore this interaction and identify where weaknesses lie. We make recommendations with regard to improving the reference frame for sea level research. To take this discussion beyond abstract concepts, we refer to specific investigations that underscore the difficulties that arise from uncertainty in the reference frame, both at the regional scale and the global scale.

The outcome of this section should be a greater appreciation of the importance of reference frames in the problem of characterizing local and global sea level change, and a better understanding of what needs to be done to reduce the level of errors introduced by complex interaction between observations, models, and reference frames.

2.2 Defining a Reference System and Frames: Terminology for the Non-Geodesist

Toward understanding sea level variation, geodetic measurements are used to determine the position of the sea surface and ocean bottom in a globally consistent **Terrestrial Reference System (TRS**). The TRS must contain physical models (e.g., Figure 1) that are gravitationally self-consistent in order to connect geometrical measurements to (1) the dynamics of the primary geodetic satellite orbits (e.g., GPS), (2) the orbits of sensor satellites (e.g., altimeter satellites), and (3) the equipotential ("level") surfaces that define sea level in static equilibrium. The connection to gravity is essential for "height variation" to be physically meaningful, allowing for interpretation within the context of a gravitationally self-consistent model. Moreover, such a system requires rigorous modeling of Earth rotation, which in turn affects the Earth's gravity field from the perspective of a terrestrial frame co-rotating with the Earth (e.g., centrifugal forces), as well as from the rotationally-forced redistribution of mass in both the solid Earth response and the oceanic response (e.g., pole tides). Moreover, gravitational variation caused by mass redistribution changes the Earth's geometrical surface (including the ocean bottom) in a predictable way through surface loading models. Finally, the TRS must be connected to the "real world" through a **Terrestrial Reference Frame (TRF**), where physical points have assigned coordinates that are consistent with the mathematical definition and physical models of the TRS.

Thus the TRS is far more than a mere coordinate system, and to think of a TRS as only a coordinate system would be a serious mistake leading inevitably to miscommunication, misunderstandings, and false conclusions. This represents perhaps the most significant barrier to understanding the significance of geodetic observations of sea level in non-geodetic communities, which is why we place so much emphasis on the reference frame in this section of the document (moreover, observational techniques and Earth models are discussed in detail by other concurrent papers). In this sub-section we define and explain the components of a TRS with the non-geodesist in mind, thus we avoid the more technical and rigorous definitions that are more familiar to geodesists, for whom the definitive document today is IERS [2003], and references therein.

First of all, the relative positions of points in space can be completely specified by coordinates within a defined **coordinate system**. Coordinates actually over specify the problem; the parameters that need to be defined are origin, orientation, and scale of the coordinate system (and their evolution in time), which are implicitly defined by assigning arbitrary coordinate values to points. For global-scale geodesy, is convenient to choose a Cartesian coordinate system, from which transformations into other coordinate system can be *mathematically* defined (for example, a conventional ellipsoidal system such as WGS-84, World Geodetic System 1984 of the GPS). It is useful therefore when thinking about more familiar systems such as WGS-84 to think of the underlying Cartesian system as being more *fundamental*. For example, inside a GPS receiver the GPS positioning problem is solved in a Cartesian system (x, y, z), and only the position in WGS-84 (longitude, latitude, height) is displayed at the very last step.

Secondly, as we have already pointed out, a **terrestrial reference system (TRS**) should not be confused with a **coordinate system** or a **reference frame**[1]**,** both of which are realizations of the reference system. In general, a **TRS** is composed of three main components:

(1) A **datum**, which can be an ideal definition of the **origin**, **orientation**, and **scale** of the coordinate system, and their evolution in time. For example, the coordinates of a physical point can be defined as part of the datum definition (such as fixing the height of a benchmark for the height datum, or defining the longitude of a fiducial mark at Greenwich). Of particular relevance to sea level is the choice of **vertical datum**. Tide gauges measure sea level with respect to a **tide gauge datum** that is only useful locally, and not suitable for global studies. An attempt to measure the relative height between local tide gauge datums does not provide an effective global solution to this problem, though it may be useful for some regional studies. For the modern TRS, the use of local fiducial marks (e.g., "fundamental stations") to define the datum is no longer used, except perhaps in some average sense over the entire reference frame (item 3 below). Thus the vertical datum is secondary, in that it must be defined in terms

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[1] Reference terms as defined in [Kovalevsky et al., 1989]:

1. The ideal Terrestrial Reference System (TRS) is a mathematical, theoretical system;
2. The conventional TRS then is the sum of all conventions, parameters, constants (e.g., GM, c, etc.) that are necessary to realize the TRS;
3. A conventional TRF: any TRF is conventional by definition because using (2) and in the mean time the TRF is a realization of the TRS.

The distiction must be clear between the TRS and the TRF, that is, the latter is the realiztion of the former, and for that conventions are required.

of the global datum parameters. Now the origin can be ideally defined as the center of mass of the Earth system, and the scale can be defined by the SI **meter** as realized by atomic clocks together with the conventional speed of light. Observations of satellite orbits can be used to infer an origin at the center of mass of the Earth system, thus connecting the geometric Earth's surface to the gravity field. This is especially important for global-scale observation of sea level change. The center of mass of the Earth system can be considered a unique, static equipotential surface (surrounding an infinitesimal point) that can be chosen as the **vertical datum**. However, such a choice of vertical datum, being so far away from the actual sea surface, requires an ability to position points at the Earth's surface with respect to the Earth center of mass with high accuracy. This in turn requires a stable scale, and therefore scale plays a very practical role in this realization of the vertical datum for sea level studies, even though it is not directly related to equipotential surfaces as such. In order to realize a practical **global vertical datum** it is convenient to link the gravity field to the geometry of the Earth's surface (land and sea), a natural choice of TRS origin and scale. Such a capability has only recently become possible with the advent of space geodesy, through which the origin can be realized through the dynamics of the satellite orbits by satellite laser ranging (SLR), and through which scale can be stabilized through observations of distant quasars using very long baseline interferometry (VLBI). The **orientation** of the modern TRS is such that the **z-axis** points towards to the **Earth's pole** at some reference epoch (as the Earth's pole actually moves at a detectable level from day to day), with the x- and y-axis defining a conventional equatorial plane. The **x-axis** is chosen to define the meaning of **Prime Meridian** (zero longitude, which is no longer defined by the fiducial mark at Greenwich and actually lies ~200 m away), and the **y-axis** completes the right-handed frame, thus completing the datum definition. Among the datum parameters, the choice of orientation of the three axes is of least consequence to the problem of sea level variation.

(2) The **conventions** of the reference system, which typically specify how to compute the coordinates of a point on the Earth's surface at an arbitrary time, given the **epoch coordinates** of that point at some initial time (the **reference epoch**). This transformation typically corresponds to a physical motion model. (including, for example, solid Earth tides). The **epoch coordinates** here generally refer to parameters that are required to initialize the motion model, for example, initial position coordinates and velocity coordinates. As the motion models improve (by theory and/or experiment), so the reference system conventions might be updated from time to time. The datum can be considered part of the conventions, though it is so important that it can be useful to consider it separately.

(3) A **reference frame**, which is a list of epoch coordinates of a set of physical reference points (sometimes called benchmarks), derived from observations and conventions in a way that is self consistent with (1) and (2). This procedure is known as reference frame realization. A reference system can have several associated reference frames derived by different realizations specific to observation systems or different spans of observations. Typically there will be a unique reference frame that is recommended as the definitive frame, and commonly such a definitive frame represents a synthesis of various observational types, using as much data as possible. Hence the definitive frame requires updating from time to time. Note that in practice, it is the reference frame that implicitly defines the origin, orientation, and scale of the reference system. If, for example, the ideal orientation cannot be realized uniquely by observations alone, one can expect different reference frame realizations to produce coordinates that might differ quite significantly. This problem can be mitigated by frame alignment of subsequent realizations to some initial frame to ensure a level of consistency. For some applications, maintaining consistency in this manner is of primary importance. For other applications, it is less desirable to maintain consistency than to achieve the highest accuracy. The latter demands progressively improving the frame's accuracy in terms of how well it is aligned with the ideal datum, such as improving the alignment of the origin with the center of mass of the Earth system. This might arise as a result of an improvement in geodetic data analysis models, or upgrades to the physical models in the TRS itself. As frames are updated in this manner, this often requires the complete re-analysis of data and its interpretation within the new system. This is the reality faced by sea level investigations, for which the entire time series of sea level will, in general, be changed as improvements are made to the frame.

The most accurate realizations of the ITRS are called the **International Terrestrial Reference Frame (ITRF).** There is no single ITRF, but rather a series of updated versions of ITRF. The versions are identified by the year associated with the date of last data used in the analysis, and should not be confused with the date of applicability. The most recent versions are ITRF1997, ITRF2000 and ITRF2005 (soon to be released). Generally, as time progresses, there is less need for frequent updates, because longer time may be needed to make significant improvements through the addition of new data and improved models. However, for expected increasing accuracy requirements, the ITRF will need to be updated to incorporate more advanced models for the time-dependent reference coordinates, and certainly updated after large earthquakes.

The International Terrestrial Reference System (ITRS) was developed by the geodetic community for the most demanding scientific applications under the auspices of the International Earth Rotation Service (IERS), which was renamed the International Earth Rotation and Reference Systems Service (still IERS) to reflect the importance of ITRS today. The IERS is a service of the International Association of Geodesy (IAG).

2.3 Geodetic Techniques for Realizing the ITRF

The fundamental techniques through which these measurements have been acquired include Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), Doppler Orbitography Radiopositioning Integrated by Satellite (DORIS), and Global Navigation Satellite System (GNSS) satellites (GPS, GLONASS and future Galileo). Changes in the surface geometry are measured via microwaves using radar altimetry [e.g. Fu et al., 1994], using lasers (e.g. ICESAT reference) or interferometric synthetic aperture radar (InSAR). The orbits of the satellites making these surface change observations must be computed as precisely as possible in a coherent and stable reference frame. The orbits are derived from precise geodetic observations using SLR, DORIS, or GNSS. For example on Topex/Poseidon and Jason-1, orbits are computed for these radar altimeter satellites to a radial accuracy of 1-2 cm. This accuracy can be verified through intercomparison of orbits computed by different geodetic techniques [Haines et al., 2003, Luthcke et al., 2003].

Today, the geodetic techniques that contribute to the realization of the ITRF are organized as scientific services within the International Association of Geodesy (IAG):

- International Earth Rotation and Reference System Service (IERS) [IERS 2003]
- International GNSS Service, formerly the International GPS Service (IGS) [Dow et al., 2005]
- International VLBI Service (IVS) [Schlüter et al., 2002]
- International Laser Ranging Service (ILRS) [Pearlman et al., 2002]
- International DORIS Service (IDS) [Tavernier et al., 2005]

These scientific services, as well as gravity field services and an expected future altimetry service, are integral components of GGOS [Rummel et al., 2005]. The GGOS (http://www.ggos.org) focus on a collective effort suggests that closer cooperation and understanding can bring significant improvements to the ITRF.

Since the eighties, continuous improvement of space geodesy techniques, in terms of technology and modeling of their observations, has drastically improved our ability to determine the terrestrial reference frame (TRF) toward reaching the 1 mm accuracy level on the surface of the continents (certainly not on the ocean bottom). These space geodetic techniques include satellite laser ranging (SLR), Very Long Baseline Interferometry (VLBI), Doppler Orbitography Radiopositioning Integrated by Satellite (DORIS), and Global Navigation Satellite System (GNSS) satellites, e.g., the Global Positioning System (GPS) and GLONASS. While any individual space geodesy technique (VLBI, SLR, DORIS, GNSS including Galileo in the future) is able to provide observations contributing to a TRF determination, combination of station positions and velocities from independent techniques has long been the standard method to realize the ITRF.

Each of the observational techniques has unique characteristics. VLBI connects the ITRF to the celestial reference frame and is important for realizing the scale accurately. SLR is the satellite technique that is used to locate the center of mass of the Earth system, and so defines the origin. GPS primarily contributes to the number of sites that define ITRF (densification of ITRF), and to monitoring polar motion precisely. GPS, DORIS, and SLR are used to position space orbiting platforms in ITRF, and GPS is used to position instruments on the Earth's land and sea surfaces, such as tide gauges and buoys. Connections between the techniques are enabled by collocation at a subset of ITRF sites where two or more space geodesy instruments are operated and local site ties between monuments as derived using terrestrial surveying techniques.

None of the space geodesy techniques is able to provide all the necessary parameters for the TRF datum definition (origin, scale and orientation). While satellite techniques are sensitive to the Earth center of mass (a natural TRF origin; the point around which a satellite orbits), VLBI is not (whose TRF origin is arbitrarily defined through some mathematical constraints). The scale is dependent on the modeling of some physical parameters, and the absolute TRF orientation (unobservable by any technique) is arbitrarily or conventionally defined through specific constraints. The utility of multi-technique combinations is therefore recognized for the reference frame determination, and in particular for accurate datum definition.

Since the creation of the IERS, the current implementation of the ITRF is based on multi-technique combination, incorporating individual TRF solutions derived from space geodesy techniques as well as local ties at co-located sites. In principle, the particular strengths of one observing method can compensate for weaknesses in others if the combination is properly constructed, suitable weights are found, and accurate local ties at co-located sites are available. Obviously the ITRF quality suffers from any network degradation over time because it is heavily dependent on the network configuration. To cite only one pertinent network issue, the current configuration of co-located sites as depicted in Figure 6 (in particular sites with 3 and 4 techniques) is far from optimal.

Over a decade, the stability of the ITRF2000 geocentric origin (defined by SLR) is estimated to be at the few-mm level and the accuracy of its absolute scale (defined by SLR and VLBI) is around 0.5 ppb (equivalent to a shift of approximately 3 mm in station heights) [Altamimi et al, 2002]. While SLR currently provides the most accurate realization of the Earth's long-term center-of-mass for the ITRF origin, estimates of geocenter motion still need to be improved by the analysis centers of all satellite techniques. From ITRF2000 results it was found that the best scale agreement was between VLBI and SLR solutions.

Since the mid-1990's, initiated first by International GNSS Service (IGS, formerly the International GPS Service until 2005) [Dow et al., 2005] several technique analysis centers started to make available time series of daily (VLBI) or weekly (satellite techniques) solutions of station positions and daily Earth orientation parameters (EOP) provided in SINEX format (solution independent exchange format - SINEX). The methodology has since been extended to combine time series of results [Altamimi et al., 2005] and to extract all the benefits offered by time series combinations, for instance, detecting and monitoring non-linear station motions and other kind of discontinuities in the time series: site instabilities, earthquake related dislocations, seasonal loading effects, etc. Time series combination also allows Earth orientation parameters (EOPs) to be treated in a fully consistent way, that is, to rigorously ensure the EOPs alignment to the combined frame. Unlike the previous ITRF solutions, the next ITRF solutions (starting with the ITRF2005) will be based on the analysis and combinations of such time series of station positions and EOPs.

2.4 Errors Related to Reference Systems and their Effects

The following three aspects of reference systems lead to uncertainty in the position of a physical point, that should be considered in addition to the observational error in position:

(1) error in physical aspects of the conventions, in particular, the motion model;
(2) error in the alignment of the frame that is used to realize the reference system;
(3) error in coordinates of the reference frame that have been used to position the points of interest.

For the problem of sea level variation, the following issues relate to the above errors:

(1) The solid Earth's surface (including the ocean bottom) in some ways is moving much like the sea surface itself, in the sense that it has tides (~30 cm). Some of the motion is predictable such as tidal motion, much of the short period motion tends to average out in the long term, and some of the motion can be unpredictable or imprecisely known. On the time scale of a century, motion of the Earth's surface can be of the same order of magnitude as motion of the sea surface (0.1 m) and locally can exceed this by a significant amount. Thus the problem of the impact of sea-level variations requires consideration of the land motion. Of course a tide gauge measures the displacement of the sea surface relative to land directly at a point, and so would seem ideal to assess impacts. However, the use of tide gauge data alone to infer global measures of sea level change is fundamentally problematic due to sample bias of the relative motions of the sea surface and land over a broad range of spatial and temporal scales. Processes such as post-glacial rebound have been given considerable attention and are addressed elsewhere in this workshop. Moreover, the land beneath tide gauges may be forced to move by processes unique to (or more biased at) coastlines (versus deep ocean floors), such as coastal erosion, sedimentary loading, subsidence, atmospheric loading, anthropogenic activities, tectonic processes (e.g., strain accumulation at locked subduction zones along much of the western coasts of the Pacific rim and Sumatra), and the different ocean-land response to current day mass redistribution such as cryospheric loading and terrestrial hydrologic loading. Other problems include the stability of the structures to which tide gauges are attached, and the local stability of the land beneath. In general, coastlines are well known to host unique oceanic processes that can bias sea level, however we make the crucial point that this is also true for the land, in that coastlines provide a very poor sample distribution of Earth deformation processes that will not generally tend to average out on the global scale.

(2) We cannot currently rule out the possibility of an error in the tie of the reference frame origin to the Earth's center of mass at the 1-2 mm/yr level, or an error in scale rate at the level of 0.1 mm/yr. An error in the realization of the reference frame origin at the center of mass of the solid Earth implies an error in the height of the sea surface inferred by satellite altimetric observations with very long wavelength (hemispheric-scale) correlated errors (Figure 5). If the error happened to point in the direction of large oceans such as the Pacific Ocean, this could give the erroneous impression of global sea level change. More generally, the degree-1 terms of the spherical harmonic expansion of the ocean function imply a direct correlation of errors between realization of the origin (with time) and global mean sea level variation. Specifically, errors in the velocity of the origin at the level of 2 mm/yr will map into global mean sea level errors by as much as 0.4 mm/yr. This is as large as the physical contributions of mass exchange and thermal expansion. An error in scale rate will appear as a secular change in the height of ocean altimeters, thus giving the erroneous impression of global change in sea surface height. Tide gauge measurements of course are immune to reference frame problems and so, despite the problems with sampling bias and possible land movements, they do provide a measure of ground truth that can be useful for comparison with satellite altimeter measurements. Note that the old concept of "calibrating" tide gauges for land motion may on the one hand be useful for removing very local land motion from the tide gauge record, but on the other hand would introduce all of the reference frame biases that affects altimeter measurements, thus reducing the complimentary strength of tide gauge data and essentially removing – at the present time – the ability to assess impacts at any given location.

(3) As reference systems are updated because of improved conventions or improved frames (using more recent measurements and models), so the entire time series of coordinates of a monitored station will change. Even the sign of vertical velocity can change. Thus we must abandon the notion of “measuring and archiving” the heights of tide gauges, for example. The heights of stations cannot be measured absolutely, and the entire time series are always going to be subject to changes as reference frames continue to be updated, and certainly improved.

2.5 Challenges and Future Requirements

From a reference frame perspective, the challenge for monitoring long-term variability in sea level is to define the frame origin and scale with greater accuracy than the signal to be estimated. This requires a frame stability of 0.1 mm/yr, and the scale with a stability of 0.01 ppb. These requirements would reduce the frame-related bias to the level of a few percent of the total effect of sea level change. Current errors may be about a factor of 10 larger than this, though the level of errors are currently difficult to assess.

The most critical TRF parameters of interest to mean sea level studies are the origin and the scale and their long-term stability. For example, any scale bias in the TRF definition propagate directly to the height component of the stations and vice versa. As the ITRF relies on SLR to define its origin and on SLR and VLBI for its scale, the importance of these two techniques should not be underestimated for the ITRF accuracy and stability over time. Unfortunately, the current SLR and VLBI networks and their co-locations are severely poorly distributed and decreasing over time, implying a threat for the long-term ITRF permanency. To give a simple example, from the ITRF2005 preliminary analysis, the estimated impact of the poorly distributed SLR network and thus its co-locations with the other technique induces a scale bias of about 1 ppb and 0.1 ppb/yr. This is a large effect by itself and about 10 times larger than the science requirement to address sea level change.

To meet these challenges and future requirements, the geodetic networks must be well distributed, maintained and evolved for continued state of the art observations as providing the fundamental context for understanding sea level change.

3 Linking GPS to Tide Gauges and Tide Gauge Benchmarks

3.1 Tide Gauges and the Reference Frame

Tide gauges measure sea-level changes as variations in the relative position between the crust and the ocean surface. These measurements are difficult to interpret because they are influenced by several phenomena inducing vertical crustal movements. At present, vertical crustal motions at tide gauges can be measured to high accuracy independently of the sea-level reference surface by means of space geodetic techniques, therefore it will be possible to separate the crustal motions from geocentric sea-level variations. Tide gauge measurements are difficult to compare because tide gauges are referred to local reference systems and they have not yet been connected on a common global datum. However, it should be pointed out that several international efforts are underway both at global [IOC, 1997] and regional scales [Zerbini et al., 1996; Becker et al., 2002] which aim to overcome this challenge.

At present, vertical crustal motions at tide gauges can be measured to high accuracy by means of space techniques such as GPS and DORIS [Soudarin et al., 1999]. Continuous GPS, however, has shown to be the technique of use in this particular application due to the ease of use, high precision, and its direct connection to the ITRF through the products of the IGS. On the other hand, by means of simultaneous GPS measurements performed at tide gauges and at fiducial reference stations of the global reference frame, tide gauge benchmarks can be tied in a global well-defined reference system. The possibility to refer the tide gauge data to the same high precision global reference system allows the comparison between the different tide gauge data sets to be made. This was not the case until about 15 years ago when tide gauge benchmark coordinates were mostly available in the different national height systems [Woppelmann et al., 2006].

In order to determine long term height changes due to vertical crustal movements, it is necessary to correct the GPS measurements for seasonal oscillations which can corrupt the estimate of the long-term trends up to a few mm/yr. Loading components due to seasonal variations of the atmosphere, hydrology and non-tidal oceanic effects [Blewitt and Lavalée, 2001; van Dam et al., 2001; Zerbini et al., 2004] have been recognized as major contributors of the observed seasonal oscillations in GPS time series. Concerning non-tidal oceanic effects, recent studies at global and regional level [Chao et al., 2003; Zerbini et al., 2004] show that modeled ECCO[2] bottom pressure amplitudes are a factor of 2 smaller than those observed. Furthermore, deficiencies in the

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[2] Group for Estimating the Circulation and Climate of the Ocean, http://www.ecco-group.org/

physical models can create spurious periodic effects including annual and semi-annual signals. Penna and Stewart [2003] show how mismodeled short period tides (semidiurnal and diurnal) can alias into height time series, Stewart et al. [2005] showed how truncation of the observation model - and even the arbitrary choice of processing data in 24 hour segments - causes similar propagation effects. Penna et al [2006] demonstrated that mismodeled (sub-) daily periodic signals in horizontal coordinates can propagate into periodic signals in the vertical component, sometimes with an admittance greater than 100%. Boehm et al. [2006] showed that deficiencies in the Niell mapping function (used to relate the tropospheric delay in the zenith direction to the delay at any elevation angle) cause season-dependent height errors of up to 10 mm, in particular in the Southern Hemisphere. Watson et al. [2006] showed how improvements in the modeling of the solid Earth tides have reduced the annual signals in global GPS analysis, with the implication being that any errors in the model currently used in all space-geodetic techniques can be expected to be contributing to seasonal variations that still remain in geodetic height time series.

The accuracy required by GPS to monitor tide gauge benchmark positions on shorter time scales requires more accurate GPS positions, which in turn, requires advances in network and observational configurations and geodetic data analyses. The IGS is intent on continuing to improve the accuracy of its GNSS products, and in collaboration with sister services, to strive towards meeting the demanding requirements of these longer-term studies. [http://igscb.jpl.nasa.gov/components/prods.html; Altamimi et al., 2001; Dow et al., 2005].

Independently from space geodetic techniques, an alternative approach to monitoring site velocities is provided by the measurement of absolute gravity at tide gauge benchmarks. Absolute gravity does not directly estimate the vertical displacement of the crust as gravity is affected both by mass in the ocean itself, as well as the processes responsible for vertical crustal movement. If the processes are well understood, then it can provide independent confirmation on the GPS results, particularly at inland sites [Zerbini et al., 1996; Becker et al., 2002, 2002, Teferle et al., 2006].

3.2 Tide Gauge Measurements: Historic Perspective

For more than a century, tide gauge measurements in estuaries or coastal shorelines have been widely used for monitoring local sea or estuary levels, for the assimilation into local tidal models for port operations and surge warnings, harbor safety monitoring, and monitoring of the flooding level in populated areas. The tide gauge systems are or have been operated by port authorities or national maritime services with a high level of accuracy and reliability. From the geodetic point of view, the tide gauge system, in particular the tide gauge zero or pole staff, is leveled to a primary tide gauge benchmark (TGBM) surrounded by and tied to several distant secondary benchmarks. In addition, most of the tide gauges are connected to the first order national height system. All benchmarks should be leveled on a regular basis to ensure the long-term stability of the height reference.

Recently, in the public and scientific climate discussions, data from tide gauges is increasingly important in providing long-term and reliable measures of the sea level. Here, the tide gauge measurements are used as a primary input to study changes in local mean sea level, the tidal amplitudes, surge studies, and as boundary conditions in oceanographic circulation models. They also act as ground truth for, e.g. satellite radar altimetry. Tide gauges also help to define the global height system, and many national datums, both historically and even currently, refer their vertical measurements to ‘mean sea-level’ (MSL).

An increasing number of tide gauge benchmarks have been equipped with continuously operating GPS receivers. A small number of these stations are part of the global IGS network, but most of the stations are only contributing to smaller local or regional networks. However, there is an increased demand from, e.g. IOC/GLOSS or WMO, to continuously provide highly precise GPS height time series with an accuracy of better than 1 mm/yr.

3.3 The TIGA Pilot Project

At present, about 280 tide gauge stations are known to have continuous operating GPS stations within less than 10 km (Figure 7) [Woeppelmann et al., 2006]. This number of stations is by far too high for current IGS analysis centers, although schemes are under development for routine analysis of up to an order of magnitude number of stations by 2010. In addition, the current IGS accuracy is not fully meeting the requirements of the sea level community in terms of (a) station completeness, and (b) accuracy for the vertical component.

In response to the demands by the scientific community, the IGS in 2001 initiated the “GPS Tide Gauge Benchmark Monitoring - Pilot Project” (TIGA-PP). The pilot study is establishing a service to analyze GPS data from stations at or near public tide gauges on a continuous basis (cGPS@TG – continuous GPS at tide gauges). The primary objectives of the TIGA-PP are to promote and establish, maintain and expand a high-quality global cGPS@TG network and to compute precise daily or weekly station coordinates and velocities for this network. This goal is achieved by processing a large number of stations and also by reprocessing older data sets. TIGA-PP, as an IGS pilot project, is relying on the network infrastructure, the processing capability, and expertise of the IGS community and is supported by IOC/GLOSS for the tide gauge component.

The primary product is weekly sets of coordinates for analyzing vertical motions of tide gauges and tide gauge benchmarks (TGBM). All products are made publicly available to support and encourage other applications, e.g. sea level studies. In particular, the products of the service facilitate the distinction between absolute and relative sea level changes by accounting for the vertical uplift of the station, and are, therefore, an important contribution to climate change studies. The service may further contribute to the calibration of satellite altimeters and other oceanographic activities.

3.4 Current status of TIGA

The IGS has very strict requirements on the data quality and availability, and latency in data delivery of network stations. Moreover, in contrast to the tide gauge station networks, the GPS network coverage is reasonably balanced geographically. Therefore, many of the GPS tide gauge stations important for sea level research are not part of the IGS network either for geographical reasons (too close to existing stations) or because of latency in data provision (remote stations with poor data communications). Also in terms of completeness TIGA is providing solutions with a latency of at least 460 days to permit the data from remote and manually operated stations to be included in the analysis.

The tide gauge stations contributing to TIGA must have a high level of reliability. One prerequisite for stations to be included in the TIGA networks is the public availability of the tide gauge data at GLOSS data centers. Preferably, the stations are equipped with a primary GPS on or near the tide gauge and a secondary GPS station, inland [Plag et al., 2000]. Maintenance of the equipment should be repeated on a regular basis, including first order leveling to all the available benchmarks (the latter is often difficult to accomplish due to limited geodetic surveying resources).

It is imperative that the relative vertical movement between the tide gauges (and/or tide gauge benchmarks) and the nearby GPS stations is known to a higher accuracy than either the accuracy of the GPS vertical velocities or the tide gauge estimates of relative sea level; otherwise, the measurement of the connection between the two systems becomes the limiting factor on the overall accuracy. To observe a height tie with an accuracy of < 0.5 mm over a distance of up to 10 km is a challenge even for the highest precision leveling. An alternate approach that could be considered for the future is InSAR where theoretical and experimental accuracies of velocity estimates from the permanent scatterers technique is 0.1-0.5 mm/yr [Colesanti et al., 2003].

Data from GPS stations co-located at 102 tide gauges are processed on a regular basis by TIGA analysis centers (TAC). Other GPS stations complement this network in order to define a common reference frame. Currently six TACs are processing TIGA GPS data not limited to IGS stations on a best-effort basis. In addition, a re-analysis of past data, again not limited to the IGS network, is performed leading to a homogeneous data set. The TACs are using almost identical processing and analysis strategies as the IGS Analysis Centers, thus later solutions are comparable, while the reprocessed past solutions are supposed to be less affected by e.g. software changes, changes in the processing strategies and correction models, or late detected station hardware failures. In the more recent years, additional cGPS@TGs were included in the TIGA network, thus, the reprocessing also needs to be repeated frequently in order to process newly available data.

First tests are performed to combine the different solutions from the TACs. Due to processing on a best-effort basis, all solutions are available only for selected weeks. In addition, complementary studies are being carried out, for e.g. the identification and removal of undetected jumps in station time series, or testing the strategies for a TIGA dedicated combination strategy. Based on this experience, the individual TAC solutions will be improved and when necessary reprocessed. In particular, the combination of the individual solutions will be frequently updated in order to incorporate new stations and new solutions and to always use the newest correction models, e.g. from atmospheric pressure loading models.

3.5 Recommendations (TIGA)

- Promote the establishment and maintenance of high-quality ties between tide gauge and GPS stations and their benchmarks
- Promote the establishment of a dual-GPS receiver concept for high-quality GPS@TG monitoring stations
- Promote leveling of tide gauge benchmarks and nearby geodetic markers by continuous GPS, first-order leveling on a regular basis or permanent scatterers InSAR
- Establish a common data base of known or possible jumps in GPS and tidal time series
- Study loading effects of shore- or island-based GPS@TG points versus inland GPS stations
- Study secondary ocean loading effect caused by barotropic changes in ocean surface
- Study the effects in the height component by the combination of TIGA stations with the global geodetic reference system
- Study the use of consistent loading corrections in TIGA processing (e.g. apply atmospheric loading corrections during the processing or during the combination)

4 Recommendations for Geodetic Observations

(Preliminary, pre-workshop)

1. The International Terrestrial Reference Frame (ITRF) needs to be made more robust and stable over multi-decadal time scales. The target accuracy is 0.1 mm/yr in the realization of the center of mass of the entire Earth system ("geocenter stability"), and 0.01 ppb in scale stability. Geocenter stability depends on accurate dynamic modeling and observation of geodetic satellites, such as SLR and GNSS. Scale stability might be better ensured by minimizing source-related errors, which would imply VLBI, but it also requires accurate tropospheric delay modeling, which would imply SLR (because of the observed frequencies, the tropospheric delay effects are considerably smaller in SLR observations than in either VLBI or GNSS), so some combination of VLBI and SLR is likely to be required. The increase in GNSS satellites over the next decade to ~100 suggests the strong potential of GNSS to contribute significantly to both geocenter and scale stability.

2. To achieve the best stability requires strong connections between the reference frames of the various geodetic systems. We therefore recommend to

   a. Implement more sites of every technique with a good (even) global distribution,
   b. Collocate VLBI and SLR wherever possible, and that GPS is required instrumentation at every VLBI and SLR site,
   c. Sustain and evolve support for the technique specific scientific services and their critical components, from infrastructure to analyses (i.e., IERS, IGS, IVS, ILRS, IDS),
   d. Place laser retroreflectors on all future GNSS satellites, with the research that may be required to make laser ranging more effective to Medium Earth Orbiters (MEO),
   e. Support GGOS as the new paradigm for integrating space geodetic techniques,
   f. Conduct research into understanding biases between the various techniques and types of satellites and instrumentation, and
   g. Conduct research towards improving tropospheric delay models.

3. To ensure long term stability and consistency in the measurements of sea level by altimetry and of mass by GRACE-type missions, we recommend that (a) analogues of current altimeter and gravity missions be continued indefinitely with sufficient overlap between missions, and with no gaps or dead time between missions; and (b) a world vertical datum be established, possibly based on a precise, high-resolution global geoid model, to which all elevation-type measurements should be referred (unification of national and regional vertical datums). This will require international agreements for free exchange of gravimetric, elevation and other relevant data, and collaborative research work integrating satellite, terrestrial and airborne gravity and gradiometer data, which could be undertaken under the auspices of GGOS.

4. We recommend that tide gauges be monitored for height variations using continuous GPS systems installed directly at the tide gauge. This could be accomplished by expanding efforts such as the TIGA project within IGS and by encouragng expansion of related regional activities such as the European Sea Level Service (ESEAS). Specific recommendations for the TIGA project are detailed in section 4.4. In order to have an as uniform as possible distribution of tide gauges around the globe, additional tide gauges, co-located with GPS, will have to be installed in areas with poor tide gauge coverage.

5. It is only through physical models that progress can be made toward understanding measurements of sea level variability. We therefore recommend research and development of comprehensive Earth models that can assimilate all geodetic data types (including tide gauge data) that are relevant to determining sea level change. Such models need to be self-consistent both gravitationally and with respect to the conservation of mass. At the first level, models integrating geodetic data would be developed. At the next level, the models should be integrated with terrestrial hydrological models, cryospheric models, and ocean/atmospheric circulation models.

6. In order to achieve the goal of determining sea level changes at the level of 0.1 mm/yr, support for the recommended systems and research activities must be brought up to a level capable of meeting that goal, and the support must at least be sustained for decades. This requires commitments that go beyond the current typical relationships between government funding agencies and science projects. We therefore recommend that UNESCO/IOC, the IGOS-P Coastal Zone theme, together with the funding agencies assess what is required by their agencies to make the funding system work for projects of such long-term commitment. We also recommend that agreements be sought at the international level to ensure global-scale international commitment toward solving a global-scale international problem. As a first step toward this goal, we recommend that the importance of the reference frame for sea level in particular, and Earth observation in general, be recognized by GEO as a transverse activity that affects all benefit areas addressed by GEO.

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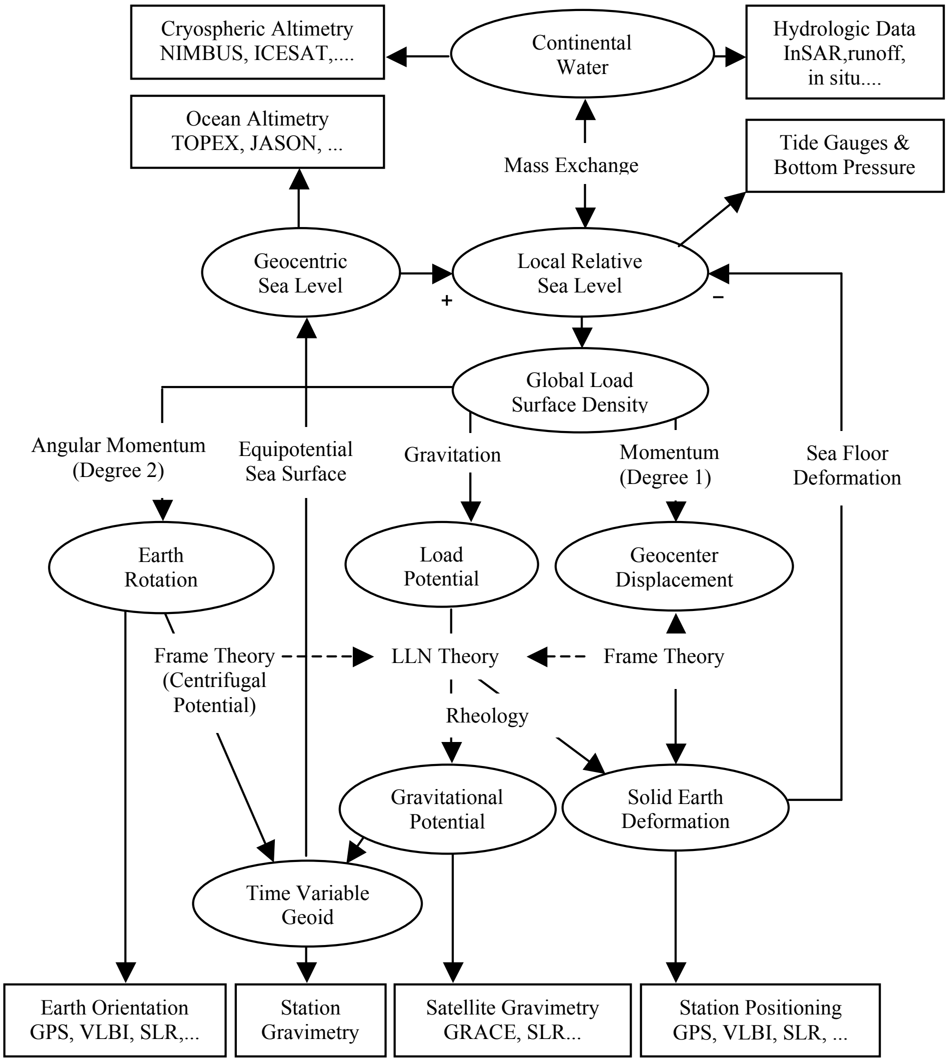

Figure 1. A model that incorporates self-consistency of the reference frame [*Blewitt*, 2003], loading dynamics, passive ocean response, and Earth rotation. Closed-form inversion solutions have been demonstrated [*Blewitt and Clarke*, 2003], thus setting the scene for data assimilation. Note that everything is a function of time, so "continental water" in its most general sense would include the entire past history of ice-sheets responsible for post-glacial rebound. (Arrows indicate the direction toward the computation of measurement models, phenomena are in round boxes, measurements are in rectangles, and physical principles label the arrows).

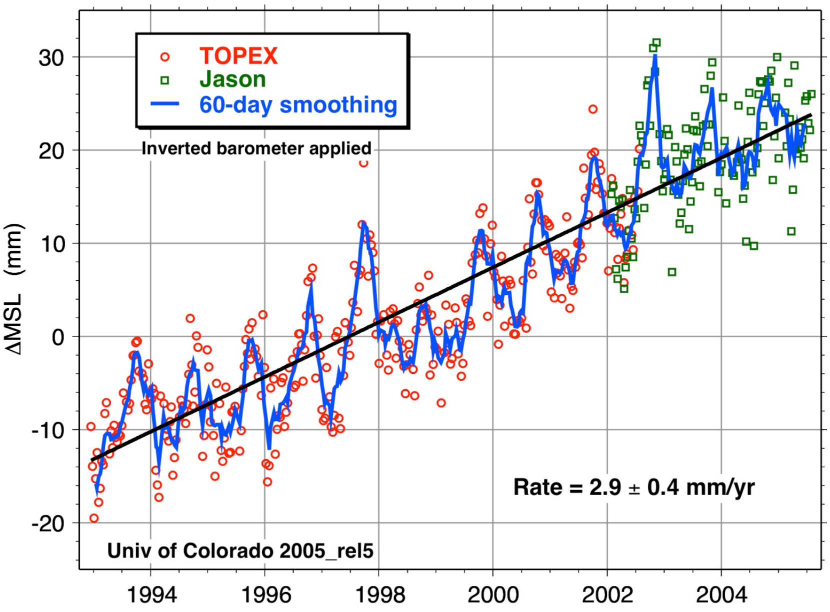

Figure 2. Change in global mean sea level over the last decade as measured by satellite altimetry [from Nerem et al.,http://sealevel.colorado.edu/]

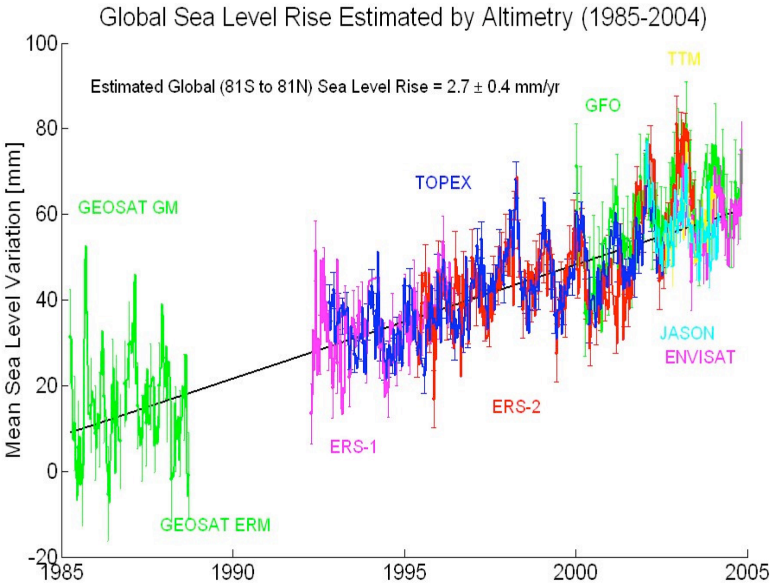

Figure 3. Change in global mean sea level over the last decade as measured by multiple satellite altimetry missions [Kuo 2006].

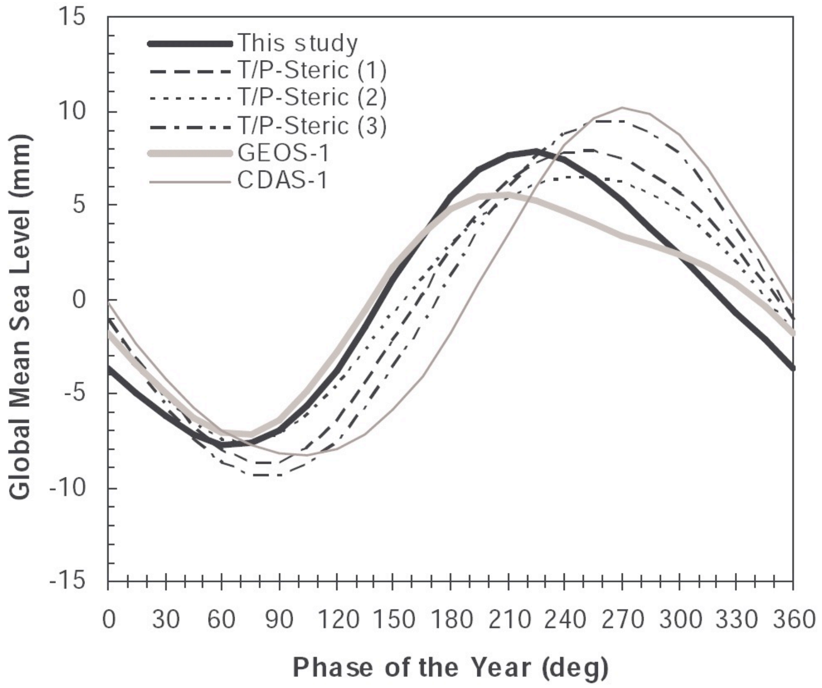

Figure 4. Global mean sea level determined through the theory of loading by GPS measurements of Earth's shape (This study) compared with direct measurements by Topex/Poseidon corrected for steric effects, and terrestrial hydrology, as inferred by mass conservation.

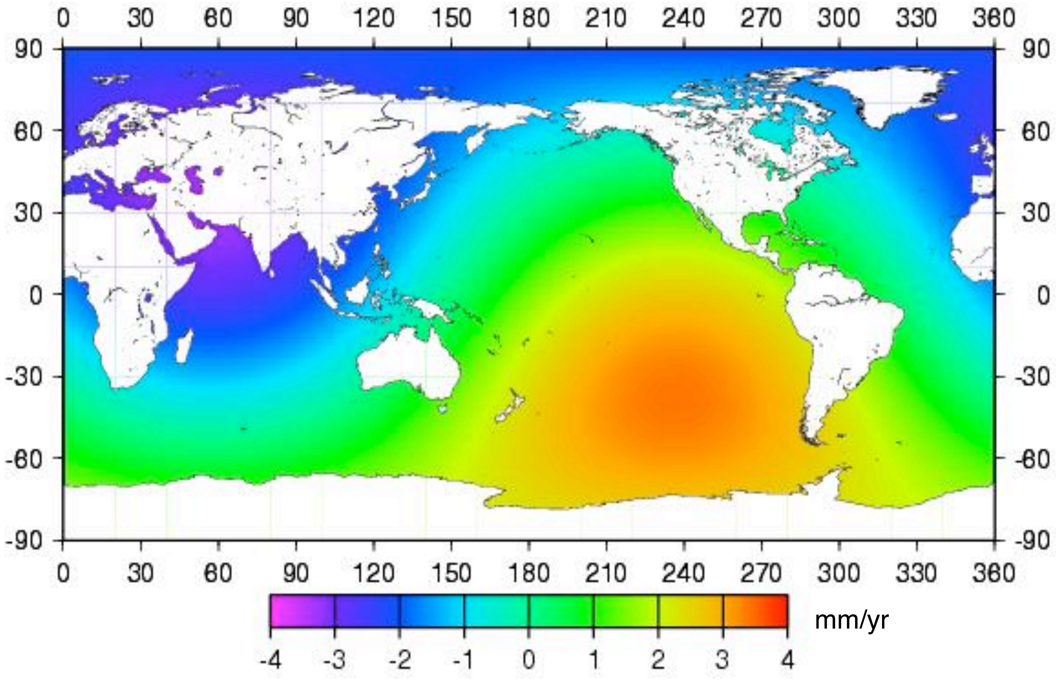

Figure 5. Simulated effect on sea level error inferred by satellite altimetry caused by an error in realizing the reference frame. This example shows the effect of differences between two frames realized by the IGS: one is IGb00 which is aligned with ITRF2000, the other is the frame of the IGS precise point positioning products [Kierulf and Plag 2005]. The difference in sea level ranges from -3 to +3 mm/yr, with a mean sea level error of 0.4 mm/yr caused by asymmetric distribution of the ocean.

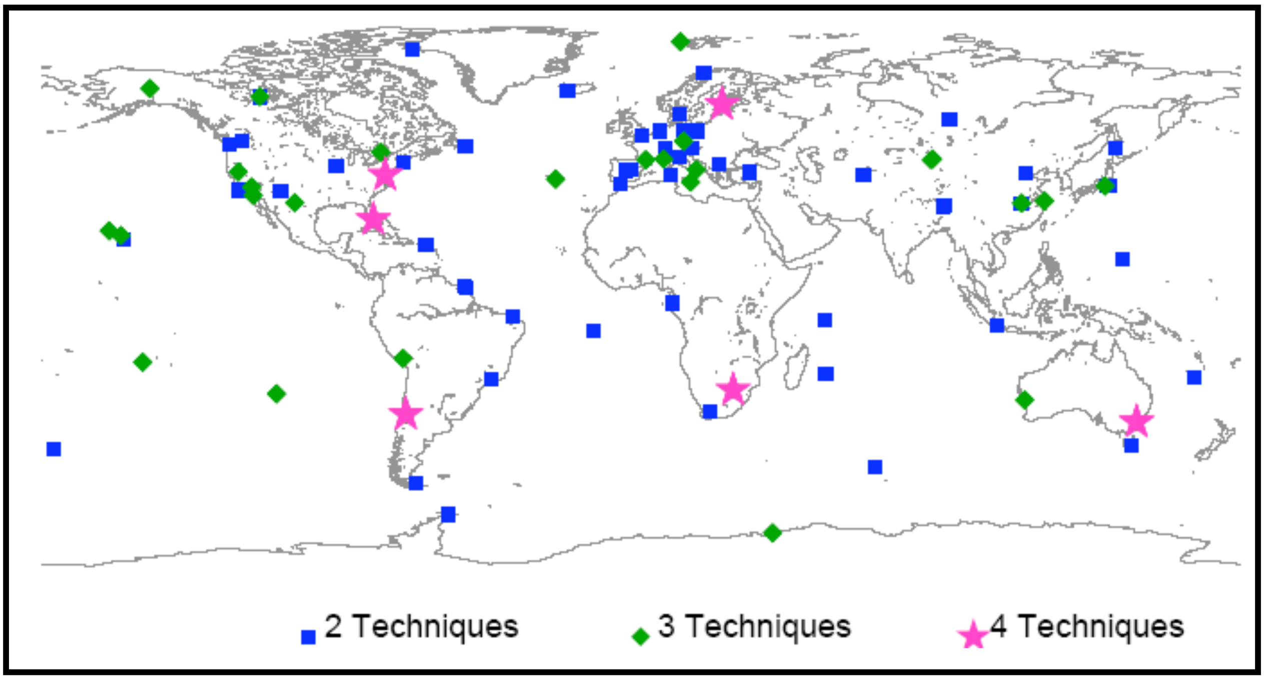

Figure 6. Current (from 2000) distribution of co-located space geodesy sites.

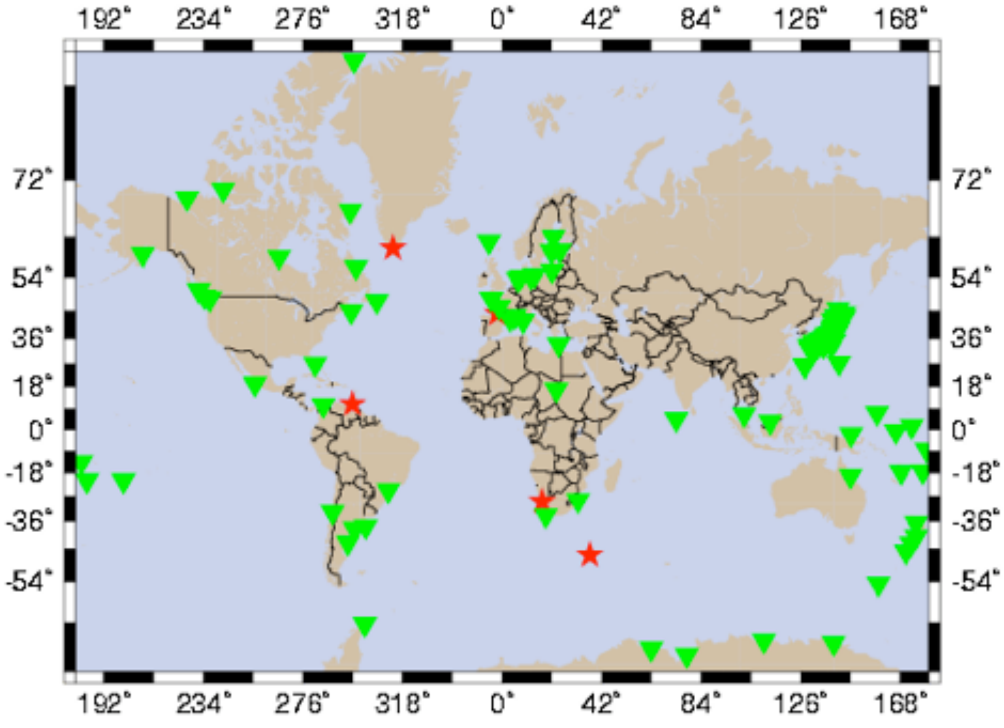

Figure 7: Current network of GPS stations at tide gauges contributing to TIGA-PP, green symbols are current TIGA Observations Stations (TOS), red stars are new stations expected to be available in the near future.