Environmental geodesy: variations of sea level and water storage in the Australian region

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AIMS AND BACKGROUND

Preamble: This project seeks to quantify aspects of environmental change and its impact in the Australian region using new geodetic methods. Changes at local, regional and global scales have resulted in rising sea levels and changing rainfall patterns over the past decade (IPCC, 2007). These circumstances pose substantial challenges for the scientific and broader community, but there now exists an opportunity to take advantage of international space-geodetic missions and recent injections into geospatial infrastructure to significantly advance our knowledge of changes in regional sea-level, combined ground and surface water storage and Antarctic ice-mass balance.

An integrated monitoring and analysis program investigating sea level, continental water and ice mass balance will be undertaken through the use of terrestrial and space-based geodetic observations. Changes in the Earth's geometry, gravity field, and rotation - all of which relate to mass transport within the solid Earth, its oceans, ice sheets and atmosphere - can be 'sensed' with modern terrestrial- and space-based geodetic techniques. Moreover, this project brings closer together the four main geodetic research institutions in Australia.

Aims: Through careful analysis of geodetic observations, it is now possible to monitor the mass transport and the dynamics of the solid Earth and its fluid envelope with unprecedented spatial and temporal resolution and accuracy. These observations capture the 'fingerprints' of mass movements in the ocean, atmosphere, ice sheets and terrestrial water storage; e.g., they provide the 'scales' to weigh changes in the mass in the ocean; they allow the deduction of the motion and strain field of the Earth's surface and the determination of the displacement field associated with earthquakes; they provide crucial constraints for all models of geophysical processes. The principal aims of this proposal are:

1. to better quantify contemporary sea level changes in the Australian coastal region using complementary data from satellite altimetry, satellite gravimetry and Global Navigation Satellite System observations,
2. to monitor temporal changes in ground- and surface-water storage using ground-based and satellite gravimetry, and
3. to better define changes to the shape of the Earth and the coastal environment through the use of new and existing space-geodetic data from observational tools such as Very Long Baseline Interferometry, Satellite Laser Ranging and Global Navigation Satellite Systems.

Our proposal brings together all key geodetic expertise in four Universities (ANU, Curtin, UNSW, UTas) to tackle an innovative and cutting-edge project that will have significant outcomes.

Recent international progress: Many satellite-geodetic missions have been successfully launched over the past decade enabling the estimation of spatial and temporal variations in sea level and global mass changes. Satellite altimetry missions have provided estimates of sea level change at the few mm/yr level (Cazenave and Nerem, 2004), the Gravity Recovery and Climate Experiment mission (GRACE) has provided monthly global mass changes (Tapley et al, 2004) from which one can infer land uplift and/or water mass changes (Wahr et al., 2004). The Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) mission is dedicated to measuring the Earth's gravity field and modelling the geoid with extremely high accuracy and spatial resolution of ~100 km. Scheduled for launch at the end of 2007, GOCE will enable accurate determination of global ocean circulation and its associated heat transport, sea level change, ice sheet dynamics, such as glacial isostatic adjustment and ice thickness changes.

Whether global climate change is causing the polar ice caps to shrink is one of the most hotly debated environmental issues of today. By monitoring precise changes in the thickness of the polar ice sheets and floating sea ice, the CryoSat-2 mission, scheduled for launch in 2008, aims to address this question. *Each of these space missions has a limited life span. The proposed research needs to be funded now to capitalise on these limited windows of opportunity for studying changes in the Australian region.*

Progress in geodetic analysis and spatial accuracy of points on the Earth has meant that sub-cm accuracy in three(four)-dimensions is readily achievable. However, with improvements in analysis techniques and consequent spatial accuracies, we are presented with new possibilities to detect smaller - but equally important - geophysical signals. Australia has not yet capitalised on the potential of space-geodesy to provide valuable information on how sea levels are changing around our coastline, nor made use of the new space-gravity missions to study changes in our water resources. We need to improve further on the current accuracies of "state-of-the-art" analysis in order to provide answers to the pressing scientific questions in our own region.

Relationship of this proposal to other work in the field generally: There is currently an international initiative called the Global Geodetic Observing System (GGOS), with a vision to integrate multiple geodetic techniques at the observation level, central to the objective of achieving "millimetre geodesy" by 2020 (Drewes, 2007). Our proposal aims to tackle many of the key elements of GGOS, including reference frame definition and geocentre motion (variations of the origin of the coordinate system, that is, the centre of mass of the Earth). Thus, the proposed research is both timely and exactly in line with trends held to be of greatest international importance at the present time. The fundamental science issues to be addressed (sea level variations and water storage changes) require advances in geodetic research, advances comparable to those that the research team have made in the past and will continue to contribute to at the international level.

This proposal brings together the four major 'powerhouses' of Australian geodetic research (ANU, UNSW, UTas, Curtin) in complementary areas of, for example, geophysical analysis from satellite positioning data and radar reflections (e.g., Tregoning and Herring, 2006; Watson et al., 2006), altimetric measurements of the oceans by satellite radar (e.g., Church et al., 2004; Watson et al., 2004; Deng and Featherstone, 2006), gravitational feedback effects of sea level change (e.g., Kuhn et al., 2007), gravity field modelling from dedicated satellite gravimetry (e.g., Featherstone, 2002), reference frame definition by radio sources and Earth-orbiting satellites.

In December 2006, the National Collaborative Research Infrastructure Strategy (NCRIS) funding of \$15.8M (along with \$21M co-investment from State governments, Geoscience Australia and universities) was allocated to significantly upgrade and improve Australia's core geodetic infrastructure. This provides Australia with the research infrastructure to address some of the most fundamental environmental problems that Australia faces, both today and into the next decade. It is both timely and pressing for the four key University-based geodetic analysis centres to provide Australian-focused benefit from this injection of funding, as well as training graduate students and postdocs for the longer term benefit to Australia. The proposed research utilises NCRIS-funded and existing Australian geodetic facilities (observing sites, computing hardware etc), and extends on our previous ARC grants and areas of expertise as demonstrated by sole and joint publications (see Section B).

However, the benefit also goes much further with geodesy being - by definition - a global science. Australia is now in its best-ever position to make a truly major contribution to global geodesy. Historically, the majority of geodetic observatories, instruments and teams have been biased towards the Northern Hemisphere, notably Europe and North America. Properly augmented by the new joint-force approach from the four major Australian University-based geodetic centres and coupled with training for Australia's geodetic future, the NCRIS infrastructure can and should be used to start to reverse this Northern Hemisphere bias. Australia can now seize this once-in-a-generation strategic opportunity to use these data to not only quantify the temporal changes to the shape, size and gravity field of the Earth due to environmental change but also to contribute to Australian and global geodesy in general (cf. Drewes, 2007).

SIGNIFICANCE AND INNOVATION

This proposal will provide the most accurate, coherent and spatially detailed information on the state of Australia's broad-scale ground water resources and variations in sea level around its territories. Through combinations and improvements of various geodetic measuring and analysis techniques, it will generate - for the first time- estimates of the vertical movements of Australia's tide gauges (permitting unbiased absolute sea level change estimates to be made), sea surface heights around the Australian continent, demonstrated capability to estimate inshore ocean heights in regions where satellite altimetry fails to work reliably, temporal changes in ground water, validation - through independent techniques - of the gravity anomalies used to infer water mass changes, and mass balance changes of East Antarctica and its effect on global sea level change.

Behind most of these scientific, geophysical/oceanographic goals lie the fundamental geodetic objectives of improving the accuracy of the reference systems upon which the observing techniques rely. In this case, these objectives are defining the geocentre of the Earth and its motion, and improving the fundamental modelling of the physics involved from transmission to reception of space-geodetic observations. There are many complex objectives, but the size and demonstrated capability of the research team make such objectives both feasible and deliverable.

Water is one of Australia's most precious resources, yet we do not accurately know even how much stored water we have, let alone how this resource varies with time and location. Furthermore, of the known annual precipitation that falls on the Australian continent, only ~ 15% ends up in our rivers and groundwater storage systems, with the vast majority being captured in the soil layers until it evaporates back into the atmosphere. In January 2007, the Federal Government announced the National Plan for Water Security, funded at $10 billion over 10 years (NPWS, 2007) in which it is stated "You can't manage what you don't measure".

The combination of measurement data from space gravimetry and remote sensing missions (e.g., GRACE, GOCE) provides the opportunity to commence an integrated, Australia-wide program of broad-scale water resource monitoring that will contribute to the national initiative in a way that only space geodesy can provide. The demonstration and commencement of this capability is a goal of this proposal and the assembled research team are the most qualified in Australia to attempt such research by improving the analysis of the raw geodetic observations.

While there is general agreement that global warming and sea level rise is occurring (IPCC, 2007), there is much debate on the rates of these phenomena and the consequences to our society. Understanding these processes encompasses important scientific issues that are of direct societal importance and of value to federal, state, and local agencies since they underpin many management and political decisions. About 6% of Australian addresses (residential, commercial or industrial) are located within 3 km of the coast with an elevation of less than 5 m above sea level (Chen and McAneney, 2006), with the majority of these adjacent to sea-connected lakes, lagoons and estuaries rather than directly facing the oceans. These are the members of our community who will be most directly affected by the increase in sea level that is predicted from recent measurements.

Monitoring and quantifying the spatial changes in sea level will be critical for Australia and the surrounding island nations because of the increase in frequency and severity of extreme hazard events, such as storm surges (IPCC, 2007), and the damage to existing infrastructure and inundation of low-lying communities that are predicted to occur. The projected sea level rise translates to approximately 10-880 m of shoreline recession (based on the Bruun rule), a serious coastal management issue for the future. The effect of sea level rise on society will differ enormously depending on whether the higher or lower end value occurs; therefore, it is essential for planning mitigation strategies that highly accurate monitoring of spatial variations in sea level around the populous Australian coast is undertaken to provide governments and decision-makers with the most accurate information possible. There is already evidence that sea-level rise is accelerating (Church and White, 2006) and that global sea level is seen at the upper limits of previous IPCC predictions (Rahmstorf et al., 2007).

Mitigation of the effects of sea level rise is difficult and expensive and needs to be supported by strong scientific justification. Too little response will be disastrous, whereas over-reactions could lead to unnecessary and expensive counter-measures. Only space-geodetic observational and analysis techniques can provide information on spatial and temporal scales across the whole Australian continent in order to understand how sea level and water resources are changing in today's climate. Knowing accurately what the exact rate of sea level variation is around the Australian continent has important ramifications for how Australian society will be affected in the coming decades.

How anticipated outcomes advance the knowledge base: This proposal will yield two types of significant outcomes: 1) new knowledge about the changing state of water in and around Australia and 2) improvements in a suite of space-geodetic observation and analysis techniques. The former will fill a current void of knowledge in Australia, while the latter will continue the advances of international geodetic science and its application to understanding geophysical problems. To address the science questions of the next decade, we will require an order of magnitude improvement in the accuracy of geodetic analyses (Drewes, 2007). Reference frames underpin all science endeavours and geospatial activity and are fundamental components of any scientific study relying on geodetic observations. The multi-technique approach of this proposal will address this issue directly with anticipated improvements in temporal gravity field estimates, accuracies of ground motions and satellite orbit estimates and more accurate mass balance changes in East Antarctica.

Why the Proposal aims and concepts are innovative: The innovation of this proposal lies in the potential to conduct research into Australia's resources in ways not previously possible. No one in Australia is analysing raw GRACE observations, nor validating secular variations against ground-based estimates of land movement to verify that the gravity trends are indeed related to water mass variations. No one in Australia is recomputing altimeter orbits utilising new advances in geodetic analyses, then recomputing sea surface heights to obtain better estimates of sea level variations. No one in Australia is currently measuring basin-scale water mass variations, nor focusing on improving sea level estimates from multi-technique analysis. This proposal will commence such research in order to address water-related issues for Australia.

The geodetic techniques described below include state-of-the-art analysis procedures and, more importantly, new initiatives that have never before been attempted in Australia and rarely or never elsewhere. While there is always some risk associated with such ventures, here the potential scientific benefits outweigh the risks. The track record of the combined research team demonstrates that investing in geodetic research yields significant breakthroughs in understanding the Earth and predicting how present-day changes will affect our lives.

Bringing together expertise in all facets of space geodesy into one scientific team has not been achieved before in Australia, yet multi-technique approaches are required to understand the science issues. There are currently not enough qualified researchers in Australia capable of exploiting all the data that will be produced by the geodetic infrastructure that is to be installed and operated over the next 5 years, nor to take advantage of the current and planned space missions. Developing the careers of the junior CIs plus the new postdoctoral researchers that will be funded through this proposal will begin to address this issue, and is therefore a key component of this proposal and the rationale behind assembling a large research team. We need the expertise and critical mass that exists across all four Universities to tackle the main science objectives. The core expertise exists and will be augmented to take advantange of data from new satellite missions.

New methodologies to be developed: Fundamental development of methodology will be required across core components of this proposal in order to address the scientific questions.

Antarctic Mass Balance: Data from Cryosat II will enable the changes in ice heights over glacier regions to be measured, from which mass balance changes can be calculated (first taking into account vertical continental movement). Watson, Coleman and Tregoning have submitted a proposal to the Cryosat II Announcement of Opportunity to undertake calibration experiments over frozen lakes in Antarctica, co-located with their existing remote Global Navigation Satellite System (GNSS) installations for measuring glacial isostatic adjustment. The inclusion in the international Cryosat II team will provide the CIs with access to the mission data. Calibration and use of the Cryosat II altimeter will be new science.

Water Mass Variations: A critical component of this proposal is to recompute the reduction of GRACE observations for the Australian region - using more accurate modelling techniques such as proposed by Luthcke et al. (2006) or Kusche (2007) - along with ground-truth estimates of vertical land movement from GNSS observations and differential Interferometric Synthetic Aperture Radar to verify the accuracy of mass variations from GRACE. If the signals are found to be spurious, the focus of the research will turn to reanalysing the GRACE raw observations to improve the gravity anomaly estimates. This component of the research complements a similar experiment already underway by the CIs to investigate the positive gravity secular variation seen in East Antarctica (Chen et al., 2006).

Geocentre: The geocentre (centre of mass of the Earth and origin of the coordinate system) is a fundamental and critical part of the reference frame. Within this proposal, we will investigate recent changes in geocentre motion through ice mass simulations (Kuhn et al., 2007) and tracking of Global Positioning System (GPS) satellites with Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR). We propose to use the existing and new VLBI equipment in Australia to track GPS satellites, thereby making the VLBI technique sensitive to the centre of mass of the total Earth. Such studies have never before been attempted on a continental-wide scale but become feasible through the funding and operation of the new VLBI software correlator at Swinburne University. Dr Steven Tingay has developed this software and is eager to collaborate with us on this aspect of the proposal. Only minor modifications are required to the existing software correlator to provide the capacity to handle data from the tracking of GPS data.

On the other hand, there is currently no geodetic software capable of combining GPS and VLBI observations at the observation level as required for such a study. Thus, the development of such software is a key component of the geodetic analysis improvement studies of this proposal. The benefits of such advances will be to provide an additional means of defining the origin of the terrestrial reference frame; therefore - for the first time - providing an independent comparison to the SLR results. A request for the scheduling of VLBI tracking of GPS satellites has been submitted to the International VLBI Service for inclusion in the 2007 observation program in anticipation of the commencement of this research. Additionally, we will incorporate SLR observations to GPS satellites, thereby tying the SLR, VLBI and GPS techniques together into a common analysis.

VLBI observations to GPS satellites were first made in the US in the 1980s but the possibility was abandoned due to difficulty in correlating the data because of hardware issues. Now, with new software-based correlators, this will become relatively simple. It will not be possible to estimate the geocentre from just VLBI observations to GPS satellites in Australia alone (because of limited geometric separation between VLBI stations) but we will demonstrate that this is a viable concept and that it is feasible. We can then lead the international VLBI community to commence a global initiative to track GPS satellites. There is a great opportunity here for Australian scientists to take the international initiative but it must be done now while we still have the edge provided by the software correlation capability.

How the research addresses National Priority Goals: This proposal contributes directly to the National Research Priority "An environmentally sustainable Australia" by providing new Australia-wide information on our ground water and surrounding oceans, both of whom are in flux because of climate change. How we should respond and adapt to the warming of the Earth should be decided based on accurate information as to how the Earth is responding with sea level variations, extreme weather events and changed precipitation patterns and water storage. An ill-informed response could result in costly and unnecessary measures being invoked.

APPROACH AND METHODOLOGY

Framework: The research will be structured in several interlocking science-based themes, with expertise and capabilities of several space-geodetic techniques utilised as required to address the science questions. The general themes are outlined below as well as how they will be tackled.

Sea Level Studies: The rate of 20th Century sea level rise has been estimated to be 3.1 +/- 0.7 mm/yr (IPCC, 2007) and a significant acceleration has recently been detected (Church and White, 2006). The range of predicted sea level rise for the period 1990-2100 is 90-880 mm (IPCC, 2001) and recent measurements show that we are already at the upper limit of these estimates. If the acceleration continues, sea level will rise by more than even the upper original IPCC estimate. Changes will not be uniform: some areas may experience a greater rise while sea level may even fall in some regions (e.g., Church et al., 2004; Kuhn et al., 2007).

Current estimates of sea level change have been derived from tide gauge records and, more recently, from satellite altimetry observations. Vertical movement of tide gauges needs to be accounted for and this will be estimated from a combination of GNSS monitoring of the land movement and regular measuring of the height change between the GNSS installation and the tide gauge. It is not currently known what vertical motion occurs at tide gauges in the Australasian region; however, during 2008 each tide gauge will be co-located with GNSS equipment, funded through NCRIS. Traditionally the relative movement between GNSS and tide gauges has been measured through precise levelling and/or electronic distance measuring (EDM) height traversing. We will utilise the relatively new Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) remote sensing technique (Ferratti et al., 2000) and software developed at UNSW and ANU to compute the relative movement between GNSS installations and the tide gauges. While not a new technique, it has not previously been applied for this particular purpose.

Significant research in geodetic analysis of GNSS data is still required before sub-mm accurate uplift rates can be estimated. The CIs will undertake this research to further understand many error sources that have yet to be addressed, such as modelling correctly the atmospheric propagation effects, reducing spurious periodic signals seen in height estimates, improving non-gravitational force modelling on the satellites, improved modelling of tidal elastic deformation and understanding the noise characteristics of the GNSS measurements themselves. These will be investigated systematically through careful assessment of noise characteristics of temporal coordinates and identification of likely error sources, leading to the development and application at the observation level of new models for geophysical processes. Already, significant improvements have been achieved by some of the CIs (e.g., Watson et al., 2006; Tregoning and Herring, 2006, Ge et al., 2002, Satirapod and Rizos, 2005) and we expect such advances in the accuracy and understanding of error sources to continue.

Through the analysis of data from these new co-located GNSS installations, and PS-InSAR to connect the GNSS movement to the tide gauge, we will generate the first high-accuracy estimates of the vertical movements of Australia's tide gauges in a global reference frame. Such information is crucial if we are to be able to extract absolute estimates of sea level changes from tide gauge records.

Altimetry measures the distance from the satellite to the ocean surface. If the orbit of the satellite is known accurately, then the height of the ocean relative to the Earth's geocentre can be estimated. Altimetry provides the only technique capable of determining temporal change in sea level at both regional and global scales. The technique is limited in the first part due to errors in the orbit estimates, propagating directly into estimates of sea surface height. Altimeter missions also have limited life spans, therefore requiring that the combination of successive missions be achieved with an accuracy greater than the expected rate of sea level variation. The continuity of sea level from altimetry depends entirely on the ability to ensure continuity in the estimates of the orbits of each altimeter satellite. This, in turn, depends on an accurate definition of the reference frame and centre of mass of the Earth about which the satellites orbit. Significant research is required in developing new analysis methods for reducing the raw SLR observations to the altimeter satellites in order to estimate more accurate orbit trajectories, recomputing the sea surface height estimates with the new orbits and then producing improved estimates of sea level change following rigorous calibration (Watson et al., 2004).

Tide gauges provide discrete estimates of temporal sea level variations only where there is a land/water interface. Satellite altimetry provides spatial and temporal coverage of sea surface heights only distant (about 15-30 km) from the land/ocean boundary. This leaves the inshore coastal zone as the only region that is not sampled, the region that will have the greatest effect on the Australian population. A new technique has been proposed (Anderson, 2000) and demonstrated recently (Soulat et al., 2004) that utilises GNSS signals reflected from the water surface to estimate the sea state, including sea surface height. GNSS 'reflectometry' is a challenging but feasible means of estimating inshore sea surface heights, although considerable work is required before the technique can be considered 'mature'. The group at UNSW are leading developments in GNSS hardware and associated software/firmware to identify and track the low-strength reflected signals (Mumford et al., 2006, also ARC DP0342867 and DP0556848). This proposal includes a pilot project to build on existing technological developments and demonstrate the viability of GNSS reflectometry for monitoring near-shore sea level variations. A prototype instrument will be completed by 2008 and will be tested first on still water, then installed for one year at Burnie, Tasmania, the only Southern Hemisphere satellite altimetry calibration/validation site. A simultaneous GPS buoy experiment will be conducted there to verify the technique.

Water: Changes in continental water (integrated surface, ground water and soil moisture) can be detected from space-based observations of the Gravity Recovery and Climate Experiment (GRACE) satellites, with an accuracy of ~2 cm (Tapley et al., 2004; Wahr et al., 2006). Ground water estimates will depend largely upon the analysis of GRACE gravity data over the Australian region - in particular, separating the long-term secular trends from seasonal variations. The accuracy of GRACE results are about 40 times worse than the mission specifications (Wahr et al., 2004), yet the raw K-band measurements between the two satellites meet design specifications. Thus, the degradation lies in the analysis of the observations (cf. Kusche, 2007), implying that an order of magnitude improvement is possible. The raw K-band measurements are available for non-GRACE Project Team researchers to become involved in their analysis - indeed, already two independent software systems have been developed in Europe to analyse the raw measurements - and will be utilised by the CIs to estimate gravity variations across Australia, in particular the Murray Darling Basin and the Great Artesian Basin.

The contribution to sea level variation from East Antarctica will be estimated from a combination of glacial isostatic adjustment estimates from GNSS data, gravity variations from GRACE data and present-day ice volume changes from Cryosat data. The latter can be taken to model gravity and sea level changes in the Australasian region (e.g. Kuhn et al., 2007) and validated by GRACE data. Furthermore, the change in the mass redistribution (e.g. melting of ice and distribution over the oceans) can be used to derive the corresponding change in the geocentre (Chao & O'Connor, 1987) and will be compared to geodetic estimates of geocentre motion.

Improving Geodetic Analyses: Both inertial (celestial) and terrestrial reference frames are needed for space-geodetic analysis. The inertial frame is used primarily for orbit determinations, and the terrestrial reference frame for expressing the position of points on the Earth, and geo-referencing the Earth's gravity field and other dynamic phenomena. Current limiting factors in many investigations lie in the reference frame definitions because the errors in definition of the coordinates of celestial bodies, and the origin, scale and orientation of the terrestrial reference frames are of the same order of magnitude as the geophysical signals being studied (e.g. sea level rise). This is the most fundamental part of the proposal and arguably the most important, as the reference frame definition underpins all science results from the analysis of geodetic data. Errors in the definition of the origin or scale of the terrestrial reference frame could introduce biases in the estimates of geophysical signals larger than the order of magnitude of the signals themselves.

Observations from VLBI, GNSS (including GPS, GLONASS and, when available, Galileo), GRACE and SLR will be used to improve the analyses of each technique individually and, collectively, reduce the errors in the estimates of the geophysical phenomena being studied, enabling smaller and smaller signals to be detected. It is becoming clear that many of the apparent seasonal variations seen in vertical time series of GNSS analyses are actually caused by analytical and/or modelling shortcomings. Recent model improvements at the observation level by the CIs will be further exploited to continue the advances in high-precision global GNSS analysis (e.g., new tidal deformation models from a combination of gravity, GNSS and atmospheric observations) so that the accuracy of GNSS estimates of land movement will reach the levels required for extracting the geophysical signals that are sought. It is only through the combination of the existing techniques that errors specific to one (or more) techniques will be identified and subsequently mitigated.

An error in the definition of the geocentre affects present-day estimates of sea level variations from satellite altimetry. The error propagates with a spatially complex aliasing into sea level rise rates of up to the magnitude of the origin translation error. Thus, before one can estimate sea level variations with an accuracy of 1 mm/yr or better, it is essential that the definition of the origin of the reference frame be defined more accurately than this level. A recent redefinition of the origin of the most recent International Terrestrial Reference Frame, ITRF2005, has introduced a 1.8 mm/yr translation along the spin axis of the Earth relative to the previous reference frame, ITRF2000. This change derives solely from the analysis of SLR data, since it is only SLR that defines the origin in the ITRF. 1.8 mm/yr is only a small difference; however, this is nearly the rate of global sea level rise, so it is very significant and potentially affects geophysical interpretations relying on GNSS uplift estimates (e.g., adjusting tide gauge records for land movement, constraining ice sheet models by GNSS patterns of uplift).

However, based on elementary mechanics, any ice melt over Antarctica will predominantly result in a northward drift (away from the vanishing ice masses) of the geocentre (e.g. Kuhn et al. 2007), so at least a component of this rate may actually be real. To investigate this, we will use a number of simulations of short-term melt scenarios to study possible geocentre motions and will also conduct a thorough investigation into the analysis of SLR data to assess the impact of recent reductions in global satellite tracking coverage and whether this has had any effect on the geocentre definition. Additionally, a particularly novel idea is to use VLBI observations to GNSS satellites to estimate the geocentre, thereby providing an independent estimate with which to assess the accuracy of the SLR definition of the origin (see above).

Research Plan and Timeline: The science questions to be addressed require major contributions from several space-geodetic techniques; hence, significant overlap between the different expertise that resides in the four universities. The science plan and workload must be spread across all CIs/postdocs and is thus outlined below by "theme" rather than by institution.

2008: New research by CIs into errors in current GNSS analysis (such as atmospheric tidal deformation, ocean tide loading models). Commencement of analysis of GNSS data from new sites at Australian tide gauge sites. Commencement of development of software/analysis of GRACE raw K-band observations. SLR analysis using various tracking networks to simulate temporal tracking changes. Development/testing of VLBI correlator for geodetic observations (with Dr Tingay at Swinburne University). Ongoing development of GNSS receiver for reflectometry studies. Two postdocs to commence to work on SLR/GNSS and GRACE analyses.

2009: Continuation of GNSS/GRACE analysis, including ground validations of secular gravity signals from GNSS site velocity estimates. Commencement of postdoc to work on incorporation of SLR observations to GPS satellites into GPS/VLBI software. Improvements in SLR orbit and geocentre estimates, leading to new sea level variation estimates from altimetry. Field experiments in Antarctica for calibration/validation of Cryosat II and subsequent analysis. Commencement of PS-InSAR monitoring of vertical movement between tide gauges and

GNSS sites.

2010: Continuation of all above projects. Commencement of postdoc to work on GNSS reflectometry experiments and characterisation of new GNSS observables (Galileo system, new GPS frequencies, etc). SLR network simulation, geocentre and orbit studies to be finalised. GRACE analysis methodology and ground validation to be finalised.

2011: Continuation of monitoring of vertical movement of tide gauge/GNSS sites, monitoring of groundwater using GRACE observations, sea level variations using SLR/altimetry data. GNSS reflectometry experiments over still water (lake, calm ocean). Software for combined VLBI/SLR/GNSS observations to be completed.

2012: Decadal estimates of sea level variations from tide gauges and altimetry to be finalised, including tide gauge/GNSS relative movement estimates. Ongoing estimates of water mass variations to continue. GNSS reflectometry experiment at Burnie, Tasmania.

REFERENCES

Anderson K. (2000) Determination of water level and tides using interferometric observations of GPS signals, Journal of Atmospheric & Oceanic Technology, 17: 1118-1127.

Cazenave A. & Nerem R.S. (2004), Present-day sea level change observations and causes. Rev. Geophys., 42:1-20.

Chao B.F. & O'Connor W.P. (1987), Effect of a uniform sea-level change on the Earth's rotation and gravitational field, Geophys. J. Int., 93:191-193.

Chen, K., & J. McAneney (2006), High-resolution estimates of Australia's coastal population, Geophys. Res. Lett., 33, L16601, doi:10.1029/2006GL026981.

Chen J.L., C.R. Wilson, D.D. Blankenship & B.D. Tapley (2006), Antarctic mass rates from GRACE, Geophys. Res. Lett., 33, L11502, doi:10.1029/2006GL026369.

Church J. A. & N. J. White (2006), A 20th century acceleration in global sea-level rise, Geophys. Res. Lett., 33, L01602, doi:10.1029/2005GL024826.

Church, J.A., White, N.J., Coleman, R., Lambeck, K., and Mitrovica, J.X. 2004. Estimates of the regional distribution of sea-level rise over the 1950 to 2000 period. Journal of Climate, Vol. 17, No. 13, 2609-2625.

Deng, X.L. & W.E. Featherstone (2006) A coastal retracking system for satellite radar altimeter waveforms: application to ERS-2 around Australia, Journal of Geophysical Research - Oceans 111, C06012, doi: 10.1029/2005JC003039.

Drewes, H., 2007. Science Rationale of the Global Geodetic Observing System (GGOS), in "Dynamic Planet: Monitoring & Understanding a Dynamic Planet with Geodetic & Oceanographic Tools", Springer IAG Symposia vol.130, 703-710.

Featherstone, W.E. (2002) Expected contributions of dedicated satellite gravity field missions to regional geoid determination with some examples from Australia, Journal of Geospatial Engineering 4(1): 1-19.

Ferretti A, C. Prati C & F. Rocca (2000), Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry, IEEE Trans. Geosci. Remote Sens., 38, 2202-2212.

Ge, L., S. Han and C. Rizos (2002), GPS multipath change detection at permanent GPS stations, Surv. Rev., 36, 306-322.

IPCC (2001), Climate Change 2001: The scientific basis, Intergovernmental Panel on Climate Change Third Assessment Report.

IPCC: Intergovernmental Panel on Climate Change (2007), Contribution of Working Group I to the Fourth Assessment Report.

Kuhn M, Makarynskyy O, Featherstone WE, and Keller W (submitted January 2007): Implications from global sea level change due to melting ice sheets. *submitted to Science*.

Kusche J (2007) Approximate decorrelation and non-isotropic smoothing of time-variable GRACE-type gravity field models, Journal of Geodesy (in press)

Luthcke, S. B., D. D. Rowlands, F. G. Lemoine, S. M. Klosko, D. Chinn, and J. J. McCarthy (2006), Monthly spherical harmonic gravity field solutions determined from GRACE inter-satellite range-rate data alone, Geophys. Res. Lett., 33, L02402, doi:10.1029/2005GL024846.

Mumford, P.J.,K. Parkinson, K, & A.G. Dempster (2006), The Namuru Open GNSS Research Receiver. *19th Int. Tech. Meeting of the Satellite Division of the U.S. Inst. of Navigation*, Fort Worth, Texas, 26-29 September, 2847-2855.

NPWS: National Plan for Water Security, Prime Minister's Office, released 25 January 2007.

Rahmstorf, S. , A. Cazenave, J.A. Church, J.E. Hansen, R.F. Keeling, D.E. Parker, R.C.J. Somerville (2007) Recent Climate Observations Compared to Projections, *Science*, Published online 1 February 2007 [DOI: 10.1126/science.1136843] (in *Science* Express Brevia)

Satirapod, C., and C. Rizos (2005), Multipath mitigation by wavelet analysis for GPS base station applications, Survey Review, 38, 2-10.

Soulat F., M. Caparrini, O. Germain, P. Lopez-Dekker, M. Taani, and G. Ruffini (2004) Sea state monitoring using coastal GNSS-R, Geophys. Res. Lett., 31, L21303, doi:10.1029/2004GL0206680.

Tapley, B. D., S. Bettadpur, M. Watkins, and C. Reigber (2004), The Gravity Recovery and Climate Experiment: Mission overview and early results, Geophys. Res. Lett., 31, L09607, doi: 10.1029/2004GL019920.

Tregoning P., and T. A. Herring (2006), Impact of a priori zenith hydrostatic delay errors on GPS estimates of station heights and zenith total delays, Geophys. Res. Lett., 33, L23303, doi: 10.1029/2006GL027706.

Wahr, J., S. Swenson, V. Zlotnicki, and I. Velicogna (2004), Time-variable gravity from GRACE: First results, Geophys. Res. Lett., 31, L11501, doi:10.1029/2004GL019779.

Wahr, J., S. Swenson, and I. Velicogna (2006), Accuracy of GRACE mass estimates, Geophys. Res. Lett., 33, L06401, doi:10.1029/2005GL025305.

Watson C., P. Tregoning, and R. Coleman (2006), Impact of solid Earth tide models on GPS coordinate and tropospheric time series, Geophys. Res. Lett., 33, L08306, doi: 10.1029/2005GL025538.

Watson, C., White, N., Coleman, R., Church, J., Morgan, P., and Govind, R. (2004). TOPEX/Poseidon and Jason-1: Absolute Calibration in Bass Strait, Australia, Marine Geodesy, 27(1-2), 107-131.