Consistent and Accurate Representation of Surface Mass Loading Using Modified Basis Functions

Peter Clarke[1], David Lavallée[1], Geoff Blewitt[1,2], Tonie van Dam[3]

[1] School of Civil Engineering and Geosciences, Newcastle University, UK • [2] Mackay School of Earth Science & Engineering, University of Nevada, Reno, USA

[3] Faculty of Sciences, Technology and Communication, University of Luxembourg

Peter.Clarke@newcastle.ac.uk

1. Introduction

Our target is the robust estimation of surface mass loading from surface geodetic data at seasonal and longer timescales. Inversion schemes using Love number theory and spherical harmonic representation are attractive at large scales, but fine-scale (higher-degree) inversion becomes unstable due to the continent-rich, ocean-poor distribution of geodetic displacement data (Wu *et al*., 2002). A further problem is the appropriate treatment of mass conservation and of the oceanic equilibrium-tide response to the total gravitational field (Blewitt & Clarke, 2003; Clarke *et al*., 2005).

Figure 1 shows the rms change in the weekly predictions of total surface mass load over the period 1997–2005. The load has three components:

- Land hydrology, from the LaD model (Milly & Shmakin, 2002).
- ECCO ocean bottom pressure (http://www.ecco-group.org).
- NCEP reanalysis atmospheric pressure (Kalnay *et al*., 1996).

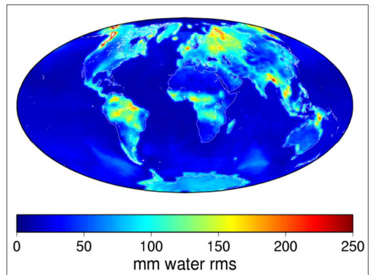


Figure 1.

2. Modified basis functions

A disadvantage of the spherical harmonic basis is that it permits unphysical load variability over the oceans, where few GPS data points exist. This poor network geometry prevents detailed spherical harmonic parameterisation of the load; conversely, aliasing of higher-degree features will bias low-degree inversions.

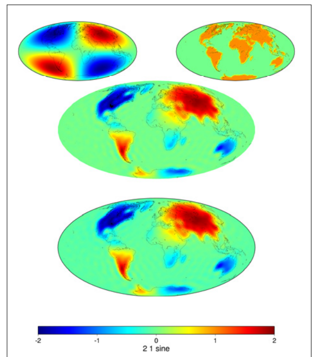


Figure 2. Example: (top) spherical harmonic Y_{21}, ocean function; (middle) raw B'_{21}; (bottom) corrected, mass-conserving B_{21} incorporating equilibrium tidal ocean response.

Our solution is to form new basis functions by masking standard spherical harmonics $Y_{nm}(\Omega)$ with the ocean function $C(\Omega)$:

$$B'_{nm}(\Omega) = \{1-C(\Omega)\} \cdot Y_{nm}(\Omega)$$

We then correct the raw (land-only) $B'_{nm}(\Omega)$ by adding an oceanic term $S(\Omega)$ to enforce mass conservation and to allow the ocean to respond tidally, where:

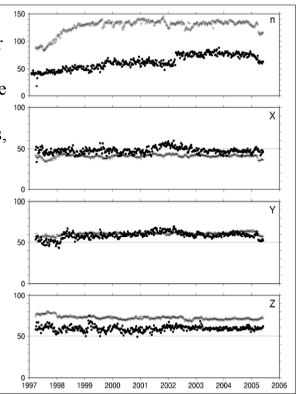
$$S(\Omega) = C(\Omega)\{(V(\Omega) + \Delta V)/g - H(\Omega)\}$$

$H(\Omega)$ is the vertical displacement of the Earth's surface, $V(\Omega)$ is the displacement of the original geoid in response to the total load, and the constant term ΔV enforces global conservation of load mass for each $B_{nm}(\Omega) = B'_{nm}(\Omega) + S(\Omega)$.

3. GPS networks and testing

The IGS network has grown considerably over the last decade, and different Analysis Centers (ACs) follow different site selection strategies in processing subsets of it (**Figure 3**). Site density and inter-hemispheric distribution have changed with time, and this has changed the aliasing of the estimated load (Lavallée *et al*., 2006). We compare the effectiveness of our new basis functions to that of standard spherical harmonics using two example AC networks. For each weekly solution, we generate synthetic site displacements using the model load, and add synthetic correlated random noise using the variance-covariance information in the weekly SINEX file. We then invert each set of 3-D displacements to obtain surface mass load coefficients. We test a range of spherical harmonic truncation degrees, and an analogous range of maximum "degree" of the $B_{nm}(\Omega)$. The coefficients of $B_{nm}(\Omega)$ are then transformed to the spherical harmonic basis for comparison.

Figure 3. Total number of sites, and percentage of sites in the hemisphere centred on each of the positive X, Y and Z axes, for the JPL (circles) and SIO (crosses) weekly GPS analyses 1997–2005. Inter-hemispheric bias is strongest in the Z direction, especially for SIO, and is also evident in the Y direction for both networks.



4. Global fit to synthetic data

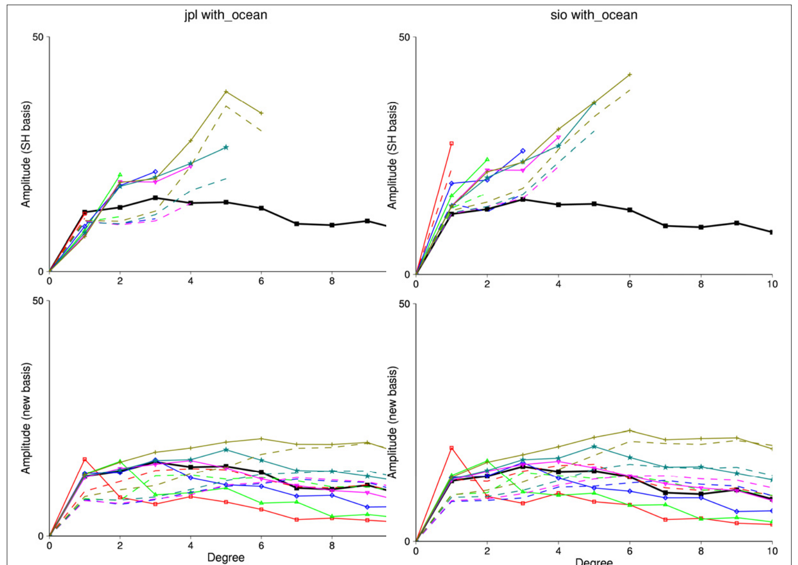


Figure 4a. Root mean square fitted degree amplitude (solid lines) and misfit degree amplitude (dashed lines) using the JPL (left) and SIO (right) network geometry for GPS weeks 0898–1322. Maximum degree of fit: (1) red, (2) green, (3) blue, (4) magenta, (5) pale blue, (6) brown.

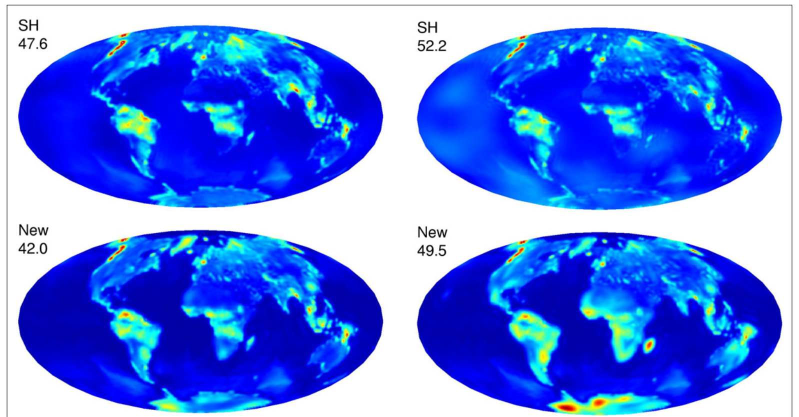


Figure 4b. Root mean square difference between fit truncated at degrees 3 (left) and 5 (right), and the known synthetic load, using the spherical harmonic basis (top); likewise using the new basis functions (bottom). JPL network geometry is used in all cases. Note the widespread erroneous loads in the spherical harmonic inversion, especially over the Pacific and Southern oceans. In contrast, the new basis concentrates the erroneous load into relatively small areas. Colour scale as Fig. 1.

5. Fit to low-degree load coefficients

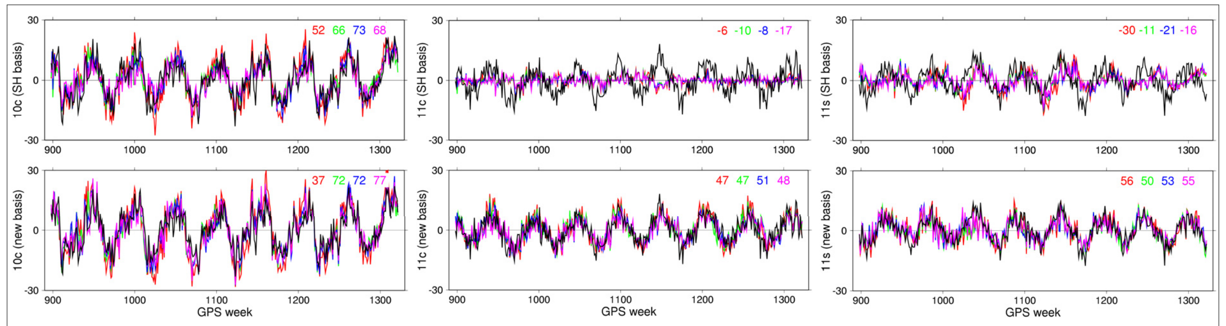


Figure 5a. Comparison between synthetic degree-1 load coefficients (black lines) and fit using spherical harmonics (top) and the new basis (bottom); JPL network geometry. Colour indicates maximum degree of fit: (1) red, (2) green, (3) blue, (4) magenta. Numbers represent percentage of variance fitted.

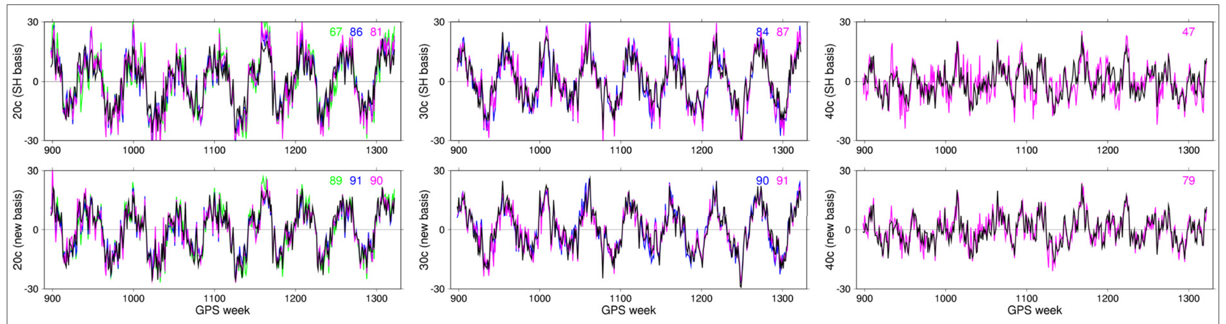


Figure 5b. Comparison between synthetic low-degree zonal load coefficients (black lines) and fit using spherical harmonics (top) and the new basis (bottom); JPL network geometry. Colour indicates maximum degree of fit: (1) red, (2) green), (3) blue, (4) magenta. Numbers represent percentage of variance fitted.

6. Conclusions

We have demonstrated that a physically reasonable set of basis functions, derived from spherical harmonics, can be used to represent the variation in surface mass loading and to infer it from associated displacements of the solid Earth. We achieve a more accurate fit to realistic synthetic data than with a spherical harmonic fit using the same number of parameters, are more robust to the biasing effect of network geometry, and are less prone to large-scale oscillation in unconstrained regions. The basis functions directly incorporate the physics of reference frame definition, conservation of mass, and equilibrium ocean response to the land load, whilst describing the land load in a model-independent way. GPS observations may be of particular use to complement GRACE data by constraining low-degree surface mass loading (Kusche & Schrama, 2005), and these basis functions will improve the accuracy and robustness of this.

References

Blewitt, G. (2003). Self-consistency in reference frames, geocenter definition, and surface loading of the solid Earth. *J. Geophys. Res.*, **108**(B2), 2103.

Blewitt, G., & P. Clarke (2003). Inversion of Earth's changing shape to weigh sea level in static equilibrium with surface mass redistribution. *J. Geophys. Res.*, **108**(B6), 2311.

Clarke, P.J., D.A. Lavallée, G. Blewitt, T. van Dam, & J.M. Wahr (2005). Effect of gravitational consistency and mass conservation on seasonal surface loading models. *Geophys. Res. Lett.*, **32**(8), L08306.

Kalnay, E., *et al.* (1996). The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Met. Soc.* **77**(3), 437-471.

Kusche, J. & E.J.O. Schrama (2005). Surface mass redistribution inversion from global GPS deformation and Gravity Recovery and Climate Experiment (GRACE) gravity data. *J. Geophys. Res.*, **110**, B09409.

Lavallée, D.A., T. van Dam, G. Blewitt & P.J. Clarke (2006). Geocenter motions from GPS: A unified observation model. *J. Geophys. Res.*, **111**, B05405.

Milly, P.C.D. & A.B. Shmakin (2002). Global modeling of land water and energy balances: Part 1. The Land Dynamics (LaD) Model. *J. Hydrometeorology*, **3**, 283–299.

Wu, X., D.F. Argus, M.B. Heflin, E.R. Ivins, & F.H. Webb (2002). Site distribution and aliasing effects in the inversion for load coefficients and geocenter motion from GPS data. *Geophys. Res. Lett.*, **29**(24), 2210.

Acknowledgements

This work was funded in the UK by NERC grant NER/A/S/2001/01166 to PJC and a Royal Society University Research Fellowship to DAL, and in the USA by NASA and NSF grants to GB. We would like to thank the authors of the LaD, NCEP and ECCO datasets for making their results available.