Satellite altimeter calibration and validation using GPS buoy technology

By

Christopher S. Watson, B. Surv (Hons) UTAS

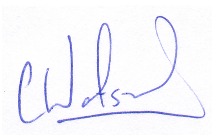
Submitted in fulfilment of the requirements for the
Degree of Doctor of Philosophy

Centre for Spatial Information Science
University of Tasmania

July 2005

Declaration

This Thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the Thesis, and to the best of the candidate's knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the Thesis.



Digitally signed by Christopher Watson
Reason: I am the author of this document
Location: Hobart, Australia
Date: 2005.10.26 16:32:55 +11'00'

....

Christopher S. Watson

Authority of Access

……………………………………………..

Christopher S. Watson

Supporting Publications

A number of publications have been produced while undertaking this Thesis. Where parts of these publications have been reproduced in this Thesis, the work is my original contribution to the publication. Dr Neil White is acknowledged with undertaking the initial data processing of the oceanographic moorings, and extracting the altimeter GDR data. The publications include:

Watson, C., Coleman, R., White, N., Church, J., and Govind, R. (2003). "Absolute Calibration of TOPEX/Poseidon and Jason-1 Using GPS Buoys in Bass Strait, Australia." *Marine Geodesy*, 26(3-4), pp285-304.

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), pp107-132.

Watson, C., Coleman, R., White, N., Church, J., and Govind, R. (2002). "In situ Calibration Activities in Bass Strait, Australia." *Poster at the NASA/CNES Jason-1 Science Working Team (SWT) meeting,* Biarritz, France, June 10-12, 2002.

Watson, C., Coleman, R., White, N., Church, J., and Govind, R. (2002). "In situ Calibration Activities in Bass Strait, Australia." *Poster at the NASA/CNES Jason-1 Science Working Team (SWT) meeting,* New Orleans, USA, October 21-23, 2002.

Watson, C., White, N., Coleman, R., Church, J., and Govind, R. (2003). "TOPEX/Poseidon and Jason-1: Absolute Calibration in Bass Strait, Australia." *Poster at the NASA/CNES Jason-1 Science Working Team (SWT) meeting,* Arles, France, November 18-22, 2003.

Watson, C., White, N., Coleman, R., and Church, J. (2004). "Updated Results from Bass Strait and Other Sites in the Australasian Region." *Poster at the NASA/CNES Ocean Surface Topography Science Team Meeting,* St Petersburg, Florida, USA, November 4-6, 2004.

To A.R. Gear

Abstract

Satellite altimeters have become an important tool for the study of global and regional mean sea level change, offering near global coverage and unprecedented accuracy. Issues of calibration and validation remain central to their ability to determine estimates of change at accuracies of better than 0.5 mm/yr. This Thesis provides an absolute calibration of the TOPEX/Poseidon (T/P) and Jason-1 satellite altimeters, undertaken in Bass Strait, Australia. The research provides a contribution to the international calibration effort, with the Bass Strait site situated as the only one of its kind in the Southern Hemisphere.

A unique in situ absolute calibration methodology is presented, reliant on the episodic deployment of GPS equipped buoys at an offshore comparison point. In contrast to other calibration studies, data from the GPS buoys are used to solve for the absolute datum of an offshore oceanographic array (incorporating a pressure sensor, temperature and salinity recorders and a current meter array). Combined with data from a coastal tide gauge and a regional GPS network, the methodology enables the cycle-by-cycle computation of absolute bias, without the necessity of estimating a marine geoid. Emphasis within this Thesis is given to the design and development of the GPS equipped buoys, in addition to the standardisation requirements of the geodetic analysis. The GPS buoy design is applied to both the altimeter calibration problem, in addition to a near shore application involving the calibration of tide gauges in the Antarctic and Sub-Antarctic. The attention to standardisation ensures comparable estimates of in situ and altimeter sea surface height. Differences at the 9 mm level for the pole tide displacement and $\pm$15 mm for the solid Earth tide displacement are revealed when using the GAMIT GPS analysis suite. The implications of non-standardisation are further illustrated with the presentation of time series analysis from various continuous GPS datasets.

Absolute bias and 1-sigma uncertainties from a formal error budget are 0 $\pm$ 14 mm for T/P and +152 $\pm$ 13 mm for Jason-1 (for the GDR POE orbits, computed over the calibration phase, 18 Jan 2002 – 14 Aug 2002). Results over the duration of the T/P mission confirm a dependence on the choice of Sea State Bias (SSB), with the overall mean absolute bias not statistically different from zero. Extending the comparison period between Jason-1 cycles 1 to 101 (18 Jan 2002 – 06 Oct 2004) reduces the Jason-1 mean absolute bias by approximately 10 mm and reveals a significant slope of -7.6 $\pm$ 5.6 mm/yr. Whilst the cause for the significant absolute bias remains unexplained, the source of the drift appears attributable to the microwave radiometer, observed to be measuring drier over time (-5.9 $\pm$ 2.1 mm/yr). Drift of the POE orbit relative to the JPL GPS orbit is shown to account for the remaining trend observed at the Bass Strait site. After considering geographically correlated errors, absolute bias results show excellent agreement with other international calibration studies. These results aid in understanding the performance of both the T/P and Jason-1 altimeters, further underscoring calibration and cross calibration of altimeters as essential for the study of low frequency oceanographic processes, including regional and global mean sea level change. The inference of geographically correlated orbit errors, and the significant unexplained Jason-1 absolute bias emphasises the need for maintaining globally distributed verification sites and makes it clear that further work is required to improve our understanding of the Jason-1 instrument and its algorithm behaviour.

Table of Contents

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Appendices

Acknowledgements

I can not escape a feeling of selfishness by writing just one name on the cover of this Thesis. Many people are to be thanked for their contribution, both professionally and personally.

Firstly, I sincerely thank Richard Coleman for his supervision, guidance and friendship so generously given both before and throughout my candidature. I can't imagine a better mentor, and I have no doubt this Thesis would not be what it is without Richard's untiring involvement. John Church and Neil White also deserve special thanks for their significant contribution to the fieldwork, analysis, and persistence in answering so many questions. It has been a delight to work as part of a team and be considered an equal with these people.

Peter Morgan and Tony Sprent have also provided significant assistance throughout this project. I thank Peter for sharing his knowledge of satellite geodesy, particularly the intricacies of the GAMIT/GLOBK software suite. Peter also generously provided his time series for analysis in this Thesis. Tony came up with the GPS buoy design and provided numerous answers to practical questions along the way.

Roger Handsworth and the Australian Antarctic Data Centre team are thanked for their assistance in the field work undertaken at Macquarie Island and in Antarctica. Thanks to John Hunter for providing his tidal analysis software and answering questions in relation to the tide gauge work. The CSIRO Marine Research mooring group are thanked for undertaking the setup, deployment and retrieval of the mooring array.

Numerous individuals and groups must be thanked for providing funding and data for this study. The CSIRO Earth Observation Centre (EOC) provided funding for main component of this study. I was supported by an Australian Postgraduate Award and CSIRO scholarship for which I was very grateful. Bob Twilley and the Geoscience Australia team maintain the data from the BUR1 GPS installation and also operate the Australian Regional GPS Network (ARGN). The National Tidal Facility (NTF) operates and maintains the Burnie tide gauge with the assistance from the Burnie Ports Corporation. Neil Adams from the Australian Bureau of Meteorology provided atmospheric pressure information. Veronique Dehant and Leonid Petrov generously provided their solid Earth tide routines. Bob King and Tom Herring answered many questions in relation to the GAMIT/GLOBK and Track software suites. Altimetry products were obtained from the Jet Propulsion Laboratory (JPL) PO.DAAC and Centre National d'Études Spatiales (CNES) AVISO archives. Bruce Haines, Pascal Bonnefond, Phil Callahan and other members of the TOPEX/Poseidon and Jason-1 SWT/OSTST provided valuable responses to numerous technical questions. Bruce Haines was particularly patient in answering my many questions and also providing the GPS reduced dynamic orbits. Michael and Bradley Hardy operated the boat in Bass Strait and provided assistance during the buoy deployment campaign. Thanks to all these people for their valuable contributions.

I would like to thank my colleagues within CenSIS and my wider group of friends for making the last three and a bit years an enjoyable time. The regular coffee group has done a fine job in keeping my caffeine levels at their optimum best.

Before I make my final acknowledgement, I would like to thank my parents, Janne and Stephen. It is a great privilege to be in the position to undertake academic research, and I thank my parents for providing the opportunities to learn and explore, enabling me to do now what I so much enjoy.

I reserve my final thankyou to Rachael for sharing in the successes and struggles that this work represents. Rachael has comforted and motivated during the difficult times and celebrated and congratulated during the good times. I look forward to the next phase in our lives together.

List of Figures

List of Tables