THE UNIVERSITY OF NEWCASTLE AUSTRALIA

ADAPTIVE RETRACKING OF RADAR ALTIMETRY WAVEFORMS OVER HETEROGENEOUS INLAND WATERS

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DECLARATION

STATEMENT OF ORIGINALITY

I hereby certify that the work embodied in the thesis is my own work, conducted under normal supervision. The thesis contains no material which has been accepted, or is being examined, for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made. I give consent to the final version of my thesis being made available worldwide when deposited in the University's Digital Repository, subject to the provisions of the Copyright Act 1968 and any approved embargo.

Andrew Marshall

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I hereby certify that the work embodied in this thesis contains published paper/s/scholarly work of which I am a joint author. I have included as part of the thesis a written declaration endorsed in writing by my supervisor, attesting to my contribution to the joint publication/s/scholarly work.

By signing below, I confirm that Andrew Marshall contributed as joint author to the paper entitled 'Image analysis for altimetry waveform selection over heterogeneous inland waters'.

Xiaoli Deng

31 August 2020

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LIST OF ABBREVIATIONS

AGC	Automatic gain control
AGD66	Australian Geodetic Datum 1966
ALES	Adaptive Leading Edge Sub-waveform (retracker)
ALOS	Advanced Land Observing Satellite
AltiKa	Altimeter in Ka-band
ARM	Approximate river mile
ASAR	Advanced synthetic aperture radar
AVISO	Archiving Validation and Interpretation of Satellite Oceanographic Data
CNES	Centre National d'Etudes Spatiales (National Centre for Space Study)
COG	Centre of gravity
DAC	Dynamic atmosphere correction
DAHITI	Database for Hydrological Time Series of Inland Waters
DEM	Digital elevation model
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
DSM	Digital surface model
ECMWF	European Centre for Medium Weather Forecast
EGM96	Earth Gravitational Model 1996
EGM2008	Earth Gravitational Model 2008
Envisat	ENVIronmental SATellite
ERS-1	European Remote Sensing Satellite-1
ERS-2	European Remote Sensing Satellite-2
ESA	European Space Agency
ETM7	Enhanced Thematic Mapper (Landsat 7)
FAN	File Array Notation
GDR	Geophysical Data Record
GFO	Geosat Follow-on
GIM	Global ionospheric map
GNSS	Global Navigation Satellite System
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GRRATS	Global River Radar Altimetry Time Series
HH	(SAR) horizontal transmit/horizontal receive

IDL	Interactive Data Language
IE	Individual echo
InSAR	Interferometric SAR
ITRF92	International Terrestrial Reference Frame 1992
L1B/L2	Level 1B and Level 2
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
LEGOS	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales
LEP	Leading-edge position
LRM	Low-resolution mode
LRR	Laser retro-reflector
MIR	Middle infra-red
MLE	Maximum likelihood estimator
MMSE	Minimum mean square estimator
MSL	Mean sea level
MWaPP	Multiple Waveform Persistent Peak (retracker)
MWR	Microwave radiometer
NASA	National Aeronautics and Space Administration
NDVI	Normalised Difference Vegetation Index
NDWI	Normalised Difference Water Index
NetCDF	Network Common Data Form
NIR	Near infrared
NM	Nautical mile
NPPR	Narrow Primary Peak Retracker
OCOG	Offset Centre of Gravity
OHD	Ok Tedi Height Datum
OLCI	Ocean and Land Colour Imager
OLI8	Operational Land Imager (Landsat 8)
OLTC	Altimeter Open Loop Tracking Command for Hydrology
OMG	Ok Tedi Map Grid
OSCAR	Observing Systems Capability Analysis and Review
OSTM	Ocean Surface Topography Mission
OSU	Ohio State University
OTML	Ok Tedi Mining Limited

PNG	Papua New Guinea
PNGMG94	PNG Map Grid 1994
PRF	Pulse repetition frequency
PVC	Polyvinyl chloride
RA-2	Radar Altimeter 2
RANSAC	RANdom SAmple Consensus
RMSE	Root mean square error
SAR	Synthetic aperture radar
SARAL	Satellite with ARgos and AltiKa
SD	Standard deviation
SGDR	Sensor and Geophysical Data Record
SIRAL	SAR Interferometric Radar Altimeter
SMASH	Small Altimetry Satellites for Hydrology
SRAL	Synthetic Aperture Radar Altimeter
SRTM	Shuttle Radar Topography Mission
SSB	Sea state bias
SSH	Sea surface height
SWH	Significant wave height
SWOT	Surface Water Ocean Topography Mission
TEC	Total electron content
TM5	Thematic Mapper (Landsat 5)
T/P	Topex/Poseidon
UCLA	University of California, Los Angeles
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
VV	(SAR) vertical transmit/vertical receive
WATeR	Waveform Adaptive Threshold Retracker
WGS84	World Geodetic System 1984
WLS	Weighted least squares
WSE	Water surface elevation

LIST OF SYMBOLS

A	waveform amplitude (OCOG and Threshold Retracker)
d	along-track distance
d_1	waveform power difference between adjacent gates
d_2	waveform power difference for a separation of 2 gates
G_{LEP}	waveform gate of the leading-edge position
G_{REF}	altimeter reference tracking gate
G_{2m}	conversion factor from gate to metres
H	satellite altitude above the reference ellipsoid
H_i	satellite altitude at time i
h_i	height above reference ellipsoid at time i
h	height above reference ellipsoid
Δh_{dac}	dynamic atmosphere correction
Δh_{earth}	solid earth tide correction
Δh_{geoid}	geoid correction
Δh_{WSE}	total range and geophysical corrections for inland waters
Δh_{load}	ocean loading tide correction
Δh_{ocean}	ocean tide correction
Δh_{SSH}	total range and geophysical corrections for sea surfaces
Δh_{pole}	geocentric pole tide correction
N	geoid–ellipsoid separation
$P(t)$	the returned power waveform as a function of time
$P_{FS}(t)$	average flat surface response
P_i	waveform power at gate i
P_N	thermal noise
Pu	waveform amplitude of Brown–Hayne retracking model
q	Threshold Retracker amplitude percentage
$q_s(t)$	surface probability density of specular points
R	correlation coefficient
R_{earth}	spherical radius of the Earth
R_i	range to reflecting surface at time i
R_{corr}	corrected altimetric range
R_{obs}	observed altimetric range
R_{obs}'	observed slant range

ΔR	range error
$rNIR$	near infrared band reflectance
$rRed$	red band reflectance
ΔR_{dry}	dry tropospheric propagation delay
ΔR_{iono}	ionospheric propagation delay
ΔR_{ssb}	sea state bias
ΔR_{wet}	wet tropospheric propagation delay
S_{d1}	standard deviation for all power differences between adjacent gates
S_{d2}	standard deviation for all power differences for a separation of 2 gates
$S_r(t)$	radar point target response
T_h	Threshold Retracker threshold level at q%
W	waveform width (OCOG and Threshold Retracker)
β_1	thermal noise of β-parameter retracking
β_2	return signal amplitude of β-parameter retracking
β_3	midpoint of leading-edge ramp of β-parameter retracking
β_4	waveform rise time of β-parameter retracking
β_5	slope of trailing edge of β-parameter retracking
δ_{si}	along track distance between t_{i-1} and t_i
φ	latitude
λ	longitude
$\frac{\partial a}{\partial s}$	satellite altitude along track variation
γ	function of the antennae beam width
ξ	waveform trailing edge slope for the Brown–Hayne retracking model
σ_c	waveform rise time for the Brown–Hayne retracking model
σ^0	backscatter coefficient (sigma0)
σ_s	slope of the waveform leading edge for the Brown–Hayne retracking model
τ	waveform epoch/time delay for the Brown–Hayne retracking model

ABSTRACT

To manage the pressure that population growth, human impact and climate change is having on the allocation of, and access to, water there is an increasing need to monitor the world's water resources, independent of infrastructure and inter-government policies. Traditionally the realm of the hydrologist, this task has relied on the deployment of in-situ gauges and instruments. Recent focus has been on the capabilities of satellite-based technologies to augment the existing hydrology in-situ network with the aim of replacing it with a global water level monitoring tool for inland rivers, lakes and wetlands.

This research has focussed on the satellite altimetry coverage of the middle Fly River floodplain as well as Lake Murray—both located in the Western Province of Papua New Guinea. The Fly River floodplain is a mine-impacted environment and monitoring of water level change through the various floodplain and wetland entities is required into the future. More than for other similar environments throughout the world there will become an increasing need to support Fly River local communities with information regarding predicted changes to inundation that may have impacts on their communities and subsistence livelihood.

The current state-of-the-art satellite altimetry analysis methodologies over heterogeneous inland waters do not meet the accuracy and reliability requirements for water surface measurement. This is particularly relevant for the relatively small river and lake systems that contribute to a typical complex floodplain or wetland system. Methodologies developed in this study enable routine, accurate and reliable extraction of water surface elevations from nadir-looking pulse-limited radar altimeters over heterogeneous inland waters. This is achieved by deconstructing the shape and form of the recorded waveform and correlating that form against external inputs so that the environmental factors that have affected the shape and form of the waveform are understood and can be addressed. The external inputs comprise a range of supporting data, including information derived from satellite imagery as well as in-situ water level observations. A process of waveform footprint classification is developed with assessment of footprint inundation extent based on image analysis from both multi-spectral and synthetic aperture radar (SAR) imagery. The methodology is extended to include a full definition of the landform cover type as well as prediction capabilities for off-nadir calm water detection.

A significant advancement over conventional processes is that waveforms, and the associated water surface elevations, are assessed based on an analysis of the waveform and

adjacent waveforms as well as the nature of the altimetry footprint rather than solely on statistical agreement of the derived water surface elevation with that derived from adjacent waveforms. This facilitates the retention of water level estimates over relatively small water bodies, where multiple, statistically consistent, estimates would not be practical. The processes developed in this research offer a methodology for the extraction of reliable water surface estimates, in both a temporal and spatial context, over heterogeneous inland waters. An optimised adaptive threshold retracker, the Waveform Adaptive Threshold Retracker, is developed as part of this study with methodology and workflow detailed in the thesis. Methods for the accurate identification of waveforms impacted by hooking and other sources of contamination are developed, along with tools for the rectification of impacts and estimation of likely contamination magnitude.

Optimised waveform retracking using the adaptive retracking methodology and workflow is validated at Envisat Radar Altimeter 2 (RA-2) and Satellite with Argos and AltiKa (SARAL/AltiKa) crossings of the Fly River and achieved by comparison of the altimetric time series with in-situ gauge data. Validation is also undertaken for floodplain sites where verified virtual in-situ gauges have been established for validation of both Envisat RA-2 and SARAL/AltiKa-derived elevations. This comparison has been undertaken for the 10 years of Envisat RA-2 data acquisitions and the pre-drifting phase cycles of SARAL/AltiKa data. Elevation profiles from Envisat RA-2, SARAL/AltiKa and Cryosat-2 SAR Interferometer Radar Altimeter (SIRAL) altimeters have been derived across both the Fly River floodplain and Lake Murray and used to assess the proposed retracking methodologies for the derivation of floodplain gradients and differential elevations between various floodplain water bodies.

The methodologies developed offer potential for the reprocessing of a significant archive of data from nadir-looking pulse-limited radar altimeters as well as supporting analyses of data from currently operational altimeters into the future. The work undertaken in this study has facilitated tangible improvements in the quality and quantity of water level estimates across complex inland water environments.