REMOTE MEASUREMENT AND MONITORING OF INLAND WATER HEIGHTS GLOBALLY USING MULTI-MISSION SATELLITE RADAR ALTIMETRY

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Introduction

- The effective management of the Earth’s inland water is a major challenge facing scientists and governments worldwide.
- However, whilst demand for this often scarce resource continues to grow, the number and distribution of in-situ hydrological gauge stations is steadily falling and many catchments basins in the developing world are now entirely ungauged.
Introduction

- Satellite radar altimeters have been collecting echo series over inland water for more than 16 years.
- But only a tiny fraction of these data have been successfully mined for information on river and lake heights.
Return Power Waveform

- Time delay related to satellite altitude
- Slope of leading edge relates to wave height
- Received power relates to wave height
- Trailing edge slope relates to instrument pointing and antenna pattern
- Transmitted pulse
- Tracking point in ocean mode at mid-point of leading edge
Radar Altimetry Principle

$h_d = H - h - h_g$

- Sea surface
- Geoid
- Reference ellipsoid
- Dynamic sea surface topography
- Altimeter range measurement $h$
- Satellite orbit $H$
Vertical Datum Applications

- \( H_i \) (sea level over ellipsoid) = \( \text{Horbit} - \text{Hrange} + E_r \)
  \[ = S_g + S_s + S_v + S_t + E_o + E_r \]
  with
  - \( S_g \) = Geoid signal
  - \( S_s \) = Stationary signal
  - \( S_v \) = Variability
  - \( S_t \) = tides signal
  - \( E_o \) = Orbital error
  - \( E_r \) = remaining errors and corrections
  (solid tides, loading effect, inverse barometer effect, ...)

- Leads to different types of oceanographic analysis:
  - Meso-scale dynamic topography (currents, eddies, kinetic energy, ...)
  - Large scale topography/large scale variability (basin gyres, strong currents, mean sea level, mean sea level rise?, ...)
  - Stationary signal (mean reference surface, estimation of the stationary dynamic topography)
  - Tides study (hydrodynamic models constrained by altimetric data)
  - Assimilation to dynamic models of the oceanic circulation
Vertical Datum Applications

• Glaciology
  – DEM, Delta-DEM
  – Input data for forcing, initialisation or test of ice flow dynamic models
  – Long term monitoring of the topography for seasonal or secular variations.
  – Sea-ice thickness

• Land topography
  – Global DEM obtained from the full 336 days of the ERS-1 geodetic phase (most accurate Global DEM)

• Rivers and Lakes level
  – Long term, global, surface water monitoring
  – Study of the response of lakes to climate for water resources management, fisheries, water quality and conservation
The Basic Radar Altimetry Toolbox

http://earth.esa.int/brat

The Radar Altimetry Tutorial
So what can the current generation of altimeters recover over inland water?

- Huge global analysis carried out of waveform recovery over inland water from ERS-2, TOPEX Jason-1 and Envisat.
- Every location where at least 80% of cycles have valid waveforms over the targets was identified and flagged.
- Next slides show global plots for TOPEX, ERS-2 and Envisat with one red dot for each crossing flagged.
ERS-2 Global Targets

- Increase only partly due to 35 vs 10 day orbit: more to ERS-1/2 RA ability to maintain lock AND the wider ‘ice mode’ range receiving window
Envisat Global Targets

- Even more targets overall, although more ‘drop-out’ of waveforms (the self-adaptive tracker is mostly in high-resolution mode)
Global Mask for NRT RA-2 & Jason-1

- NRT RA-2 targets red, RA-2 & Jason-1 targets turquoise, potential targets grey-blue. Note: all targets acquired by Jason-1 also seen by RA-2 (better time sampling with both).
New NRT mask over Africa

River Congo

Lake Tana

Lake Malawi

Lake Turkana
Example Validation over Amazon basin

EnviSat: (green) RMS against Gauge: 0.4724m, Correlation: 0.9905
• Gauge data plotted in grey-blue

ERS-2 (red): RMS against Gauge: 0.6269m, Correlation: 0.9878

TOPEX (red): RMS against Gauge: 1.8376m, Correlation: 0.8611

Jason-1 (dark blue): RMS against Gauge: 1.2198m, Correlation: 0.9283

• Gauge data plotted in grey-blue
Mekong and Tonle Sap

Multi-mission data over Tonle Sap (ERS-2 + Envisat + TOPEX + Jason-1) and on Mekong (ERS-2 + Envisat: each circle is time series)
ERS-2 Statistics over Lake Nasser

Top graph shows one time series over lake Nasser from ERS2.

Second graph shows pre-filtered along-track RMS (green) and NRT system output RMS (red).

Bottom graph shows number of points:

a) from mask subset
b) After initial selection
c) As output from system
Envisat Statistics over Lake Kariba

Statistics for Envisat over Lake Kariba

Plots as last slide

Note low loss of waveforms but reduction in RMS
TOPEX Statistics over Lake Tana

Statistics for TOPEX from Lake Tana. Again, note substantial improvement in along-track RMS after system processing and retracking.

More waveforms rejected from TOPEX but RMS improves dramatically.
Here, far fewer waveforms rejected but RMS greatly reduced.

This often seen with Jason-1: retracking greatly enhances height retrieval.
Kainji Reservoir - Niger River

Time series from Envisat (left) and Jason1 (right).
Zeyskoye Vodokhranilishche

Reservoir Zeyskoye Vodokhranilishche, Russia, water level with 12 year combined timeseries derived from retracked ERS-2, EnviSat, Topex and Jason-1 waveform data. Excellent agreement is achieved over this fairly complex target. Note the very good data from Jason-1 over this reservoir. (click to zoom)
Zeyskoye Vodokhranilishche
Near-Real Time Products

data over 1 day

6 measurements per day over Africa, ONLY!
Near-Real Time Products

All Data generated in Near Real Time over a 35-day cycle
Near-Real Time Products

Need Denser Time Sampling!

⇒ A Swath Altimeter (WaTER, HM, SWOT) - 2D maps will give slope!

⇒ A Constellation of Nadir Altimeters
“River & Lake” Website

Information and Data Products Request:

http://earth.esa.int/riverandlake
Hydroweb: Selection of rivers and lakes

http://www.legos.obs-mip.fr/fr/soa/hydrologie/hydroweb/

Cazenave
LEGOS
USDA: Reservoirs and Lakes

Lake Volume Variation (km$^3$)

East African Lakes Volume Change

Map showing locations of Turkana, Rukwa, Mweru-Wantipa, Mweru, and Bangweulu.
The Syr Darya River Basin is shared between the four central Asian republics of Kyrgyzstan, Tajikistan, Uzbekistan and Kazakhstan. The total surface area of the Basin is 780,000 km² (below left). The runoff regime in the basin is snow-melt dominated and most of the runoff is generated in the mountainous parts of the catchment, which rise to altitudes of more than 7000 meters above mean sea level. The Syr Darya river is the Northern tributary to Lake Aral and contributed about 30% to the total inflow into Lake Aral in the near-natural state.

Locations of altimeter time-series: EnviSat (light blue), ERS2 (pink), Topex (gold) and Jason-1 (green).

Project is to model the Syr Darya river basin, incorporating multi-mission satellite radar altimetry.
Locations of altimeter time-series:
EnviSat (light blue),
ERS2 (pink),
Topex (gold) and
Jason-1 (green).
Zambesi

- The Zambezi River is the fourth largest in Africa, flowing eastward for more than 2'800 km from the Kalene Hills in northern Zambia to its mouth at the Indian Ocean in Mozambique. It has an approximate catchment size of 1'570'000 km².
- One of Africa’s most heavily dammed river systems

Combined time-series from ERS-2/Envisat and Topex/Jason-1 (where possible!) will be used. Below (click to zoom) are two combined ERS-2/Envisat time-series over the Zambesi.
The Zambezi River is the fourth largest in Africa, flowing eastward for more than 2,800 km from the Kalene Hills in northern Zambia to its mouth at the Indian Ocean in Mozambique. It has an approximate catchment size of 1,570,000 km². One of Africa’s most heavily dammed river systems.
Sample model performance on discharge
visual comparison of 1 river-crossing stage and catchment discharge
next step is to model stage-discharge relations
Goal is to study variation of water-storage in the Amazon.

Ultimate goal is to use Altimetry and GRACE to get "sub-surface" terrestrial water storage.

NASA/GSFC GRACE Mascon registers the total amount of water and it’s changes.

The EAPRS retracked ERS-2/Envisat satellite altimetry register the changing heights of the water in the rivers and tributies.

We compare the variation on monthly-annual scales.
Processed GRACE level 1B Data from July 2003 - Dec 2004
Upgraded atmospheric series, improved ocean tide models, improved processing.
Mascons solved on a 4°x4° grid every ten days, where sufficient data were available to construct a solution.
Apply a spatial & temporal constraint of the form: $e^{-(2-d_{ij}/D-|t_{ij}|/T)}$
where $d_{ij}$ and $t_{ij}$ are the distance and time differences between the mascons, where $T$ and $D$ are the correlation time and distance.
Used $T=10$ days & $D=250$ km.
Mascons are computed relative to a mean background field. The 10-day regional Amazonas mascon estimates are based on two multi-period solutions: (1) July - Jan. 2004; (2) Feb. - October 2004.
=> There is a total of 52 10-day solutions in the Amazon.
=> There is 195 blocks in the greater Amazon region.
South America Mascon solutions: July 2003 - August 2004
(wrt Julv 2003-July 2004 mean)
Altimetric Time-Series

192 time series with 95% temporal coverage in the Amazon.
Interpolate to 10 days sampling.

Rio Bravo
Water level time-series from GRACE

GRACE Water level deviation – Jul 2003

This is an animation
This is an animation

- ERS
- ENVISAT
- GRACE
Comparison of 1.5 years simultaneous "high resolution" water mass observations from GRACE gravity and satellite altimetry in the Amazon drainage region & rivers with 10 days temporal resolution.

• The high resolution GRACE MASCONS shows the "propagation" of water
• The altimetric observations from ERS-2+ENVISAT shows it too.
• Altimetry and GRACE agree on phase/time of maximum annual water level
• Simplified model shows fairly similar magnitude of the two distinct sources
Conclusions

• A huge amount of waveforms are already acquired over inland water targets globally, since 1992.
• Processing these complex echoes to retrieve decadal time-series of height changes has already recovered information over hundreds of targets worldwide.
  *ADAPTED RETRACKING IS ESSENTIAL*
• With applications ranging from near-real-time monitoring for water resource management to decadal climate change indicators, and spatial scales which both allow correlations with GRACE data, and permit monitoring of hundreds of river systems, the unique contribution of satellite radar altimetry to global inland surface water monitoring and the importance of continued measurements is evident.
  *INCREASED TIME SAMPLING IS ESSENTIAL*
Conclusions (2)

• As in-situ gauges falls out of repair, more and more catchments are becoming ungauged, whilst the demand on water continues to escalate.

• Using the remote measurement capability of altimetry, particularly the near-real-time capability, it is now possible for water resource managers to access both the NRT data and its context - decadal historical information.

• The global monitoring capability, now being achieved using multi-mission satellite radar altimetry, reveals changing patterns of use, as stress on water resources increasingly depletes drainage basins beyond their capability to recharge.

• The technology can be applied as well in the oceanic coastal zone (similar difficulties in retrieval due to contamination by surrounding land)
The scientific challenge is to fully extend to the global inland water bodies and the coastal ocean the success of altimetry in monitoring the global open ocean. To satisfy hydrologist requirements we need:

1) better techniques on current instruments;
2) better instruments for the future;
3) better spatial/temporal sampling (this will require new technology or constellations as proposed by CEOS Strategic Implementation Team)
4) integration of measurement and forecast systems (satellites, river gauges, discharge and current meters, tide gauges, hydrographic measurements, models).
Conclusions (4)

- In Hydrology and coastal altimetry cooperation is essential at EU level, but even globally, as the problems are global and the expertise needed is interdisciplinary and geographically distributed.
- The best excellences need to be networked and complementarities exploited. This is actually happening and needs to be sustained with adequate funding.
- Europe however is leading the field of altimetry for hydrology and coastal zone oceanography (important investments) and should endeavour to retain this role as a key player on the international scene.
Concerning instrument data processing and auxiliary corrections, an active network is required for gathering local data,
- for altimeter measurement corrections and validation,
- to be patchworked into a global product,
- for inland water, estuaries and oceanic coastal zone.