Challenges in detecting trend and seasonal changes in bathymetry derived from HICO imagery: a case study of Shark Bay, Western Australia

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Curtin University:

- HICO User’s since 2011
- Previous experience with airborne hyperspectral surveys, radiative transfer, bio-optics...
- Interest in bathymetry & habitat mapping for environmental management

Research question:

- Can HICO data be used to detect change in bathymetry through time?
Study site: Shark Bay, Western Australia

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- World Heritage Area
  - Very remote, approx. 700 km (440 miles) North of Perth
  - 12 species of seagrass that cover approx. 4200 km² (Walker et al. 1988)

- The rectangles represent different swath orientations of the HICO sensor.
HICO image processing for assessing temporal change

1. Removing the atmospheric radiance signal from at-sensor top-of-atmosphere radiance (Tafkaa-6S)
   \[ \rho^* \rightarrow R_{rs} \]

2. Correcting for sun-glint and air-to-water interface
   \[ R_{rs} \rightarrow r_{rs}^{deglint} \]

3. Shallow water inversion model to retrieve depth and uncertainty
   \[ r_{rs}^{deglint} \rightarrow Depth \]

4. Post-image smoothing

5. Tide Correction

6. Geo-registration

7. Change Detection Analysis
Atmospheric correction & sunglint correction

- Tafkaa-6S Atmocor
- Used co-incident MODIS Aqua imagery to estimate $\tau(550)$, cwvap, ozone
- Sunglint $\Delta R_{rs}(750)$
- Basic land/cloud masking if $R_{rs}(750 \text{ nm}) > R_{rs}(400 \text{ nm})$
HICO image processing for assessing temporal change

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   • $R_{rs} \rightarrow r_{rs}^{\text{deglint}}$

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HICO $r_{rs}^{deglined}$ imagery spanning 10 months: November 2011 to August 2012
3. Retrieving Bathymetry

Bottom Reflectance Un-mixing Computation of the Environment (BRUCE) model

- Physics-based shallow water model (Klonowski et al. 2007)

\[
r_{rs}(\lambda) = f(a(\lambda), b_b(\lambda), \rho(\lambda), H, \theta_v, \theta_w)
\]

\[
r_{rs}(\lambda) = f(P, G, X, H, B_{sg}, B_{sed}, \theta_v, \theta_w)
\]

Semi-analytical, and functions of scalar parameters

- Non-linear optimisation (Levenberg-Marquardt) algorithm:

Find \( P, G, X, H, B_{sg} \text{ and } B_{sed} \) such that

\[ r_{rs_{\text{model}}} - r_{rs_{\text{measured}}} \approx 0 \]

Cost function:

\[
\sqrt{\sum_{i=1}^{N} (r_{rs,i} - \hat{r}_{rs,i})^2}
\]
3. Retrieving Bathymetry

Bottom Reflectance Un-mixing Computation of the Environment (BRUCE) model

Propagation of spectrally correlated sensor and environmental noise through the inversion process (Hedley et al. 2010; 2012)

Estimate $\delta r_{rs}$ by sampling an “homogenous” deep water region

20 noise perturbed shallow water spectra: $r_{rs} + \delta r_{rs}$

Invert with BRUCE 20x

$P \pm \Delta P$
$G \pm \Delta G$
$X \pm \Delta X$
$H \pm \Delta H$
$B_{sd} \pm \Delta B_{sd}$
$B_{seg} \pm \Delta B_{seg}$
3. Retrieving Bathymetry
Bottom Reflectance Un-mixing Computation of the Environment (BRUCE) model

**Why use the UR-LM method?** The standard approach of using a fixed initial guess to invert each noise perturbed spectra gives high uncertainty due to the convergence to local minima by the LM method.

Depth = \((4.37 \pm 5.57)\) meters \(\rightarrow\) 127\% uncertainty
3. Retrieving Bathymetry
Bottom Reflectance Un-mixing Computation of the Environment (BRUCE) model

A brief search of parameter space to find the optimal initial guess parameters, \( P, G, X, H, B_{sg} \) and \( B_{sed} \) for each HICO-\( r_{rs} \) pixel (Garcia et al., under review);

\[
P = 0.05; \quad G = 0.05; \quad X = 0.01; \quad H = 4.0; \quad B_{sed} = 0.02; \quad B_{grass} = 0.02
\]

BRUCE model

HICO derived \( r_{rs}(\lambda) \)

Update-Repeat LM optimization (10 iterations)

Optimized model parameters randomly perturbed by 10% of their value and used as input to next inversion attempt

10 sets of optimized model parameters

\[
P_0, \quad G_0, \quad X_0, \quad H_0, \quad B_{sed,0}, \quad B_{grass,0} \quad \ldots \ldots \quad P_9, \quad G_9, \quad X_9, \quad H_9, \quad B_{sed,9}, \quad B_{grass,9}
\]

Initial guess with lowest Euclidean distance selected

BRUCE model LM optimization
Invert noise-perturbed spectra (step 2)
3. Retrieving Bathymetry
Bottom Reflectance Unmixing Computation of the Environment (BRUCE) model

The UR-LM method guides the LM optimization to the optimum minimum (Group 1).

Depth = (0.60 ± 0.01) meters
3. Retrieving Bathymetry
Bottom Reflectance Un-mixing Computation of the Environment (BRUCE) model
4. Post-processing Image Smoothing and Tide Correction

- Bathymetry images contain impulse (salt-and-pepper) noise, which are typically add abrupt and unrealistic changes in depth.

- Removing these pixels with a two-step smoothing approach:
  1. Impulse noise pixel selection and subsequent replacement with an adaptive median filter
  2. Application of $2^{nd}$ order binomial smoother
4. Post-processing Image Smoothing and Tide Correction

Smoothed Bathymetry and Uncertainty
5. Post-processing Image Smoothing and Tide Correction

- Removing influence of tide to delineate changes in depth caused by resuspension and sedimentation
- Lack of in situ tide height data, and therefore an empirical tide correction technique was developed
6. Geo-location Issues

Time series analysis requires relatively high geolocation accuracy, to ensure that a change in depth at two instances in time is a real temporal change.

A geolocation accuracy of $1/5$th of pixel is needed to detect 90% of real temporal changes (Dia and Khorram, 1998) → 20m for HICO.

The provided Geographic Lookup Tables (GLTs) are inadequate for time series analysis.
6. Geo-location Issues

Geo-Registration using Ground Control Points

A geolocation accuracy of $1/5^{th}$ of pixel is needed to detect 90% of real temporal changes (Dia and Khorram, 1998) → 20m for HICO
7. Change detection analysis

Is it possible to detect temporal change (at two time points) above uncertainty?
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Is it possible to detect temporal change (at two time points) above uncertainty?

Pixels have to satisfy the following two criteria to be classed as having observed change:
1. A difference in depth (between two time points) greater than the baseline variability (0.36m);
2. Per-pixel $t$-test analysis; Null hypothesis of “no change in depth” is rejected for pixels with $p < 0.05$ (5% significance level).
Change detection analysis of HICO-derived, tide corrected, bathymetry of the Faure Sill, between the dates of:
(a) 14-Dec-2011 and 21-Jan-2012;
(b) 21-Jan- and 27-Feb-2012;
(c) 27-Feb- and 04-Jun-2012;
(d) 04-Jun- and 08-Aug-2012

Separate image-based tide corrections were performed for the dashed magenta regions presented in (a).
Detecting trend and seasonal changes in bathymetry derived from HICO imagery: A case study of Shark Bay, Western Australia

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ABSTRACT

The Hyperspectral Imager for the Coastal Ocean (HICO) aboard the International Space Station has offered for the first time a dedicated space-borne hyperspectral sensor specifically designed for remote sensing of the coastal environment. However, several processing steps are required to convert calibrated top-of-atmosphere radiance to the desired geophysical parameter(s). These steps add various amounts of uncertainty that can cumulatively render the geophysical parameter imprecise and potentially unusable if the objective is to analyze trends and/or seasonal variability. This research presented here has focused on: (1) atmospheric correction of HICO imagery; (2) retrieval of bathymetry using an improved implementation of a shallow water inversion algorithm; (3) propagation of uncertainty due to environmental noise through the bathymetry retrieval process; (4) issues relating to consistent geo-location of HICO imagery necessary for time series analysis, and; (5) tide height corrections of the retrieved bathymetric dataset. The underlying question of whether a temporal change in depth is detectable above uncertainty is also addressed. To this end, nine HICO images spanning November 2011 to August 2012, over the Shark Bay World Heritage Area, Western Australia, were examined. The results presented indicate that precision of the bathymetric retrievals is dependent on the shallow water inversion algorithm used. Within this study, an average of 70% of pixels for the entire HICO-derived bathymetry dataset achieved a relative uncertainty of less than ±20%. A per-pixel t-test analysis between derived bathymetry images at successive timestamps revealed observable changes in depth to as low as 0.4 m. However, the present geolocation accuracy of HICO is relatively poor and needs further improvements before extensive time series analysis can be performed.
Some recent PR....

Orbital ‘camera’ snaps marine topography

Written by Geoff Vivian

“Arcing bathymetry from platforms such as airborne imagery has been around since the 1970s, however those algorithms were very scene-specific and couldn’t be transferred to other regions of the world,” Mr Garcia says.

In a world first, a Curtin University physicist used data from the International Space Station to map coastal bathymetry (underwater terrain).

Curtin PhD candidate Rodrigo Garcia says they chose Shark Bay for the project because the World Heritage listed site has the largest known seagrass meadows.

“We were just thinking of what we can use the data there for, whether we can help assess changes in depth for benthos,” he
Conclusion

We investigated challenges faced with temporal analysis of HICO-derived bathymetry

• Search for optimal initial guess produced precise retrievals of bathymetry for shallow water pixels (< 6 m)

• Retrieved bathymetry “can” detect temporal changes in depth of less than 1 m

• Post-processing image smoothing and tide correction aid temporal analysis

• Atmospheric correction still requires further improvements

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Community uptake

Increase user numbers, i.e. bigger user community – some problems *may* be solved faster

- Workshops, special sessions etc.
- Press releases
- IOCCG Newsletter
- Special HICO edition in journal?
- Open access – data + code
- Demonstration datasets
References


Additional material....
Tide offsets

Predicted Tide = 0.7043(Depth) + 0.6158

R² = 0.90

(a)

(b)

Decimal Days since 01 Jan 2011

Tide Height (cm)

Median Shallow water depth (m)

Predicted tide height at Monkey Mia (m)