Mapping the fine-scale shallow water bathymetry of the Great Barrier Reef using ALOS AVNIR-2 data

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Abstract –**Mapping the shallow water bathymetry of aquatic environments such as the Great Barrier Reef presents a number of challenges, due to both the large area which it occupies and the widely dispersed and variable shallow water reef areas which characterize it.**

The cost of implementing traditional methods, such as multi-beam sonar, and, more recently, Laser Airborne Depth Sounding (LADS), can be prohibitive when dealing with large offshore areas. In addition, ship-based techniques are often restricted to surveys in water no shallower than ~10-15m.

Spaceborne remote sensing can be used for shallow water bathymetry estimation, potentially as a cost-effective tool to complement these other survey methods. A number of techniques have been developed in this field, using a combination of various sensors and methodologies. However, restrictions to the implementation of a broader scale approach still exist due to the requirement of existing calibration depth data, high imagery data costs and small spatial coverage.

In this study we propose the application of a physics-based methodology to multi-spectral data from the AVNIR-2 sensor on-board the Japanese Advanced Land Observing Satellite (ALOS). The use of a physics-based approach enables bathymetry to be derived without the need for existing depth knowledge in the study area to calibrate the algorithm. This, combined with the large (70km^2) spatial coverage and high resolution (10m) of AVNIR-2 data, enables the potential for high resolution mapping of the entire reef with approximately 25-30 scenes.

Initial results show depths can be derived to approximately 15-20m, with an accuracy of 10-20% of existing LADS data in the study area. Further work is outlined to potentially move to a more operational, broad-scale context, and to further understand the limitations and possibilities of working with AVNIR-2 for bathymetry applications.

I. INTRODUCTION

The Great Barrier Reef (GBR) covers in excess of 340,000 km^2 and stretches for some 2,000 km along the eastern coast of Queensland, making it the largest coral reef in the world. The reef provides a significant economic contribution at both a state and commonwealth level, primarily through tourism, whilst also being a focus of considerable conservation and environmental management efforts. One of the important fundamental datasets for such applications is water depth, or bathymetry.

Mapping the variable bathymetry of such a large aquatic area presents a number of challenges, both in terms of cost and practicality. Traditional ship-based methods, such as multi-beam sonar, are restricted to depths exceeding ~15m and the cost of conducting such surveys can be prohibitive, especially in remote areas. Laser Airborne Depth Sounding (LADS) is often used as a high-resolution bathymetry mapping tool, particularly in shallow water (0 – 20m) to complement ship-based survey data. However, the acquisition of this data is costly, and not suited to the widely dispersed shallow water reef areas that characterize much of the GBR.

Spaceborne remote sensing can be used for shallow water bathymetry estimation, potentially as a cost-effective tool to complement other survey methods. However, the majority of techniques developed in this field have been based around empirical methodologies, which require known measurements over a range of depths in the study area in order to calibrate the algorithms being used [1][2]. This requirement would likely restrict the use of these methodologies in many remote areas of the GBR, preventing a continuous coverage across the extents of the numerous reef systems.

We propose the use of a physics-based algorithm, which is able to derive bathymetry from the remote sensing signal without the need for known calibration depths. A number of studies have utilized this type of approach, typically using hyperspectral data [3][4]. However, from an operational perspective of covering extended areas of the reef, utilizing hyperspectral data becomes impractical due to a small swath width and high associated costs.

In looking towards broad-scale mapping of the GBR, it is necessary to identify data options which are cost-effective: a large spatial coverage in combination with a level of horizontal spatial resolution sufficient to represent fine-scale reef bathymetry features.

We present the initial findings of a pilot study currently being undertaken to assess the suitability of multi-spectral data from the AVNIR-2 (Advanced Visible and Near Infrared Radiometer Type 2) sensor on board the ALOS (Advanced Land Observing Satellite) operated by the Japan Aerospace Exploration Agency (JAXA).

The implications of using this data source as a potential foundation for GBR-wide mapping are then discussed, in view of moving to a more operational implementation across the region.

978-1-4244-5222-4/10/$26.00

II. Data Source

A. Satellite Data

Data from the AVNIR-2 sensor is 8-bit, 4 band multi-spectral (Blue - 400nm, Green - 560nm, Red- 650nm and NIR - 825nm) with a ground pixel horizontal resolution of 10m. With a swath width of 70km, each scene covers 4,900 km^2 at a nadir acquisition. The scene used for this pilot study was acquired on the 2^{nd} April 2009 and illustrates the potential this sensor has to cover large tracts of the GBR with a single processed scene (Fig. 1); comparative scene footprints are shown for the commercial Quickbird sensor and the hyperspectral Hyperion sensor.

To enable its use in the physics-based methodology outlined in Section IV, the data must be converted from raw data to reflectance values using a MODTRAN (MODerate resolution atmospheric TRANsmission) based atmospheric correction procedure with the c-WOMBAT-c interface [5].

B. Model input parameters

The optimization process in this project, outlined further in Section IV, uses a library of benthic substrate reflectance spectra to determine, on a pixel-by-pixel basis, the ratio composition of any two substrates (e.g. 70% sand 30% coral). The spectral library used in this project consisted of 3 common benthic substrates; Sand, Massive Coral, Algae. These reflectance spectra were sourced from the Centre for Remote Sensing and Spatial Information Science of the University of Queensland.

In addition, a range of parameters associated with the optical properties of the water column constituents are required as an input to the model, describing the absorptive and backscattering components of the water. The optical water parameters used in this work were provided by the Environmental Earth Observation Group of CSIRO Land and Water.

In an optimal modeling environment, these spectra and optical water properties would be determined through site-specific fieldwork. This scenario is not realistic for broad-scale areas across the entire GBR. Therefore, a component of this work is to assess the suitability and success of using generic field data as model inputs.

III. Study Site

The selected study area is detailed in Fig. 1, and is located approximately 90km north of Bowen off the Queensland coast. The rationale for the selection of this site was based on three key criteria; 1) the availability of a high quality AVNIR-2 scene 2) high density coverage of LADS data, and 3) an area deemed representative of a typical reef environment in the GBR

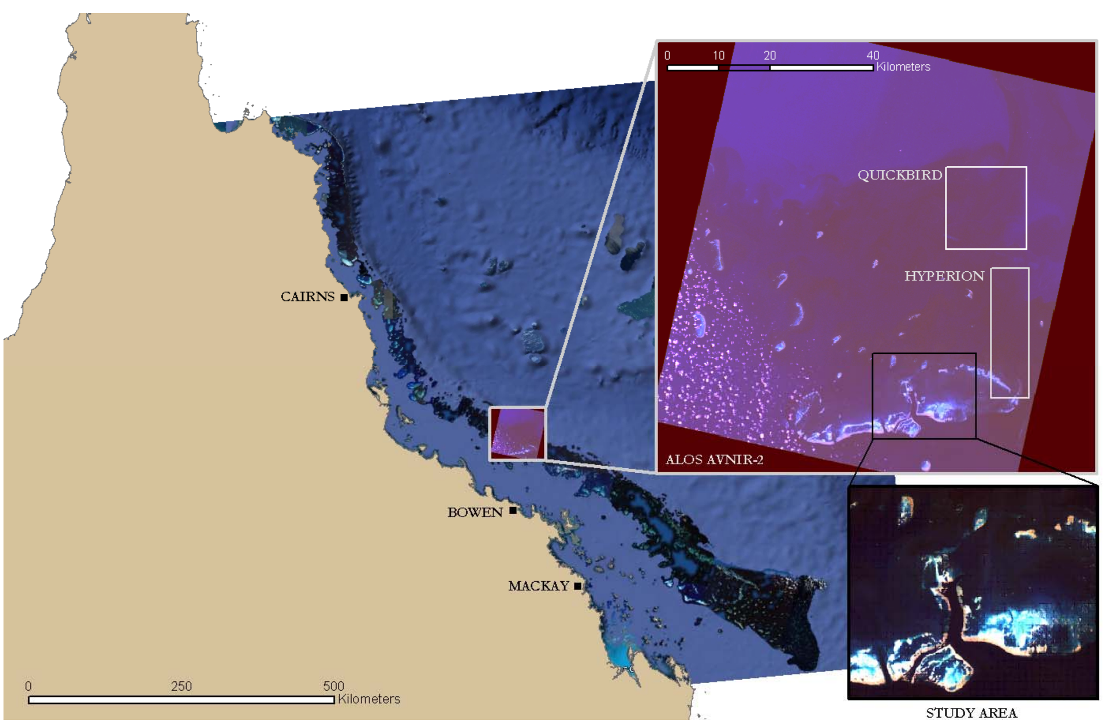

Figure 1. Location of the study site and ALOS AVNIR-2 scene (note spatially varying turbidity within the scene)
The extent of the Great Barrier Reef can be seen offshore from the Queensland Coast.
Indicative scene footprints from the Quickbird and Hyperion sensors are shown as insets for comparison.

Whilst known depth values are neither required for the modeling process nor likely to be available for many areas of the GBR, for the purposes of this study LADS data was deemed necessary to assess the accuracy of the derived bathymetry model. It is also required to underpin further work in quantifying quality indicators produced by the modeling algorithm, discussed in Section VI.

IV. Physics-Based Algorithm

This study applies a physics-based bathymetry mapping approach, SAMBUCA (Semi-Analytical Model for Bathymetry, Un-mixing, and Concentration Assessment), which was developed in the ENVI/IDL environment as an objective and repeatable algorithm for extracting aquatic environmental information on a pixel-by-pixel basis from remote sensing data [4][6]. It is based on the approach conceptualized by references [7][8] for retrieving environmental variables from remote sensing data using an analytical model and optimization routine.

The application of a physics-based, radiative transfer method has many advantages, including the ability to apply one algorithm to time series data, and data from a variety of sensors. In the context of the work in this paper, it is the ability of this type of method to extract depth, water column constituents and benthic substrate composition from a single remote sensing measurement which is essential. This is due to the anticipated lack of field data (known depths, water properties and benthic substrates) for a significant proportion of areas of the GBR.

The basis of this approach is the expression of the subsurface remote sensing reflectance $RS^{modeled}$ as a set of variables, and a parameterization of this model to define it as a function of a set of environmental parameters. An optimization routine is used to minimize the difference/error between the measured subsurface remote sensing reflectance ($RS^{measured}$) and $RS^{modelled}$ by varying the variables and retrieving the environmental parameters, including water depth, that correspond to the lowest error between $RS^{measured}$ and $RS^{modelled}$ [6].

V. Results

A. AVNIR-2 Data Assessment

An impeding factor in the use of optical imagery for aquatic applications is the presence of sun-glint: radiance from the sun reflected directly off the water surface to the sensor, induced by wave effects and/or the geometry of the sensor and sun location.

The sunglint-contaminated signal contains little information about water constituents or benthic features [9]. The bathymetry estimation process is therefore compromised in each pixel containing sun-glint.

The nadir acquisition nature of the majority of AVNIR-2 data means it is susceptible to sun-glint. This is based on the sun elevation angle at the time of acquisition, and to a lesser extent, glint produced from wave and wind induced effects. Commonly used glint-correction techniques for optical imagery assume a linear relationship across glinted and non-glinted pixels between each of the visible bands and the near-infrared (NIR), in optically deep water [10][11]. In our initial assessment of AVNIR-2 data, we have observed this linear relationship to be less defined, preventing a rigorous de-glinting of the imagery. For this reason, we prefer to look at options for the mitigation of glint when looking at image acquisition on a broader-scale, such as detailed in Section VI.

Image masking is required for pixels containing features where the bathymetry algorithm is unable to derive reliable depths, such as white-caps, breaking water, exposed reef and cloud cover. A simple NIR threshold approach was found to be the most time-efficient and reliable methodology, which are important criteria for extending mapping coverage to numerous scenes.

B. Validation and Accuracy Assessment

Extensive LADS coverage of the study area, ranging from 0.1m to in excess of 40m, was used to assess the accuracy of the derived bathymetry model. As mentioned earlier, the use of LADS data for validation is twofold, 1) to assess the accuracy of the derived model, and 2) to provide a tool to allow future quantification of the error/quality indicators produced by the SAMBUCA physics-based algorithm.

The derived bathymetry model was tide adjusted to Lowest Astronomical Tide (LAT) to correspond to the datum of the LADS data, using the average of the three surrounding tide gauge readings in the area at the time of image acquisition.

The scatterplot in Fig. 2 shows the resulting validation of the AVNIR-2 derived model depths against those of the LADS data, with a R^2 value of 0.74 and regression slope of 0.89. Points showing a large under or over-estimation were isolated and plotted over the image data to assess possible reasons for these large residuals.

Visual interpretation of these points in relation to the imagery showed a consistent relationship between the depth residual size and areas of rapidly changing or sloping bathymetry e.g. edges of coral outcrops, and the transition of reef crests to deeper water. Further investigation revealed, through identification of the locations of specific bathymetric features in both the imagery and the LADS data, a horizontal offset of some 20-30m between the two data-sets. This could account for a significant proportion of the high residual points shown in Fig. 2, and furthermore, has implications for broader mapping applications as discussed in Section VI.

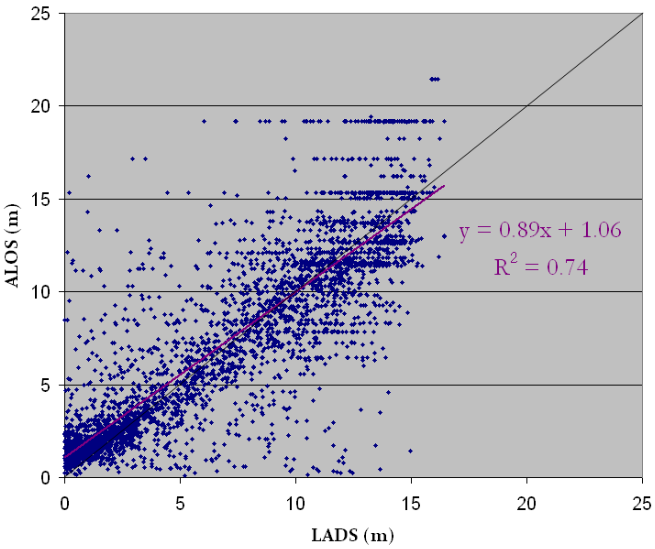

Figure 2. Regression of derived ALOS AVNIR-2 depths vs LADS data

Error and Quality indicators produced as part of the SAMBUCA methodology are an indication of the success of the modeling and inversion result, giving a pixel-by-pixel confidence estimation of the derived depth. Additional indicators are produced to highlight areas where an optical depth limit has been reached (i.e. where the sensor cannot 'see' the bottom with enough confidence to derive a reliable solution). The specifics of these indicators are beyond the scope of this paper, and we refer to Reference [4] for further details.

These indicators can be used to mask pixels in the bathymetry model in order to remove low confidence solutions from the final model. Fig. 3 shows the bathymetry model produced for the study area, with pixels masked in white using the indicators described above. The extent of the areas successfully modeled by the algorithm support the potential for using generic substrate and water parameters on a broader scale.

By combining the error and quality indicator outputs with the LADS-based accuracy assessment, we conclude that our ALOS-based approach is able to derive depths to within 10-20% of the validation depth, up to a depth of approximately 10-20m.

VI. Implications For Future Work

The combination of a large spatial coverage per-scene and a high pixel resolution gives ALOS AVNIR-2 data a strong potential as a tool for broad-scale operational bathymetry mapping of the GBR. However, there are a number of data issues to consider which this pilot project has highlighted.

A. Data coverage and Integration

Given the spatial footprint of an AVNIR-2 scene, coverage of the GBR could be achieved with approximately 25-30 scenes. However, due to issues such as glint, cloud cover and atmospheric effects, a level of data redundancy is required to ensure contiguous coverage.

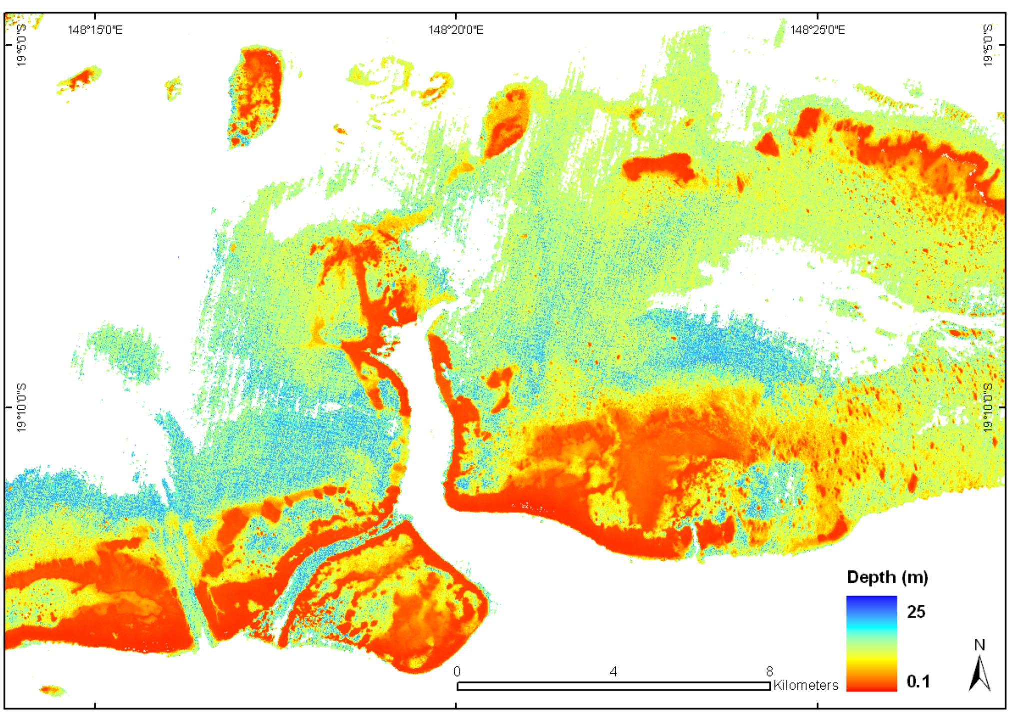

Figure 3. Shallow Water Bathymetry model derived from ALOS AVNIR-2 multi-spectral data over the GBR study area.

Methods to correct for glint in AVNIR-2 data are yet to be rigorously developed or tested. We have developed a screening tool which assesses each scene for glint potential using scene metadata and the resulting sun-sensor geometry. Further work will involve possible bulk-processing of scene metadata to evaluate glint potential across the available scenes in the GBR. Examination of the JAXA ALOS catalogue (https://auig.eoc.jaxa.jp/auigs/en/top/index.html) shows a good coverage of AVNIR-2 across the GBR, with a good level of redundancy in many areas of the reef. Assessment of how many of these scenes may be suitable for bathymetry mapping will prove a valuable step in determining the potential of moving to a more operational context.

The ability to integrate satellite derived bathymetry with other bathymetry datasets is essential to ensure the relevance of the satellite bathymetry to stakeholders. Accurate geo-referencing of the AVNIR-2 data, and therefore the bathymetry model, is important not only for the offset and validation issues described in Section V., but also to ensure seamless integration with data-sets such as multi-beam sonar and LADS. The lack of control points over aquatic areas, such as the GBR, with which to perform rigorous geo-referencing, remains an issue that must be addressed to coordinate a broad scale approach.

B. Further Technical Work

Results of the pilot project have indicated that more work is needed to understand the effects of the 8-bit radiometric resolution and the signal to noise characteristics of AVNIR-2 data.

We consider that the inability to establish linear relationships in the de-glinting process (described in Section V.) may be due to the limited range and discrete values defined in both the visible and NIR bands for deep water. Similarly, the clusters of depths derived (see Fig. 2) by AVNIR-2 at depths greater than 15m may be a function of the limited spectral discrimination given by the 8-bit data range. Further work will focus on evaluating and testing these possible quantization effects.

With a lack of validation data such as LADS likely in many areas of the GBR, accuracy of the derived models will only be able to be assessed through the error/quality indicators output of the physics-based algorithm. As these are not directly related to the accuracy of the derived depth, further work will focus on using the current study area and available LADS data to investigate the validity of adding an element of accuracy quantification to these indicators.

VII. Concluding Remarks

With the broad spatial coverage and high resolution that data from the ALOS AVNIR-2 allows, we consider it a viable and cost-effective tool to enable shallow-water bathymetry modeling to complement more traditional techniques in the extensive areas of the GBR.

Initial results have shown accuracies of 10-20% of the modeled depth to be achievable, dependant on data quality. Refinements to the process currently in progress to improve these results and quantify the quality indicators produced as part of the physics-based methodology.

We have identified issues that need to be addressed to move towards a more operational context, in aiming for a contiguous coverage of the entire GBR. This output would serve as a fundamental data-set to a variety of stakeholders involved with research, management and industry in this unique environment.

Acknowledgments

The authors thank the University of Queensland – Centre for Remote Sensing and Spatial Information Science for providing substrate spectra, and the CSIRO Land & Water group for providing optical water property parameters and the SAMBUCA source code.

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