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Coral reef applications of Sentinel-2: Coverage, characteristics, bathymetry and benthic mapping with comparison to Landsat 8

John D. Hedley[a,*], Chris Roelfsema[b], Vittorio Brando[c], Claudia Giardino[c], Tiit Kutser[d], Stuart Phinn[b], Peter J. Mumby[e], Omar Barrilero[f], Jean Laporte[g], Benjamin Koetz[h]

[a] Numerical Optics Ltd., Tiverton, UK
[b] Remote Sensing Research Centre, School of Earth and Environmental Sciences, University of Queensland, Brisbane, Australia
[c] National Research Council of Italy, Institute for Electromagnetic Sensing of the Environment, CNR-IREA, Via Bassini 15, 20133 Milano, Italy
[d] Estonian Marine Institute, University of Tartu, Tallinn, Estonia
[e] Marine Spatial Ecology Lab, School of Biological Sciences, University of Queensland, Brisbane, Australia
[f] CS Systèmes d'Information, 5 rue Brindejonc des Moulinais, 31500 Toulouse, France
[g] ARGANS Ltd., Plymouth Science Park, Plymouth, UK
[h] European Space Agency, Earth Observation - Department Science, Applications and Climate, Frascati, Italy

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ABSTRACT

The Sentinel-2A and 2B Multi-Spectral Instrument (MSI) offers a specification of potential value toward a number of objectives in remote sensing of coral reefs. Coral reefs represent a unique challenge for remote sensing, being highly heterogeneous at metre scales and occurring at variable depths and water clarity regimes. However, conservation initiatives, such as the United Nations Sustainable Development Goals, add urgency to the need for the large scale environmental monitoring information that remote sensing can provide. In the quest to meet this challenge a range of satellite instruments have been leveraged, from Landsat to high spatial resolution sensors such as WorldView-2, toward objectives such as: mapping of bottom types, bathymetry, change detection, and detection of coral bleaching events. Sentinel-2A and 2B offer a new paradigm of available instruments, with a 5-day revisit, 10 m multispectral spatial resolution and freely available data. Pre-launch simulation analyses by several of the authors suggested Sentinel-2 would have good performance for reef applications, in this paper we follow up on this study by reviewing the potential based on the substantial archive of actual data now available.

First we determine to what extent the World's reefs are covered by Sentinel-2, since the mission requirements do not by default include all reefs. Secondly we review how a 5-day revisit translates to a usable acquisition rate of clear images, given that cloud and surface glint are common confounding factors. The usable acquisition rate is the real determinant of the objectives to which the data can be applied. Finally we apply current processing algorithms to Sentinel-2 data of several sites over the Great Barrier Reef, including physics-based bathymetry inversion and object-orientated benthic mapping. Landsat 8 OLI is most comparable current sensor to Sentinel-2 MSI, so direct comparisons and the possibilities for data synthesis are explored.

Our findings confirm that Sentinel-2 has excellent performance for meeting several essential coral reef scientific and monitoring objectives. Taking into account cloud and sun glint, the usable acquisition rate for a large proportion of reefs is likely to be around 20 clear images a year on average, giving a new potential for evaluation of short time-scale disturbances and impacts. The spatial resolution of 10 m is a key threshold for delineating benthic features of interest such as coral structures, and there is evidence from image and field data that bleaching is detectable. Radiometrically Sentinel-2 data can support good results in physics-based methods, such as bathymetric mapping, comparable to Landsat 8 and WorldView-2. In addition the large scale acquisition area, provided by the 290 km wide swath, offers advantages over high spatial resolution imagery for mapping at multi-reef scales.

Sentinel-2 data can be immediately leveraged with existing methods, to provide a new level of reef monitoring information compared to that previously available by remote sensing. Combined with Landsat 8 and the historical Landsat archive, the data collected today will be invaluable for decades or even centuries to come. In this context, the main downside of the Sentinel-2 mission is that approximately 12% of the World's reefs currently lie outside the acquisition plan and are not imaged. Surprisingly, for a European initiative, coral reefs in

* Corresponding author.
E-mail address: j.d.hedley@numopt.com (J.D. Hedley).

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European governed territories are among the worst served globally. These omissions, approximately only 1/200th of the currently imaged area, limit the global scope which otherwise would be one of Sentinel-2's greatest strengths.

1. Introduction

Coral reefs are currently under threat worldwide from numerous environmental and anthropogenic stresses (Hoegh-Guldberg et al., 2007; Pandolfi et al., 2003), and effective management and policy formation requires monitoring across all scales from local to global. While not as detailed as in-situ surveys, remote sensing provides a valuable complementary monitoring approach, in particular at large scales (> 10's km^2) where manual surveys would be prohibitively expensive and impractical (Hedley et al., 2016). Key mapping objectives are the abundance, distribution and health of living flora and fauna, also known as the benthos, and include benthic type (e.g. coral and algae), benthic change detection and coral bleaching. These objectives require data within specific spatial and temporal ranges (Fig. 1). Geophysical parameters, such as geomorphic zonation and bathymetry, are essential inputs for the growing number of ecosystem models used in a management context (e.g. Hock et al., 2014).

Over the last forty years the number of satellite instruments available for coral reef applications has grown, starting with the early Landsat and SPOT sensors (Smith et al., 1975; Bour, 1988) and increasing rapidly in recent years with space agency platforms and commercial offerings such as the WorldView series of satellites. Sentinel-2 satellites A and B, part of the Copernicus programme headed by the European Commission in partnership with the European Space Agency (ESA), are the most recent addition, and with the Multi Spectral Imager (MSI) instrument provide a 5-day revisit, 10 m pixels in visible bands, and freely available data: specifications which cover a number of reef monitoring requirements (Fig. 1). Further, Sentinel-2 is a European mission and the physical area and biological, cultural and economic values of tropical reefs occurring in European territories are substantial. France is the fourth nation when listed by reef area, after Australia, Indonesia and the Philippines (UNEP-WCMC, 2010). The United Kingdom is 11th in the same list and has over half as many reefs as the United States. The European Union is committed to management and conservation of coral reefs through being a signatory to a number of international initiatives that specifically mention coral reefs: The United Nations Environment Assembly, The Johannesburg Declaration, Convention on Biological Diversity, and The UNESCO World Heritage Convention. In particular, a number of targets under the United Nations Sustainable Development Goal 14 (SDG 14) (oceans, seas and marine resources, https://sustainabledevelopment.un.org/sdg14) require region-scale information on the extent, health, resilience, and sustainability of coastal ecosystems, of which coral reefs are a key priority. The impetus for European initiatives such as Copernicus to put coral reefs central to their efforts is therefore unquestionable and the opportunity to leverage Sentinel-2 toward this aim is of great interest.

The current options for satellite based reef mapping are dominated by high spatial resolution multispectral instruments (pixels ≤ 5 m) and moderate resolution (pixels 10–50 m) e.g. Landsat 8 (30 m multispectral pixels). This is now changing with instruments such as Sentinel-2 and other initiatives such as the next generation of CubeSat imaging systems. While hyperspectral data is considered advantageous (Mumby et al., 1997; Hochberg and Atkinson, 2003), the drive with commercial instruments has primarily been toward very high spatial resolution multispectral data (e.g. Worldview-4, Pleiades, pixel size ≤ 2 m, Planet Labs constellation, 3–5 m). Coral reefs are highly heterogeneous at scales of a few meters or less (Fig. 1), differing benthic types such as corals, seagrasses or macroalgae typically occur at different spatial scales and so the optimal minimum spatial resolution may differ dependent on the objective and site (Phinn et al., 2010). High spatial resolution offers substantial benefits, and this kind of data is widely used for one-off or occasional reef mapping exercises at local scales (Yamano, 2013). However, the expense of commercial imagery, relative infrequency of acquisition, in particular of images clear of cloud and surface glint, make it unsuitable for systematic repeated monitoring or large scale change detection. With respect to scientific missions from space agencies, coral reefs are somewhere between a land and an ocean colour application and are not specifically prioritised, so the available satellite instruments are typically a compromise toward requirements. The Landsat series has seen some use in coral reef context: freely available data facilitates the potential for global applications such as the Millennium Coral Reef Habitat Mapping Project (Andréfouët et al., 2004) and time series analysis (Palandro et al., 2008). Landsat 8 in particular, with 12-bit digitisation and the additional blue band at 443 nm which offers high depth of penetration in clear waters (Table 1), has good capability for techniques based on radiative transfer models (Giardino et al., 2016). The 16-day revisit ensures a reasonable chance of clear acquisitions several times a year, dependent on location. Capturing a 185 km wide swath means larger areas can be processed without the challenges presented when mosaicing images acquired under different conditions. While restricted by 30 m spatial resolution Landsat 8 data benefit from being the continuation of a long term dataset stretching back to the early 1980's, a requirement for analysis of long term processes (El-Askary et al., 2014). Other short term missions with hyperspectral characteristics such as Hyperion or HICO have also been tested (Kutser et al., 2006; Garcia et al., 2014a) but without a long term mission commitment these applications remain scientific investigations. Upcoming missions such as HyspIRI or EnMAP (Devred et al., 2013; Guanter et al., 2015) may reinvigorate hyperspectral reef applications but currently the options for applied benthic mapping of coral reefs by satellite instruments remain dominated high spatial resolution commercial offerings and Landsat 8.

Sentinel 2 differs significantly to the previously discussed instruments in both spatial and temporal resolution. The spatial resolution of

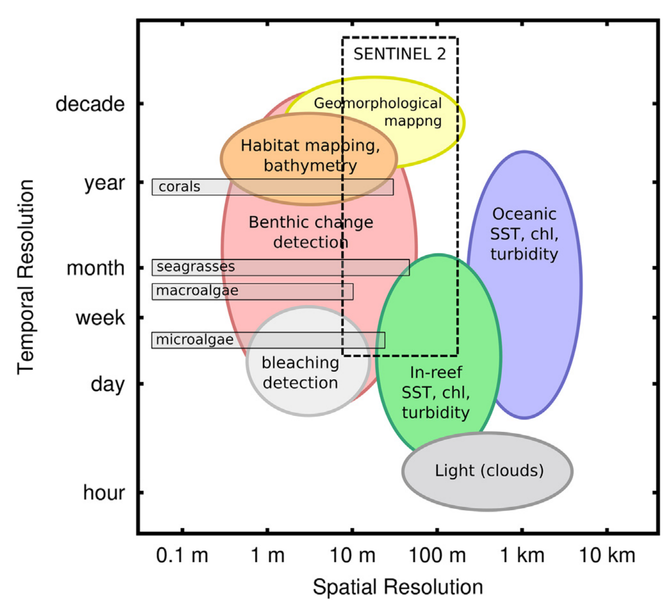

Fig. 1. The relationship between the spatial and temporal characteristics of Sentinel-2 acquisitions and the requirements for coral reef remote sensing objectives.