Coral Reefs: Living on the Edge

Eric J. Hochberg, Bermuda Institute of Ocean Sciences
Robert C. Carpenter, California State University Northridge
Steven J. Dollar, University of Hawaii at Manoa
James L. Falter, University of Western Australia
Michelle M. Gierach, Jet Propulsion Laboratory, California Institute of Technology
Robert O. Green, Jet Propulsion Laboratory, California Institute of Technology
Stuart R. Phinn, University of Queensland

1 Science and Application Target: Coral Reefs

Coral reefs are distributed throughout the world's tropical oceans (Figure 1), directly occupying an estimated area of 250,000 to 600,000 km^2 (Smith 1978; Kleypas 1997; Spalding and Grenfell 1997). These values correspond approximately to 0.05–0.15% of the global ocean area, respectively, and about 5–15% of the shallow sea areas within 0–30 m depth. Coral reefs have a global importance that is disproportionately large relative to their areal extent. They are a focus for traditional culture and provide food for innumerable small subsistence economies (White et al. 2000). They provide protection to shorelines from storm and wave damage and form barriers that provide safe passage for shipping (Moberg and Folke 1999). They are a superlative recreational resource and the foundation of a multibillion dollar tourist industry worldwide (White et al. 2000; Johns et al. 2001). Coral reefs are a major locus of global biodiversity, providing an ecological reserve of genetic complexity (Roberts et al. 2002). The high species diversity is a biological storehouse for the biotechnology industry, allowing isolation and identification of chemical substances and biochemical mechanisms (Bruckner 2002). The global economic valuation of the direct and indirect use of coral reefs has been estimated at nearly $400 billion annually (Costanza et al. 1997). While the accuracy of this dollar amount is debatable, it is certain that coral reefs are important to the cultural and economic lives of hundreds of millions of people around the world.

Reefs are among the first natural ecosystems to respond critically, dramatically, and globally to climate change (Wong et al. 2014). Already stressed by human activities at local and regional scales, the convolved influences of rising sea surface temperature and increasing ocean acidification are predicted to cause a global shift in reef benthic community structure from coral-rich to coral-poor (Figure 2; Hoegh-Guldberg et al. 2007). An estimated 33–50% of coral reefs worldwide have already been largely or completely degraded over recent decades (International Society for Reef Studies 2015), 15% are critically threatened with loss in the next 10–20 years, and another 20% are under threat of loss in the next 20–40 years (Wilkinson 2008). Surprisingly, these estimates and predictions are based on sparse observations with disparate objectives, methods, and quality. Only 10s to 100s of km^2, or 0.01–0.1% of the world's reef area, have received direct, quantitative study, as reef assessments largely rely on in-water survey techniques, which are laborious, expensive, and limited in spatial extent. Thus, the available data are insufficient for rigorous estimates of global reef status. This precludes quantitative modeling of reef-environment relationships across local, regional, and global scales (Figure 3). Global, uniform, high-density measurements and models are critical to better understand how coral reefs will respond to the environmental changes expected in the coming decades.

Remote sensing is the only feasible means to gather the required uniform, high-density measurements across vast coral reef regions (Mumby et al. 1999; Hochberg et al. 2003b). A satellite platform would be the obvious choice to develop such a dataset, but no sensors currently on orbit possess the necessary capabilities for assessment of coral reef condition. Pixel sizes are too coarse to resolve important reef features, there is insufficient ground coverage to assess global or even regional reef condition, and/or there is insufficient spectral sampling and resolution to discriminate between fundamental reef benthic cover types (Hochberg and Atkinson 2003). Targeted airborne remote sensing investigations can serve as precursors for a space mission, providing uniform, high-density data across select reef regions, which, in turn, can enable development of ecosystem-scale models linking reef condition to biogeophysical forcings (Arias-González et al. 2011). For example, the NASA Earth Venture Suborbital-2 COral Reef Airborne Laboratory (CORAL) mission will provide a one-time assessment of 3–4% of the world's reef area (~1000× more than current in situ observations). However, airborne campaigns simply cannot realistically provide the required global, repeat coverage. A satellite mission with multiple engagements of reefs worldwide can transform our understanding of reef condition and allow scientists, resource managers, and politicians to better understand how natural and anthropogenic processes impact reefs, and thus make more informed decisions toward their conservation.

The key overarching science questions:

- *What is the current condition of the world's coral reefs?*
- *How will global coral reef condition change in response to natural and anthropogenic forcing?*

Stemming from these questions, we identify several science and application objectives:

1. Measure distributions of coral, algae, and sand for reefs worldwide.
2. Examine trends of coral, algae, and sand for reefs across a range of local human impacts.
3. Determine how distributions of coral, algae, and sand vary with reef morphology, underlying geology, latitude, and oceanographic conditions (temperature, waves, light).
4. Generate map products to help regional and local monitoring, management/conservation, and scientific investigations.

These objectives are community priorities, and they address four of six principal science questions of the Carbon Cycle and Ecosystems Focus Area of NASA's Earth Science Division (*How are global ecosystems changing? How do ecosystems, land cover, and biogeochemical cycles respond to and affect global environmental change? What are the consequences of climate change and increased human activities for coastal regions? How will carbon cycle dynamics and terrestrial and marine ecosystems change in the future?).* The IPCC Fifth Assessment Report: Climate Change 2014 gives special prominence to coral reefs (Gattuso et al. 2014). The National Research Council's Decadal Survey report Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond (National Research Council 2007) recognizes that coral reefs are both valuable resources and face serious threats. The report specifically lists "health and extent of coral reefs" among the priority satellite data records and missions for land-use change, ecosystem dynamics, and biodiversity.

The science and applications targets identified here are directly linked to the Decadal Survey themes of *Marine and Terrestrial Ecosystems and Natural Resource Management* and select factors in *Climate Variability and Change: Seasonal to Centennial*. Coral reefs are a major locus of global biodiversity that provide various ecosystem goods and services. Reefs are among the first natural ecosystems to respond critically, dramatically, and globally to the combined impacts of local environmental degradation and climate change. It is well established that coral reefs are threatened or in various stages of decline, but there remains a significant gap in our understanding of how coral reef ecosystems are responding to natural (e.g., temperature, acidification, sea state, available light) and anthropogenic (e.g., coastal development, overfishing, marine pollution) forcings and how they will respond in the future. Uncertainty is due to insufficient measurements of the appropriate quantity and quality. These measurements are also required to advance quantitative modeling of reef-environment relationships across local, regional, and global scales.

2 Geophysical Variables to Be Measured to Quantify Global Coral Reef Condition

1. Benthic cover ***2. Primary production*** ***3. Calcification***

Natural, balanced coral reefs are mosaics of coral, algae, and sand. Together, these benthic types drive the structure and function of the ecosystem (Stoddart 1969; Kinsey 1985). When corals die, algae rapidly colonize their skeletons. Healthy reefs usually increase coral coverage during recovery from stress, with coral abundance often returning to the predisturbance level (Connell 1997). In contrast, algae and rubble gradually dominate degraded reefs with little or no recovery of coral. With the loss of reef-builders, the carbonate structure erodes, ultimately becoming a flat bottom with shifting rubble and sand (Figure 2). This phenomenon is called a "phase shift" in the ecosystem and represents a radical change in the character of the reef. Thus, a key geophysical variable to measure to assess the condition of a reef is ***benthic cover***: the proportional abundances of coral, algae, and sand.

Coral, algae, and sand also each exhibit distinctly different rates for the base ecosystem functions of primary production and calcification (Kinsey 1983; Kinsey 1985). Changes in the coral:algae:sand ratio can therefore result in substantial changes to ecosystem function (Odum and Odum 1955). Primary production represents the energy input that drives all biological transformations in the reef system (Odum and Odum 1955). Calcification is the net gain of biogenically derived carbonates, which determines the long-term growth of the reef structure (Kinsey 1985). Thus, rates for ***primary production*** and ***calcification*** are also important geophysical variables for understanding reef condition. Both processes are fundamental components of the carbon cycle on coral reefs.

Benthic cover can be derived directly from spectroscopic measurements due to significant differences between the spectral signatures of coral, algae, and sand (Hochberg and Atkinson 2000, 2003; Hochberg et al. 2003a; Hochberg et al. 2004). An example of benthic cover classification from the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) (Green et al. 1998) is shown in Figure 4. The information contained in spectral image data can be used to detect coral with an accuracy of 98% (Figure 5; Hochberg and Atkinson 2003). Additionally, primary production and calcification can be modeled using spectral imagery following the light-use efficiency approach described in Hochberg and Atkinson (2008).

3 Key Quality Requirements of the Measurements

<u>Temporal Requirements: Seasonal to yearly, with option for event targeting</u> — Reef benthic community structure is inherently stable on time scales of months to years (Smith and Buddemeier 1992). Barring major disturbance events, coral reef change is typically slow. Thus, it is less important to maintain a high-frequency time series for individual reefs than it is to sustain a campaign of measurements across a large, representative cross section of reefs. This type of extended, low-frequency time-series is almost entirely missing from coral reef science (except at extremely local scales, e.g., Connell et al. 1997, Moorea LTER) but is critical to

understanding reef dynamics in a changing climate. An option for targeting major disturbance events is also important. The observations must begin now, though, because many reefs are believed to already be on a trajectory of decline.

Spatial Requirements: Coverage 35°S–35°N, ground sample distance ≤60 m — The global extent of coral reefs is zonally constrained between 35°S–35°N (Figure 1). Reef community structure exhibits tremendous spatial heterogeneity over scales of centimeters to hundreds of meters. However, most reefs are only on the order of 0.5–1 km wide. Further, examination of spatial semivariance suggests that the majority of spatial heterogeneity occurs at scales less than 70–90 m (Hochberg, unpublished). This agrees with observations of reef hydrographic and ecological zonation (Stoddart 1969). The requirement for a ground sample distance ≤60 m ensures that imagery can capture/delineate important reef features, both biotic and structural.

Geophysical Variable Requirements: Discrimination of benthic cover to an accuracy of ±10% cover

Geophysical Variable Requirement	Measurement/Instrument Requirement		Driver
Discrimination of benthic cover to an accuracy of ±10% cover	Bottom Reflectance Accuracy	±5% absolute ±2% band-to-band relative	Requirements in line with National Research Council (2011) for ocean color
	VIS/NIR Spectral Range	400–1000 nm, 10–20 nm wide (see Figure 5)	Water column correction (Lee and Carder 2002); discrimination between coral, algae, and sand (Hochberg and Atkinson 2003); glint correction (Hochberg et al. 2011)
	NIR/SWIR Spectral Range	Select channels (0.865, 1.04, 1.24, 1.64, 2.25 μm)	Atmospheric correction (Gao et al. 2000; Gao et al. 2007)
	Radiometric Signal-to-Noise	See Figure 6	Detection and discrimination of dark targets
	Polarization Sensitivity	Variation ≤2%	Atmospheric correction over benthic signals
	Spectral Uniformity	Cross-track >90% IFOV mixing <10%	Atmosphere, glint, and water column correction, and benthic discrimination (National Research Council 2011)

Contiguous, 10-nm-wide wavebands over 400–700 nm provide excellent spectral discrimination between coral, algae, and sand (Figure 5; Hochberg and Atkinson 2003). Contiguous 10-nm-wide wavebands from 400-800 nm also provide an excellent band set for retrieval of shallow water bathymetry (Lee and Carder, 2002; Lee et al., 2007). A narrower range of wavebands can be used, but the results will be less accurate retrievals of seafloor optical properties that translate to misclassification of coral reef bottom-types.

Combined wavebands across both NIR and SWIR (i.e., 0.865, 1.04, 1.24, 1.64, and 2.25 μm) provide very good atmospheric correction (Gao et al. 2007). The most accurate atmospheric correction for shallow water requires SWIR wavebands. NIR wavebands can be used alone, but in complex coastal environments, significant errors can arise. These errors in VIS water-leaving radiance will cascade to errors in retrieval of seafloor optical properties that result in misclassifications of coral reef bottom-types. With wavelengths >900 nm, sun/sky glint is readily assessable and is correctable for coral reef benthic spectral signatures (Hochberg et al. 2011).

4 Affordability of the Required Measurements

This class of measurements can be achieved affordably in the decadal timeframe, due to investments in response to global terrestrial/coastal coverage missions outlined in the 2007 NRC Decadal Survey (National Research Council 2007) and NRC Landsat and Beyond report (National Research Council 2013), etc. These measurements build on a legacy of air and space instruments including airborne: AIS (Vane et al. 1984), AVIRIS (Green et al. 1998), and AVIRIS-NG (Hamlin et al. 2011); and space: NIMS (Carlson et al. 1992), VIMS (Brown et al. 2004), Deep Impact (Hampton et al. 2005), CRISM (Murchie et al. 2007), EO-1 Hyperion (Ungar et al. 2003; Middleton et al. 2013), M3 (Green et al. 2011) and MISE, the imaging spectrometer now being developed for NASA's Europa mission.

The approach described below exceeds all of the requirements including targeting critical coral impact events with spacecraft pointing.

NASA-guided engineering studies in 2014 and 2015 show that a Landsat-class VSWIR (380 to 2510 nm @ ≤10 nm sampling) (Figure 7) imaging spectrometer instrument with a 185 km swath, 30 m spatial sampling and 16 day revisit with high signal-to-noise ratio and the required spectroscopic uniformity can be implemented affordably for a three year mission with mass (98 kg), power (112 W), and volume compatible with a Pegasus class launch or ride share (Figure 8). The telescope can be scaled for higher orbits.

The key for this measurement is an optically fast spectrometer providing high SNR and a design that can accommodate the full spectral and spatial ranges (Mouroulis et al. 2014). A scalable prototype F/1.8 full VSWIR spectrometer (Van Gorp et al. 2014) with full spectral range CHROMA detector array has been developed, aligned, and is being qualified (Figure 9).

Data rate and volume challenges have been addressed by development and testing of a lossless compression algorithm for spectral measurements (Klimesh 2006; Aranki et al. 2009ab; Keymeulen et al. 2014). This algorithm is now a CCSDS standard (CCSDS 2015). With compression and the current Ka band downlink offered by KSAT and others, all terrestrial/coastal measurements can be downlinked (Figure 10).

Algorithms for calibration (Green et al. 1998) and atmospheric correction (Gao et al. 1993, 2009; Thompson et al. 2014, 2015) of large diverse data sets have been benchmarked as part of the HyspIRI preparatory (Lee et al. 2015), as well as for the AVIRIS-NG India and Greenland campaigns and elsewhere. To enhance affordability and accelerate measurement availability, there is good potential for shared launches, spacecraft, and international partnerships.

A wide swath high inclination sun synchronous affordable approach has been described. It should be noted that this approach can be tailored to work with narrower swaths and a range of swath pointing as well as implementation for lower inclination precessing orbits. The SNR in the spectral range of interest can also be optimized.

FIGURES

Figure 1. Global coral reef distribution: 9,000 reefs in the world, covering an estimated area of 500,000 km^2. Current quantitative in situ surveys cover only 10s to 100s km^2 worldwide (0.01-0.1% of the world's reef area).

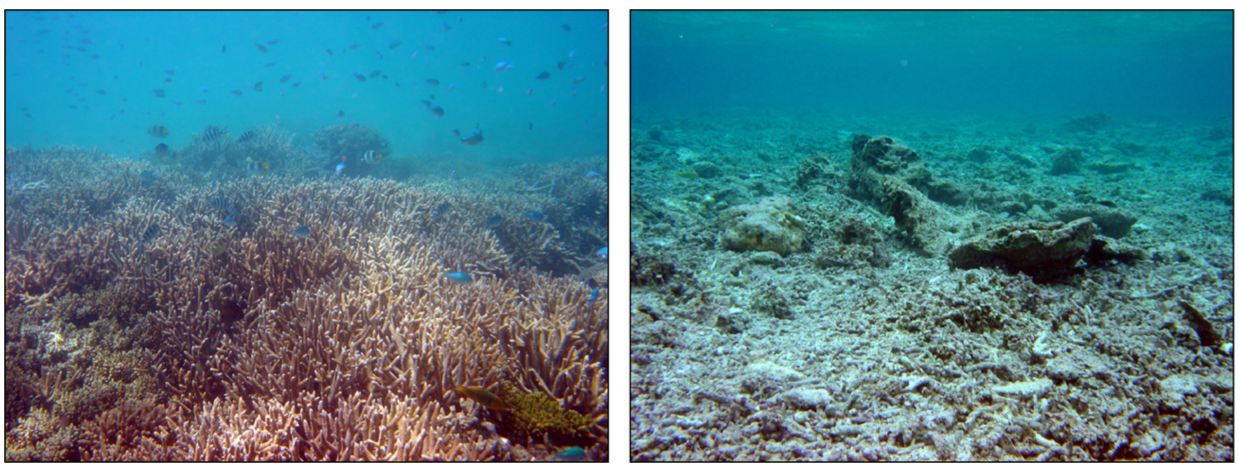

Figure 2. The coral reef problem: combined local and global impacts are predicted to cause a global shift in reef benthic community structure from coral-rich (left) to coral-poor (right). This would severely diminish the ecosystem services and economic value provided by reefs.

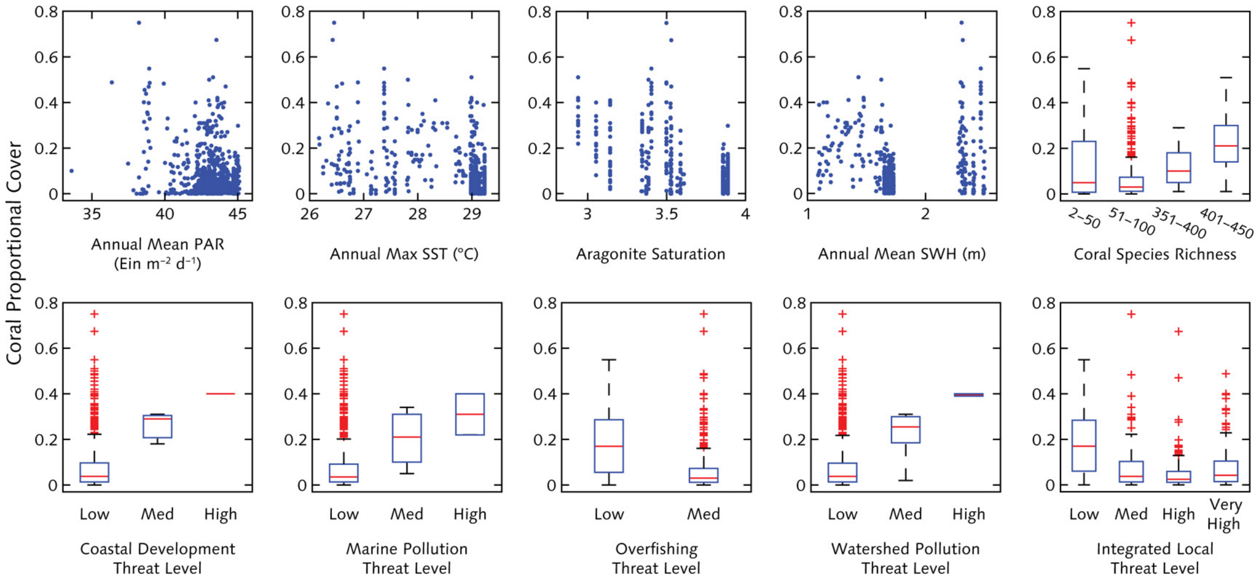

Figure 3. Existing survey data (US Caribbean, Hawaii, Great Barrier Reef) do not follow expected trends with respect to environmental factors. For example, coral cover should *increase* with aragonite saturation and *decrease* with marine pollution. Either our understanding of reefs is incorrect, or our data are inadequate (low density, mismatched scales), or maybe both.

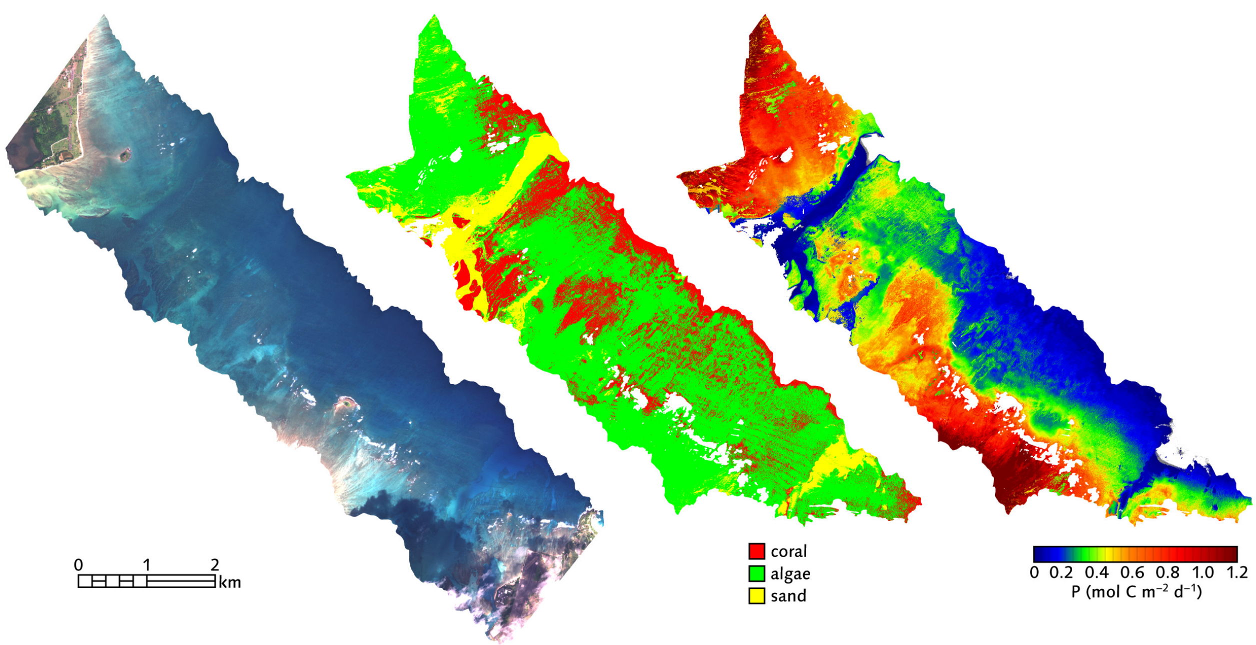

Figure 4. Benthic cover and primary production maps from the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) in Kaneohe, Hawaii. Imaging spectrometers record the intensity of wavelengths for each pixel in the scene. The spectral signature is then used to identity reef composition (coral, algae, sand) and model primary production.

Table 1
Classification error matrices for in situ spectral reflectances of three coral reef classes: coral, algae, and carbonate sand

(A) Full-resolution: overall accuracy = 98%

		Actual class		
		Algae	Coral	Sand
Predicted class	Algae	2726 (99.2)	75 (3.3)	1 (0.3)
	Coral	23 (0.8)	2168 (96.6)	0 (0.0)
	Sand	0 (0.0)	1 (0.0)	320 (99.7)

(C) AVIRIS: overall accuracy = 98%

		Actual class		
		Algae	Coral	Sand
Predicted class	Algae	2725 (99.1)	74 (3.3)	1 (0.3)
	Coral	24 (0.9)	2170 (96.7)	0 (0.0)
	Sand	0 (0.0)	0 (0.0)	320 (99.7)

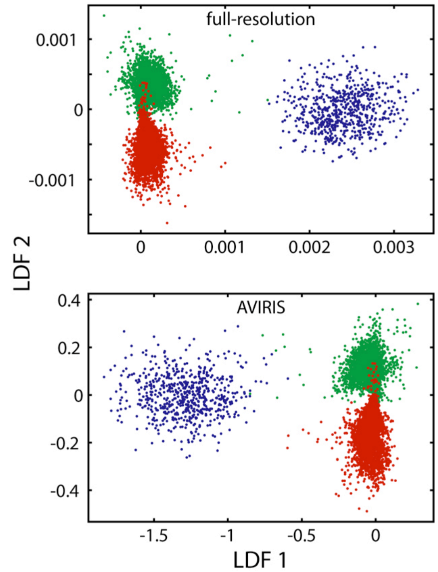

Figure 5. (left) Classification error matrices for in situ spectral reflectances of the three bottom-types. (right) Linear discriminant function (LDF) scores for full resolution (1nm spectral sampling) and AVIRIS resolution (10nm spectral sampling). Discriminant functions project the multivariate spectra onto the plane that best describes the separation between coral (red), algae (green), and sand (blue). To see additional error matrices and LDF scores for other instruments with coarser spectral sampling see Hochberg and Atkinson (2003).

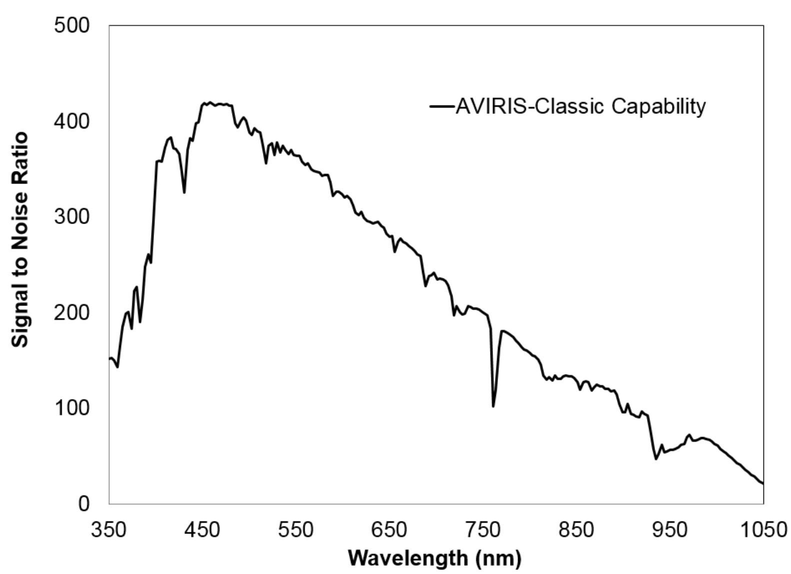

Figure 6. The baseline Signal-to-Noise Ratio (SNR) performance for benthic composition reflectance is set based on performance AVIRIS-Classic imaging spectrometer that has demonstrated the capability.

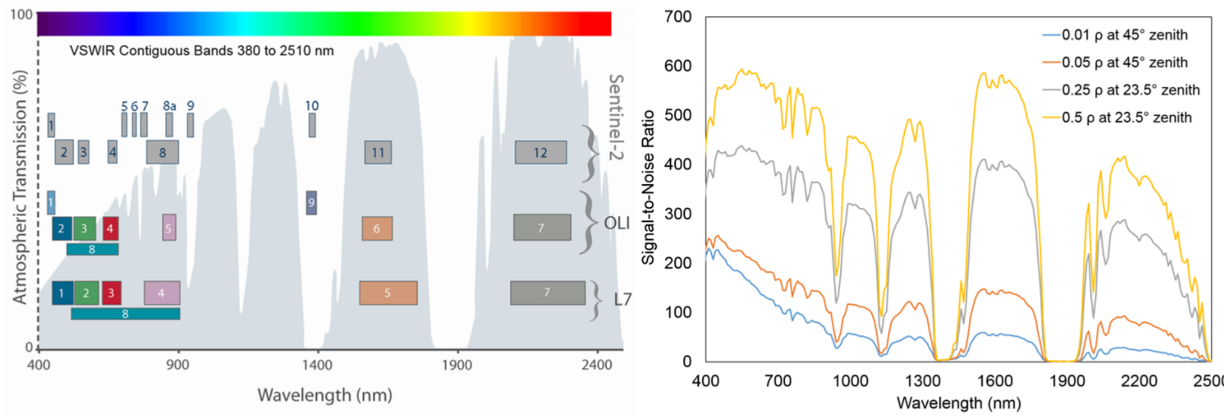

Figure 7. (left) Contiguous spectral coverage from 380 to 2510 nm of the F/1.8 VSWIR Dyson showing overlap with Landsat and Sentinal-2 bands. (right) Signal-to-noise ratio for 30 m sampling with F/1.8 VSWIR Dyson imaging spectrometer. If required, the measurement SNR can be enhanced with spectral and/or spatial averaging (e.g. convolution to multi-spectral bands).

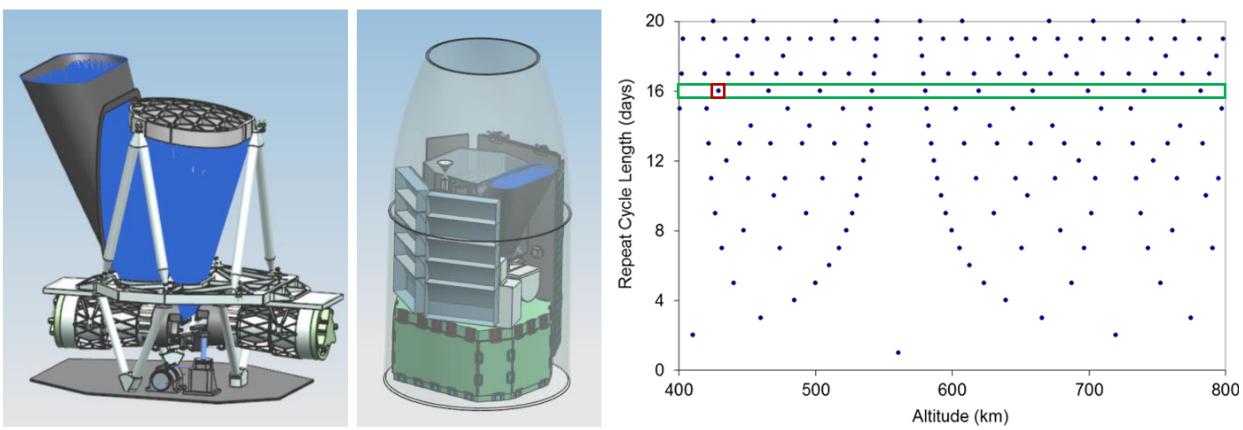

Figure 8. (left) Opto-mechanical configuration for a high SNR F/1.8 VSWIR imaging spectrometer system providing 185 km swath and 30 m sampling. (center) Imaging spectrometer with spacecraft configured for launch in a Pegasus shroud for an orbit of 429 km altitude, 97.14 inclination to provide 16 day revisit for three years. (right) Orbital altitude and repeat options. An altitude of 429 km with a fueled spacecraft supports the three-year mission with the affordable Pegasus launch. Higher orbits require a larger launch vehicle.

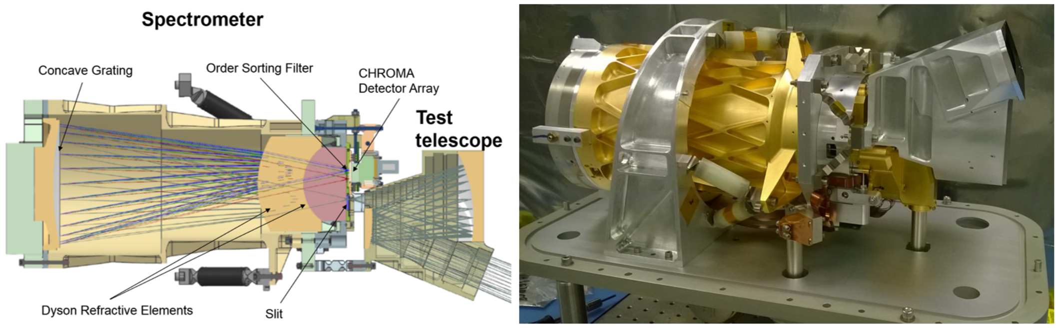

Figure 9. Design of F/1.8 VSWIR Dyson covering the spectral range from 380 to 2510. (right) Developed, aligned and qualified Dyson with CHROMA full range VSWIR detector array.

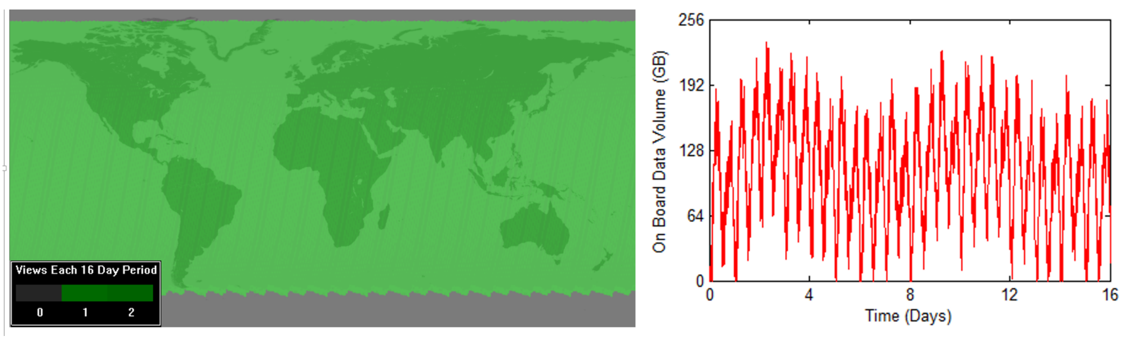

Figure 10. (left) Global illuminated surface coverage every 16 days. (right) On-board data storage usage for illuminated terrestrial/coastal regions with downlink using Ka Band to KSAT Svalbard and Troll stations. Oceans and ice sheets can be spatially averaged for downlink.

REFERENCES

Aranki N, Bakhshi A, Keymeulen D, Klimesh M (2009a) Fast and adaptive lossless on-board hyperspectral data compression system for space applications. 2009 IEEE Aerospace Conference:1-8

Aranki N, Keymeulen D, Bakhshi A, Klimesh M (2009b) Hardware implementation of lossless adaptive and scalable hyperspectral data compression for space. 2009 NASA/ESA Conference on Adaptive Hardware and Systems:315-322

Arias-González JE, Johnson C, Seymour RM, Perez P, Aliño P (2011) Scaling up models of the dynamics of coral reef ecosystems: An approach for science-based management of global change Coral Reefs: An Ecosystem in Transition. Springer, pp373–388

Brown R, Baines K, Bellucci G, Bibring J-P, Buratti B, Capaccioni F, Cerroni P, Clark R, Coradini A, Cruikshank D (2004) The Cassini visual and infrared mapping spectrometer (VIMS) investigation. The Cassini-Huygens Mission. Springer, pp. 111-168

Bruckner AW (2002) Life-saving products from coral reefs. Issues Sci Technol 18:39–44

Carlson R, Weissman P, Smythe W, Mahoney J (1992) Near-infrared mapping spectrometer experiment on Galileo. Space Science Reviews 60:457-502

Connell J, Hughes T, Wallace C (1997) A 30-year study of coral abundance, recruitment, and disturbance at several scales in space and time. Ecological Monographs 67:461-488

Costanza R, d'Arge R, De Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'neill RV, Paruelo J (1997) The value of the world's ecosystem services and natural capital. Nature 387:253-260

Gao BC, Heidebrecht KB, Goetz AF (1993) Derivation of scaled surface reflectances from AVIRIS data. Remote Sens Environ 44:165-178

Gao BC, Montes MJ, Davis CO, Goetz AF (2009) Atmospheric correction algorithms for hyperspectral remote sensing data of land and ocean. Remote Sens Environ 113:S17-S24

Gao BC, Montes MJ, Ahmad Z, Davis CO (2000) Atmospheric correction algorithm for hyperspectral remote sensing of ocean color from space. Appl Optics 39:887-896

Gao BC, Montes MJ, Li RR, Dierssen HM, Davis CO (2007) An atmospheric correction algorithm for remote sensing of bright coastal waters using MODIS land and ocean channels in the solar spectral region. IEEE Trans Geosci Remote Sens 45:1835-1843

Gatusso JP, Hoegh-Guldberg O, Pörtner HO (2014) Cross-chapter box on coral reefs. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL (eds) Climate Change 2014: Impacts, Adaptation, and Vulnerability Part A: Global and Sectoral Aspects Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp97-100

Green RO, Eastwood ML, Sarture CM, Chrien TG, Aronsson M, Chippendale BJ, Faust JA, Pavri BE, Chovit CJ, Solis M (1998) Imaging spectroscopy and the airborne visible/infrared imaging spectrometer (AVIRIS). Remote Sens Environ 65:227-248

Green R, Pieters C, Mouroulis P, Eastwood M, Boardman J, Glavich T, Isaacson P, Annadurai M, Besse S, Barr D (2011) The Moon Mineralogy Mapper (M3) imaging spectrometer for lunar science: Instrument description, calibration, on - orbit measurements, science data calibration and on - orbit validation. Journal of Geophysical Research: Planets 116

Hamlin L, Green R, Mouroulis P, Eastwood M, Wilson D, Dudik M, Paine C (2011) Imaging spectrometer science measurements for terrestrial ecology: AVIRIS and new developments. Aerospace Conference, 2011 IEEE:1-7

Hampton DL, Baer JW, Huisjen MA, Varner CC, Delamere A, Wellnitz DD, A'Hearn MF, Klaasen KP (2005) An overview of the instrument suite for the Deep Impact mission. Space Science Reviews 117:43-93

Hochberg, EJ, Atkinson MJ (2000) Spectral discrimination of coral reef benthic communities. Coral Reefs 19:164-171

Hochberg EJ, Atkinson MJ (2003) Capabilities of remote sensors to classify coral, algae and sand as pure and mixed spectra. Remote Sens Environ 85:174–189

Hochberg EJ, Atkinson MJ (2008) Coral reef benthic productivity based on optical absorptance and light-use efficiency. Coral Reefs 27:49-59

Hochberg EJ, Andréfouët S, Tyler MR (2003a) Sea surface correction of high spatial resolution Ikonos images to improve bottom mapping in near-shore environments. IEEE Trans Geosci Remote Sens 41:1724–1729

Hochberg EJ, Atkinson MJ, Andréfouët S (2003b) Spectral reflectance of coral reef bottom-types worldwide and implications for coral reef remote sensing. Remote Sens Environ 85:159–173.

Hochberg EJ, Atkinson MJ, Apprill A, Andréfouët S (2004) Spectral reflectance of coral. Coral reefs 23:84-95

Hochberg E, Bruce C, Green R, Oaida B, Muller-Karger F, Mobley C, Park Y, Goodman J, Knox R, Middleton E, Turpie K, Ungar SG, Minnett P, Gentemann C, Zimmerman RC, Turner W, Gao B-C (2011) HyspIRI sun glint report. JPL Publ 11 4 [https://hyspiri.jpl.nasa.gov/downloads/2011_Sunglint_Report/2011_HyspIRI_Sunglint_Report_11-4.pdf]

Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P, Gomez E, Harvell CD, Sale PF, Edwards AJ, Caldeira K, Knowlton N, Eakin CM, Iglesias-Prieto R, Muthiga N, Bradbury RH, Dubi A, Hatziolos ME (2007) Coral reefs under rapid climate change and ocean acidification. Science 318:1737-1742

International Society for Reef Studies (2015) Consensus Statement on Climate Change and Coral Bleaching, 21st Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change. [http://reefcheck.org/PDFs/ISRSConsensus2015.pdf]

IPCC (2007) Cross-chapter case study. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate Change 2007: Impacts, Adaptation and Vulnerability Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, 843–868

Johns GM, Leeworthy VR, Bell FW, Bonn MA (2001) Socioeconomic study of reefs in Southeast Florida: Final report:348 pp.

Keymeulen D, Aranki N, Bakhshi A, Luong H, Sarture C, Dolman D (2014) Airborne demonstration of FPGA implementation of Fast Lossless hyperspectral data compression system. 2014 NASA/ESA Conference on Adaptive Hardware and Systems (AHS):278-284

Kinsey DW (1983) Standards of performance in coral reef primary production and carbon turnover. Perspectives on coral reefs Brian Clouston Publisher, Manuka, Australia:209-220

Kinsey DW (1985) Metabolism, calcification and carbon production I: Systems level studies. Fifth International Coral Reef Congress 4:505-526

Kleypas JA (1997) Modeled estimates of global reef habitat and carbonate production since the last glacial maximum. Paleoceanography 12:533-545

Klimesh M (2006) Low-complexity adaptive lossless compression of hyperspectral imagery. Proceedings of SPIE, the International Society for Optical Engineering:63000N-1

Lee ZP, Carder KL (2002) Effect of spectral band numbers on the retrieval of water column and bottom properties from ocean color data. Appl Optics 41:2191-2201

Lee ZP, Casey B, Arnone R, Weidemann A, Parsons R, Montes MJ, Gao BC, Goode W, Davis CO, Dye J (2007) Water and bottom properties of a coastal environment derived from Hyperion data measured from the EO-1 spacecraft platform. Journal of Applied Remote Sensing 1:DOI: 10.1117/1111.2822610

Lee CM, Cable ML, Hook SJ, Green RO, Ustin SL, Mandl DJ, Middleton EM (2015) An introduction to the NASA Hyperspectral InfraRed Imager (HyspIRI) mission and preparatory activities. Remote Sens Environ 167:6-19

Middleton EM, Ungar SG, Mandl DJ, Ong L, Frye SW, Campbell PE, Landis DR, Young JP, Pollack NH (2013) The earth observing one (EO-1) satellite mission: Over a decade in space. Selected Topics in Applied Earth Observations and Remote Sensing, IEEE Journal of 6:243-256

Moberg F, Folke C (1999) Ecological goods and services of coral reef ecosystems. Ecological Economics 29:215–233.

Mouroulis P, Van Gorp B, Green RO, Dierssen H, Wilson DW, Eastwood M, Boardman J, Gao B-C, Cohen D, Franklin B, Loya F, Lundeen S, Mazer A, McCubbin I, Randall D, Richardson B, Rodriguez JI, Sarture C, Urquiza E, Vargas R, White V, Yee K (2014) Portable Remote Imaging Spectrometer coastal ocean sensor: design, characteristics, and first flight results. Appl Optics 53:1363-1380

Mumby PJ, Green EP, Edwards AJ, Clark CD (1999) The cost-effectiveness of remote sensing for tropical coastal resources assessment and management. J Environ Manage 55:157–166.

Murchie S, Arvidson R, Bedini P, Beisser K, Bibring JP, Bishop J, Boldt J, Cavender P, Choo T, Clancy R (2007) Compact reconnaissance imaging spectrometer for Mars (CRISM) on Mars reconnaissance orbiter (MRO). Journal of Geophysical Research: Planets 112

National Research Council (2007) Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond. The National Academies Press, Washington, D.C.

National Research Council (2011) Assessing the Requirements for Sustained Ocean Color Research and Operations. The National Academies Press, Washington, DC

National Research Council (2013) Landsat and Beyond: Sustaining and Enhancing the Nation's Land Imaging Program. The National Academies Press, Washington, DC

Odum HT, Odum EP (1955) Trophic structure and productivity of a windward reef community on Eniwetok Atoll. Ecological Monographs 25:291-320

Roberts CM, McClean CJ, Veron JEN, Hawkins JP, Allen GR, McAllister DE, Mittermeier CG, Schueler FW, Spalding M, Wells F, Vynne C, Werner TB (2002) Marine biodiversity hotspots and conservation priorities for tropical reefs. Science 295:1280–1284

Smith SV (1978) Coral-reef area and contributions of reefs to processes and resources of the world's oceans. Nature 273:225-226

Smith SV, Buddemeier RW (1992) Global change and coral reef ecosystems. Annu Rev Ecol Syst 23:89-118

Spalding MD, Grenfell AM (1997) New estimates of global and regional coral reef areas. Coral Reefs 16:225-230

Stoddart DR (1969) Ecology and morphology of recent coral reefs. Biol Rev Camb Philos Soc 44:433-498

Thompson DR, Green RO, Keymeulen D, Lundeen SK, Mouradi Y, Nunes DC, Castano R, Chien SA (2014) Rapid spectral cloud screening onboard aircraft and spacecraft. IEEE Trans Geosci Remote Sens 52:6779-6792

Thompson DR, Gao B-C, Green RO, Roberts DA, Dennison PE, Lundeen SR (2015) Atmospheric correction for global mapping spectroscopy: ATREM advances for the HyspIRI preparatory campaign. Remote Sens Environ 167:64-77

Ungar SG, Pearlman JS, Mendenhall JA, Reuter D (2003) Overview of the Earth Observing One (EO-1) mission. IEEE Trans Geosci Remote Sens 41:1149-1159

Vane G, Goetz AF, Wellman JB (1984) Airborne imaging spectrometer: A new tool for remote sensing. IEEE Trans Geosci Remote Sens:546-549

Van Gorp B, Mouroulis P, Wilson D, Green R (2014) Design of the compact wide swath imaging spectrometer (CWIS). SPIE Optical Engineering+Applications:92220C-92220C

White A, Vogt H, Arin T (2000) Philippine coral reefs under threat: The economic losses caused by reef destruction. Mar Pollut Bull 40:598–605.

Wilkinson CR (ed) (2008) Status of Coral Reefs of the World: 2008. Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre, Townsville, Australia.

Wong PP, Losada IJ, Gattuso JP, Hinkel J, Khattabi A, McInnes KL, Saito Y, Sallenger A (2014) Coastal systems and low-lying areas. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL (eds) Climate Change 2014: Impacts, Adaptation, and Vulnerability Part A: Global and Sectoral Aspects Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp361-409