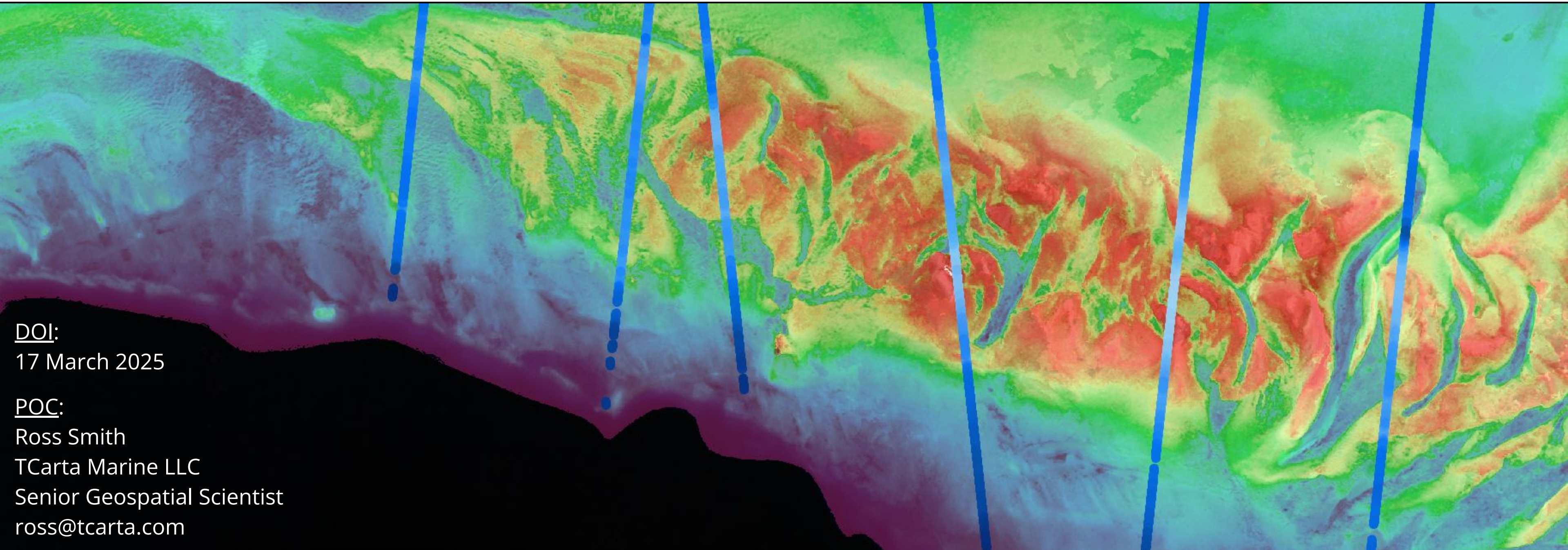
Principles of Space-Based Bathymetry

Concepts, Capabilities, Limitations, and Methods



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POC:
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Agenda:

- Background/Introduction
- Methodologies
- Sensors
- Capabilities and Limitations
- Conditions & Considerations
- Role of ICESat-2

Introduction: Relevant Experience

Organizational Background:

- **TCarta** is a **Hydrospatial** & Marine **Remote Sensing** company, located in Denver, CO, USA
- Under the **ICESat-2 Early Adopter & Applied Users Programs** and **NSF SBIR grant** (2019-2021), we have worked to expand the **coastal bathymetry** applications of ICESat-2 since Fall, 2018

My Background:

- 13-year geospatial career began as a US Army Infantryman and Company Intelligence Support Team (CoIST) leader, conducting kinetic operations, intelligence preparation of the battlefield and sensitive site exploitation
- At TCarta, focus on development of innovative **marine remote-sensing technologies** and **hydrospatial data processing** utilities, in addition to providing capacity building training to hydrographic offices and academic institutions.

ICESat-2 Early Adopter/Applied Users Program (2019-Present)

SBIR Phase 1 & 2 (2018-2022)

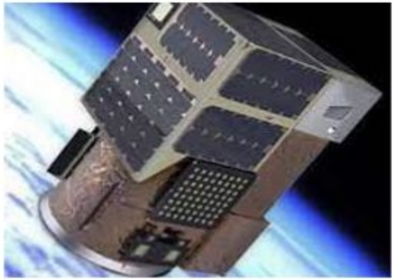
SBIR Phase 1 & 2 (2018-2022)

SBIR Phase 1 (2024 - 2025)

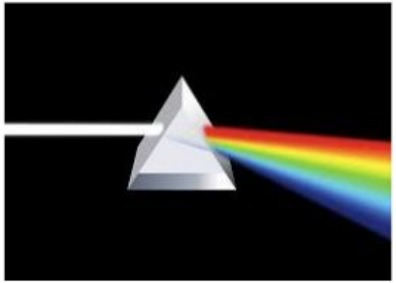
Tech Accelerator Cohort 3 (2022)

Introduction: Marine Remote Sensing; A Multidisciplinary Domain

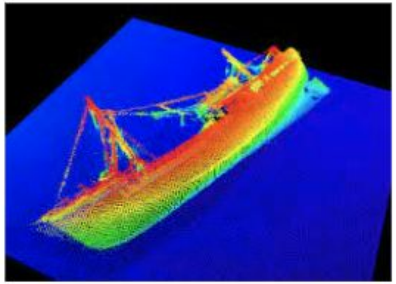
Remote Sensing



Physics



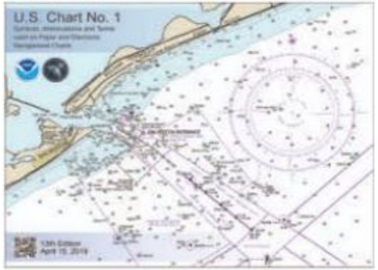
Hydrography



Geospatial Programming

Oceanography

Nautical Charting

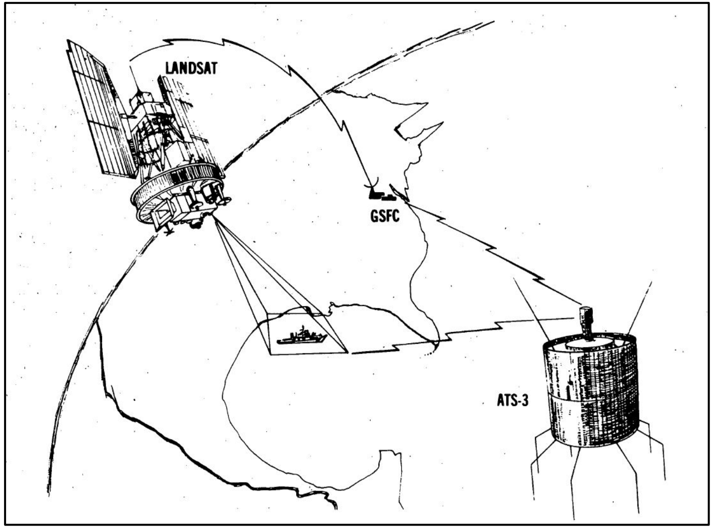


Introduction: History of Satellite-Derived Bathymetry

In 1975, NASA & Jacques Cousteau calculated bathymetry to a depth of 22m in the Bahamas using Landsat 1.

- Cousteau and dive teams collected water column characteristics, seafloor reflectivity, atmospheric conditions and other relevant in-situ measurements, coinciding with the Landsat-1 multispectral imagery collection.

- The in-situ data and Landsat 1 imagery was used to estimate depth using a radiative transfer model over the study area.



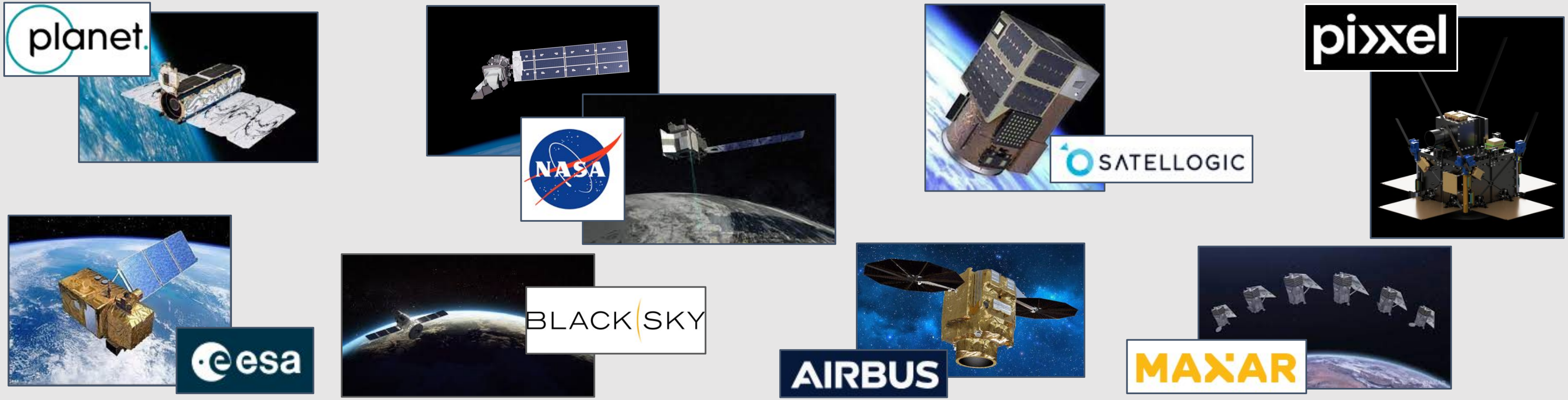
Introduction: Broad Methodologies

*Commonly referred to as “Satellite-Derived Bathymetry” or “SDB”

Modality:	Radar Altimetry (Active)	Bottom Reflectance (Passive)*	Wave Kinematic (Passive or Active)	Laser Altimetry (Active)	Space-based Photogrammetry (Passive)
Basic Concept:	Leverages variation of sea-surface topography to infer bathymetry	Reflectance of the seafloor, and concept of light attenuation through water used to derived depth	Changes in speed, direction, and distance between gravity waves used to infer depth	Space-based active sensor(s) used to derive depth based on point altimetry measurements	Leverages multiple, imbricate passive EO images in order to derive depth via stereo-photogrammetry
Benefits/Detractors/Considerations:	Generally coarse resolution, mostly delineates large features such as seamounts, but capable of resolving depths far past optical methods	Predominantly utilized methodology, requires generally clear, presence of optically shallow waters, significant availability of source data	Capable of deriving depths in highly turbid waters, but usually computationally expensive, and constrained to areas with specific wave conditions.	Significant capability to derive accurate point measurements, but limited operational sensors and relatively slow revisit time, compared to passive sensors	Can produce accurate bathymetry across variable benthic types, but requires multiple, overlapping, high-resolution images. Quality is dependent on sensor/collection geometry

Marine Remote Sensing: Commonly Utilized Sensors

Multispectral | Hyperspectral | Space-Based LiDAR

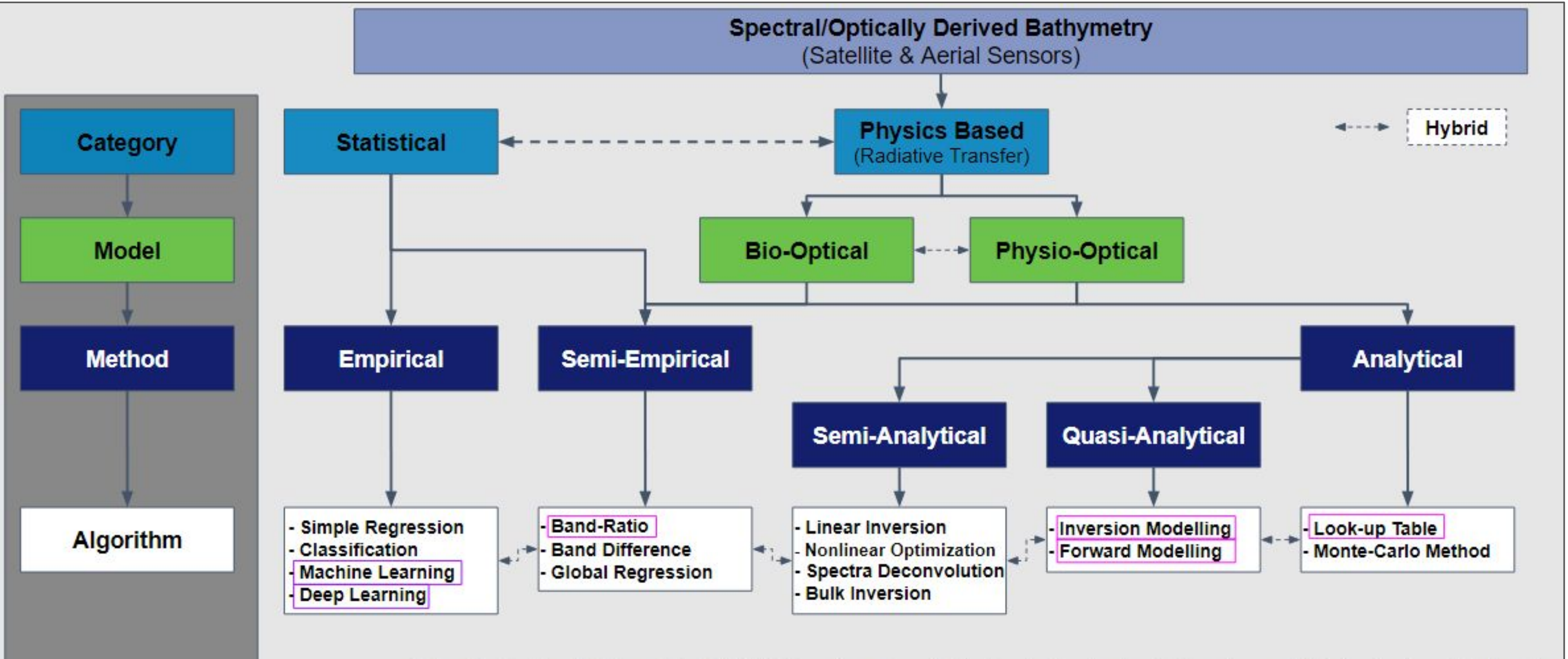


Aerial Platforms

UAV / Drone Sensors

Space-Based Sensors

Satellite-Derived Bathymetry: Methods & Algorithms



Ashphaq, M., Srivastava, P. K., & Mitra, D. (2021). Review of near-shore satellite derived bathymetry: Classification and account of five decades of coastal bathymetry research. Journal of Ocean Engineering and Science, 6(4), 340–359. https://doi.org/10.1016/j.joes.2021.02.006

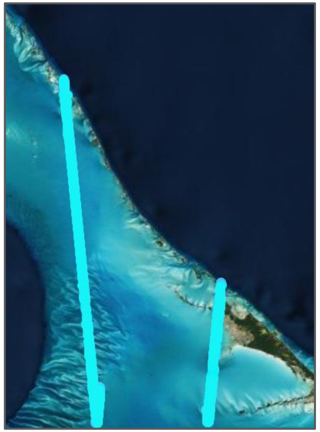
Satellite-Derived Bathymetry: Basic “Ingredients”

Satellite Derived Bathymetry (SDB): exploits the inherent relationship between light attenuation through water and benthic reflectance to derive depth. The same core concepts can be applied to multispectral imagery collected using UAV & Aerial platforms

Image Pre-processing

(Image selection, atmospheric correction, glint correction, etc)

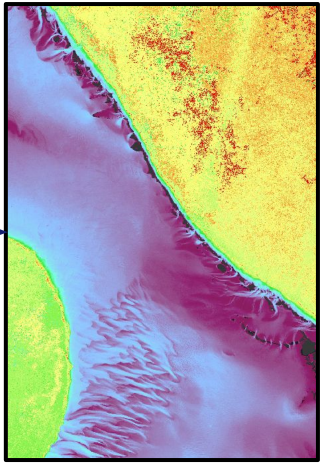
Satellite Imagery



In-situ depths*

SDB Algorithm

- Band-ratio
- Machine Learning
- Radiative Transfer
- Other



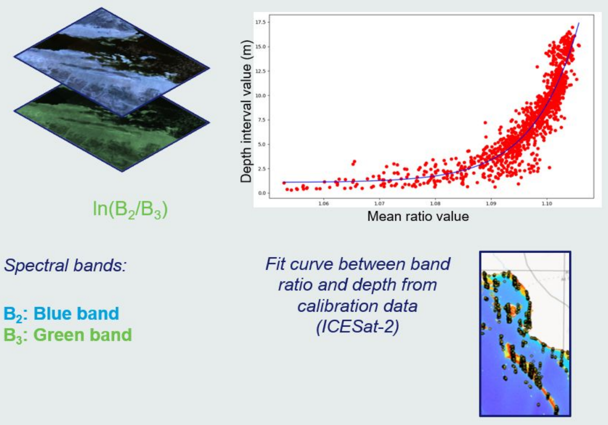
SDB

Post- Processing

(Shallow water delineation, uncertainty quantification, outlier mitigation)

Satellite-Derived Bathymetry: Comparison of Common Methods

Band Ratio Method

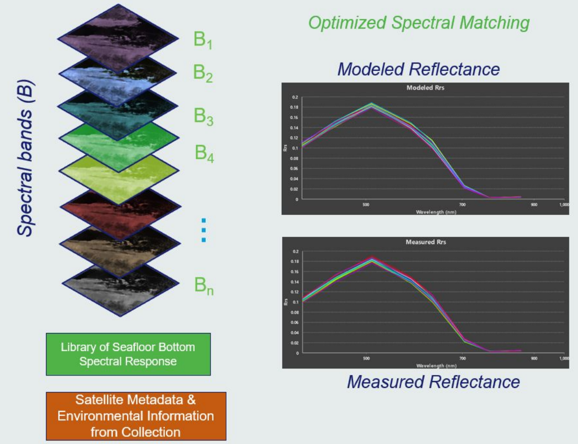


√ Simple, fast, repeatable processing

√ Able to extrapolate outside of in situ range

X Assumes uniform water column characteristics and seafloor reflectance

Radiative Transfer Model

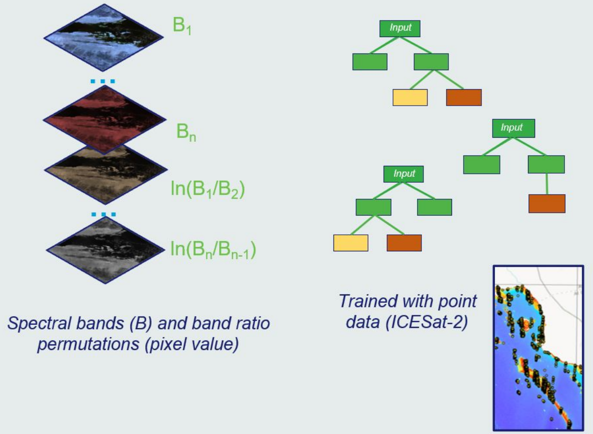


√ Capable of resolving depths without in situ

√ Scientifically robust solution

X High accuracies typically achieved through finite parameterization of *a priori*

Random Forest Model



√ Ensemble-learning trained with in situ; leverages multiple bands to resolve dark objects

√/**X** Good results with proper parameters; bad with bad

X No extrapolation outside outside in situ range

Satellite-Derived Bathymetry: Value/Limitations/Capabilities

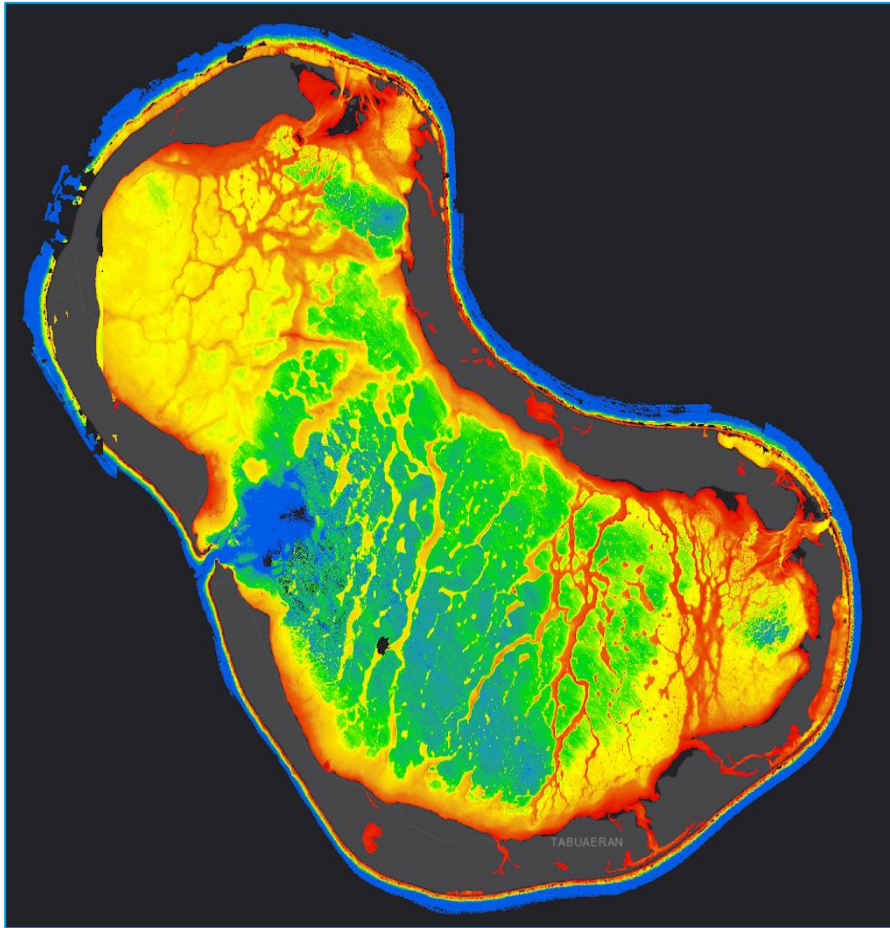
Value of SDB:

- No mobilization of equipment or personnel
- Reduced risk to environment
- Highly Repeatable
- Highly Scalable to survey broad areas
- Fraction of cost of airborne survey

Capabilities/Limitations:

- Capable of deriving depths up to 30 meters in ideal conditions, variable/limited depths in turbid waters

- Generally requires benthic reflectance present in source imagery, occlusion of the seafloor due to various factors such as turbidity, specular reflection, clouds, and anthropogenic activity limit viability.



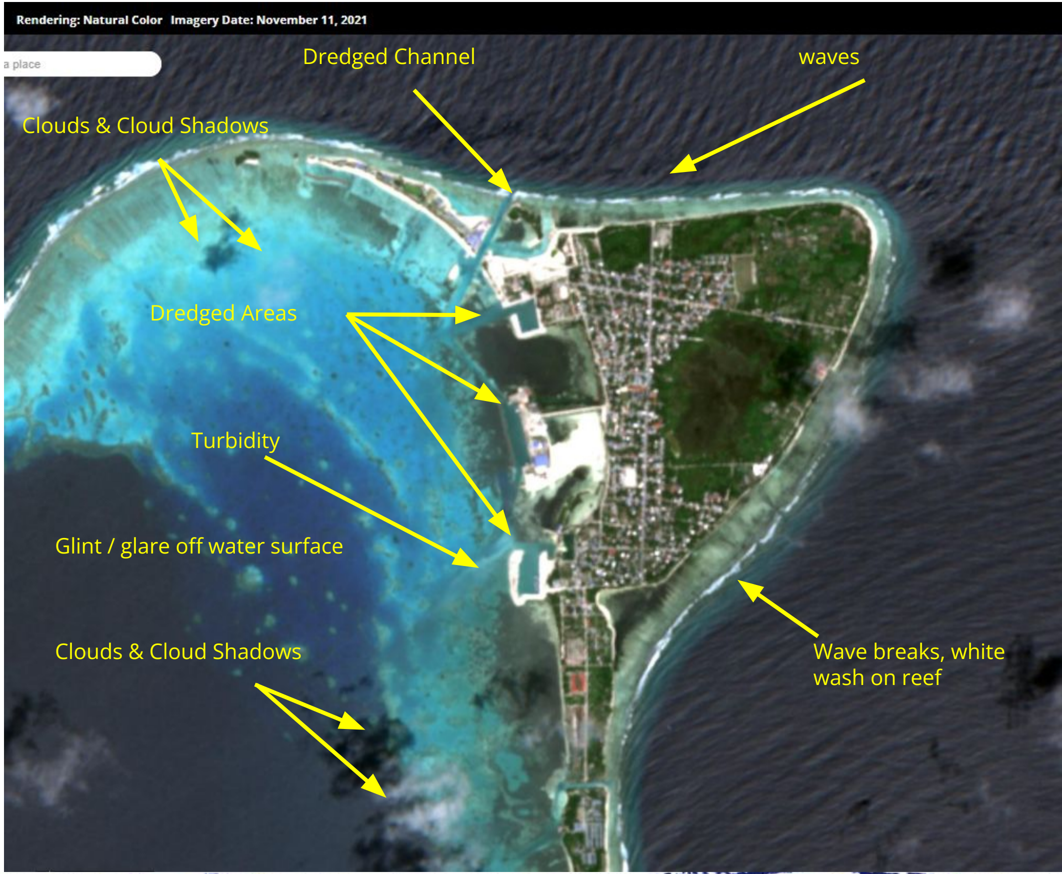
Satellite-Derived Bathymetry: Environmental Factors

Positive Environmental Factors:

Clear, calm water within atoll: no river discharge; generally cloud-free

Negative Environmental Factors:

Equatorial Solar glare / glint; Wave action on outer reef edge; clouds & shadows; turbidity in channels

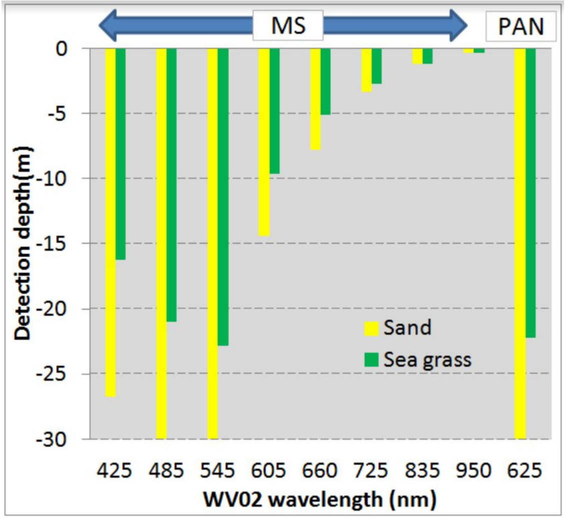


Satellite-Derived Bathymetry: Sensor Radiometric Resolution

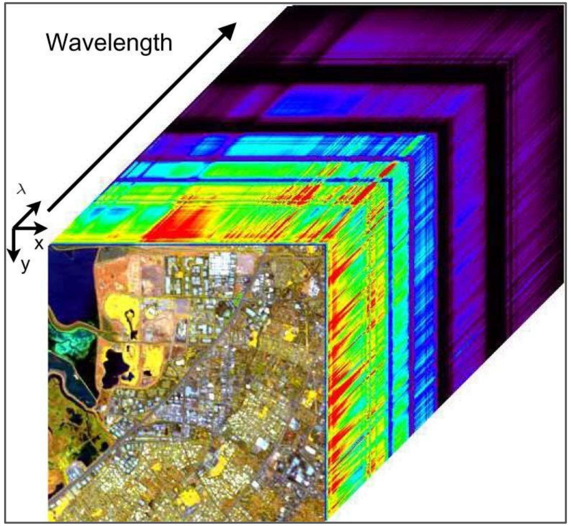
Multispectral

- "Coastal" Blue (~430nm)
- Blue (~485nm)
- Green (~550nm)
- Yellow (~560nm)
- Red (~650nm)
- Red Edge (~725nm)
- NIR (~850nm)
- SWIR (~2250nm)

Blue + Green → Minimum



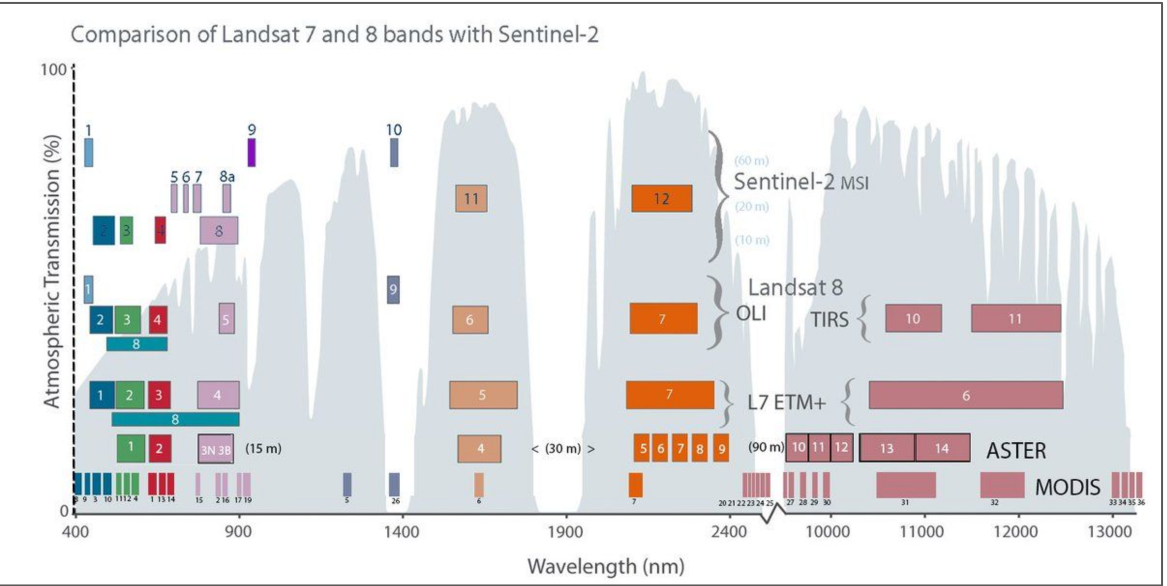
Hyperspectral

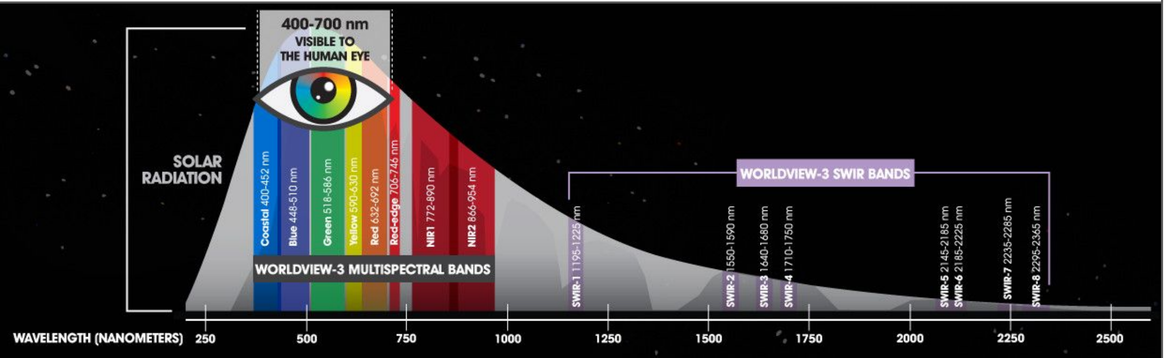


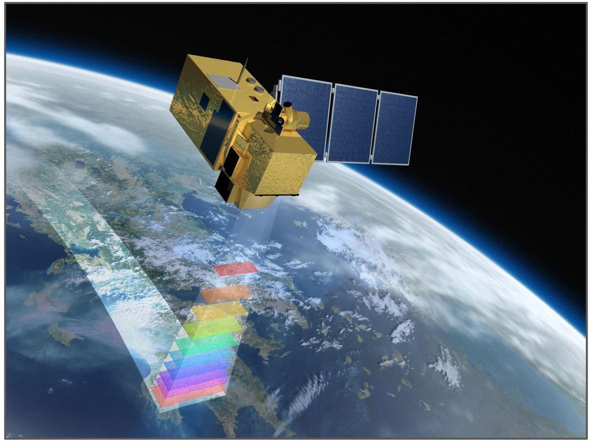
*Non-visible bands are primarily used for delineation & mitigation of detractive high-reflectance features such as land/vessels/clouds

Type	# of bands	Bandwidth (FWHM)	Wavelength Range
RGB	3	~ 50-70 nm	Red (700-635 nm) Green (560-520 nm) Blue (450-500 nm)
Multispectral	5-20	~ 15-35 nm	Visible + Infrared
Hyperspectral	100+	< 10 nm	400-2500 nm

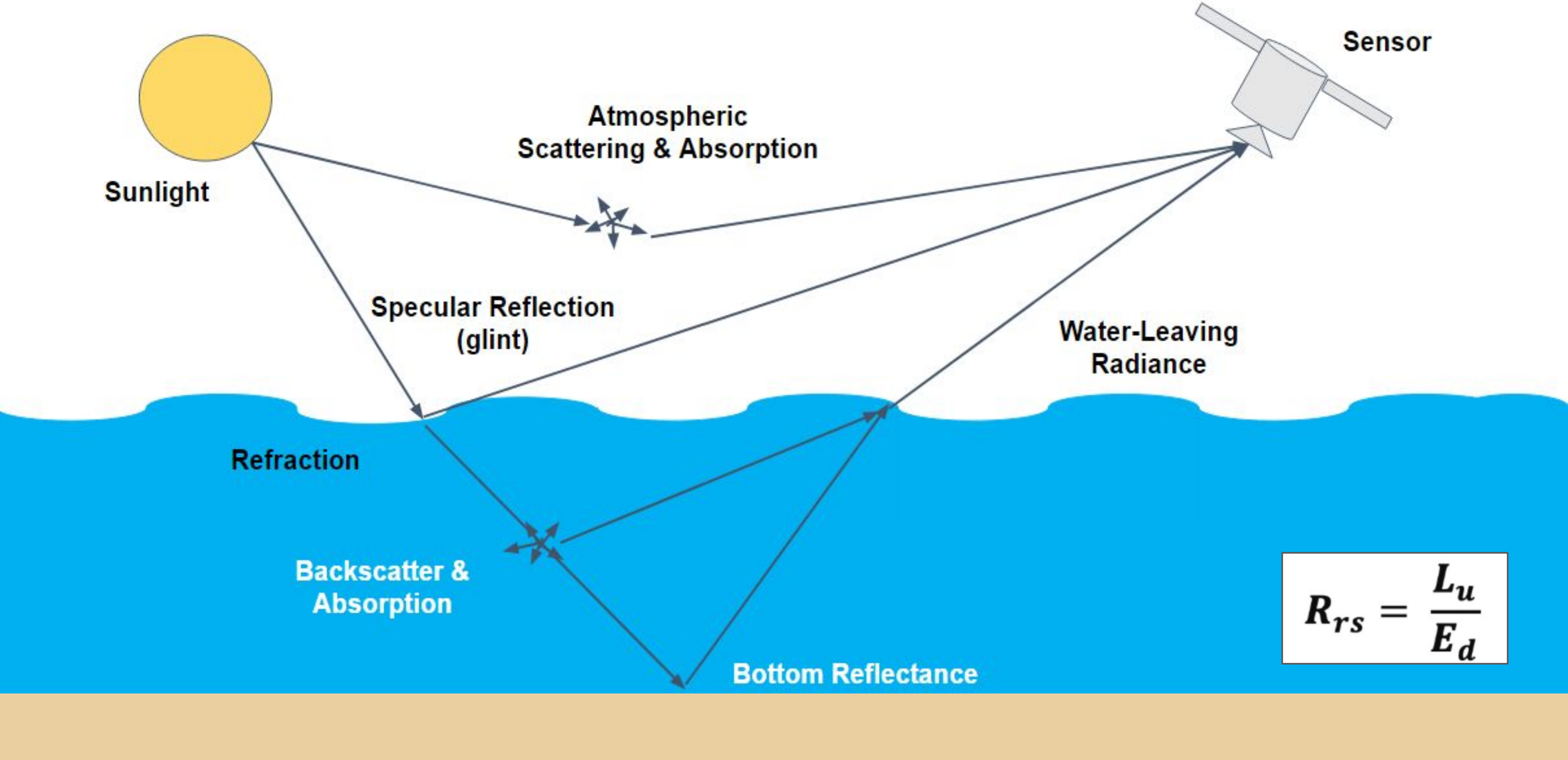
Satellite-Derived Bathymetry: Sensor Radiometric Resolution



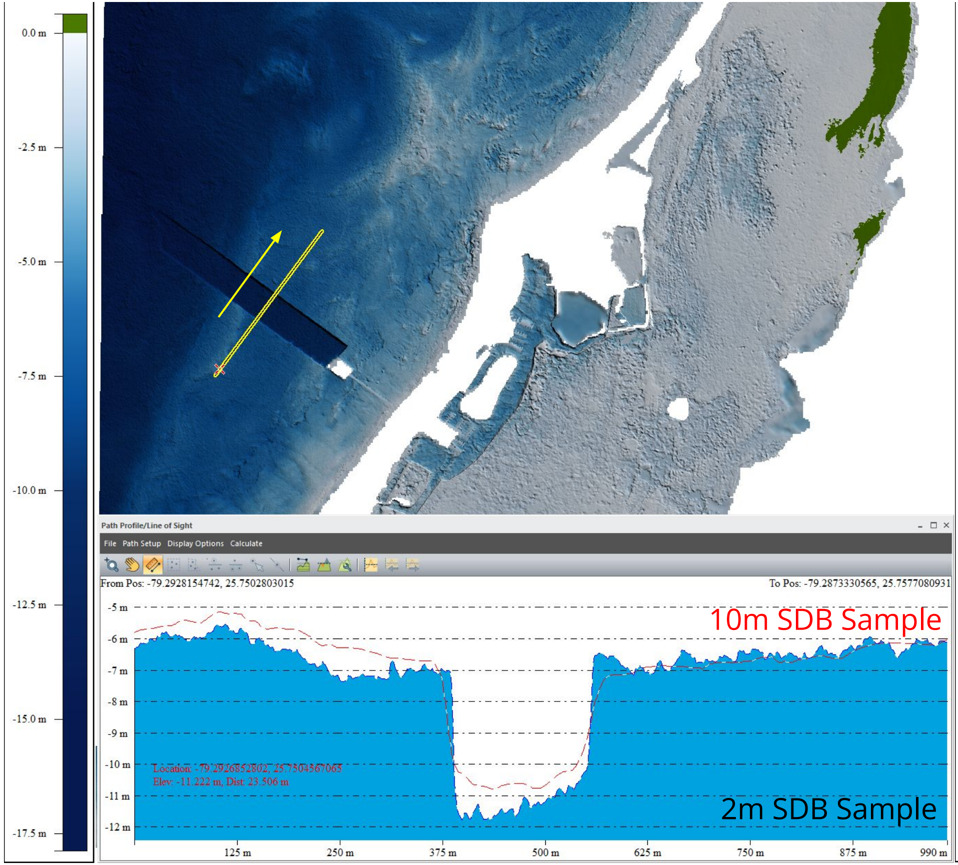


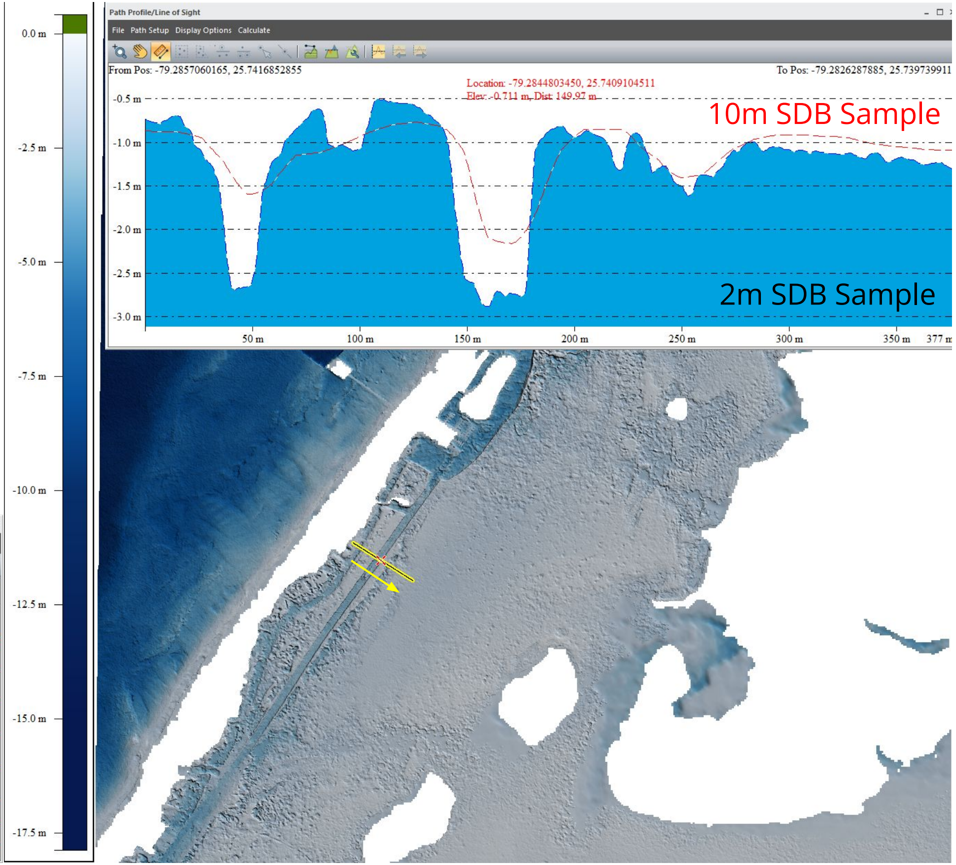


Satellite-Derived Bathymetry: Light Attenuation



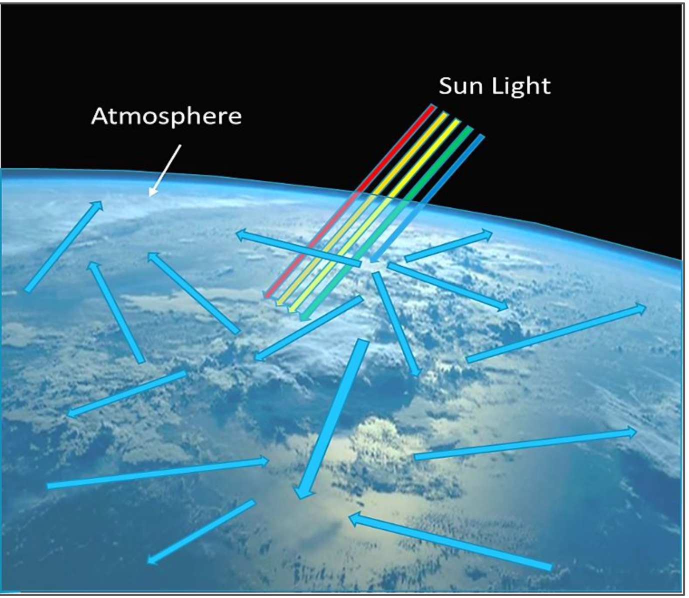
Satellite-Derived Bathymetry: Spatial Resolution





Satellite-Derived Bathymetry: Atmospheric Correction/Compensation

~90% of the signal received by optical satellite sensors is due to atmospheric path radiance (absorption & scattering in the atmosphere).



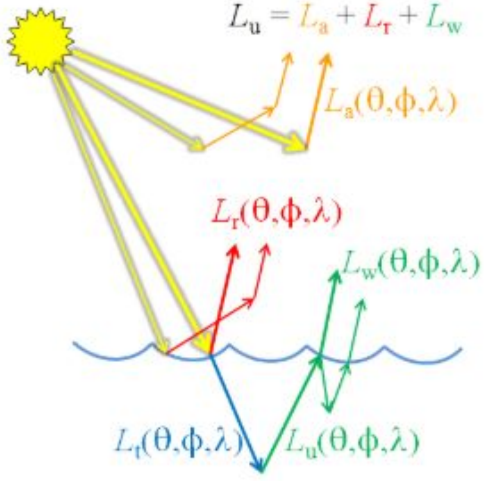


Figure: Fig. 1. Contributions to the total upwelling radiance above the sea surface, L_u. Yellow arrows are the sun's unscattered beam; orange arrows are atmospheric path radiance L_a; red is surface-reflected radiance L_r; green is water-leaving radiance L_w. Thick arrows represent single-scattering contributions; thin arrows illustrate multiple scattering contributions.

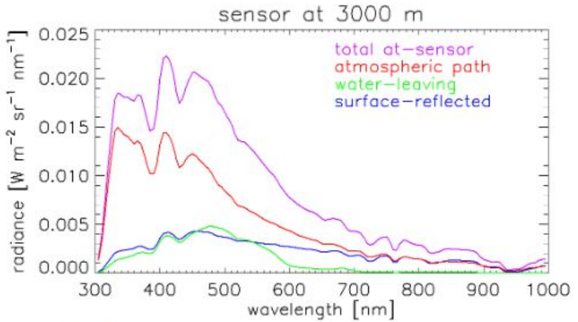


Figure: Fig. 3. The total radiance curve of Fig. 2 at 3000 m sensor altitude partitioned into the contributions by water-leaving radiance, surface reflectance, and atmospheric path radiance.

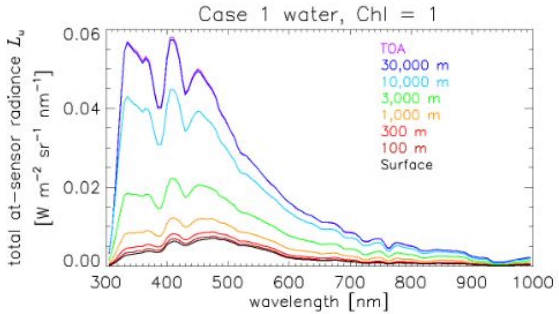
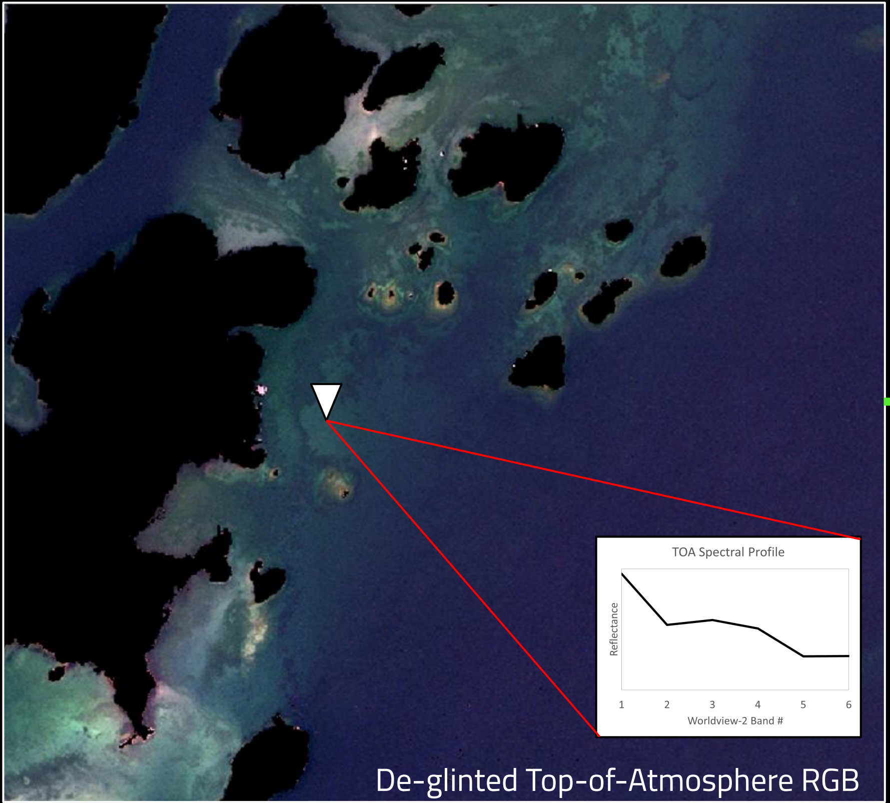
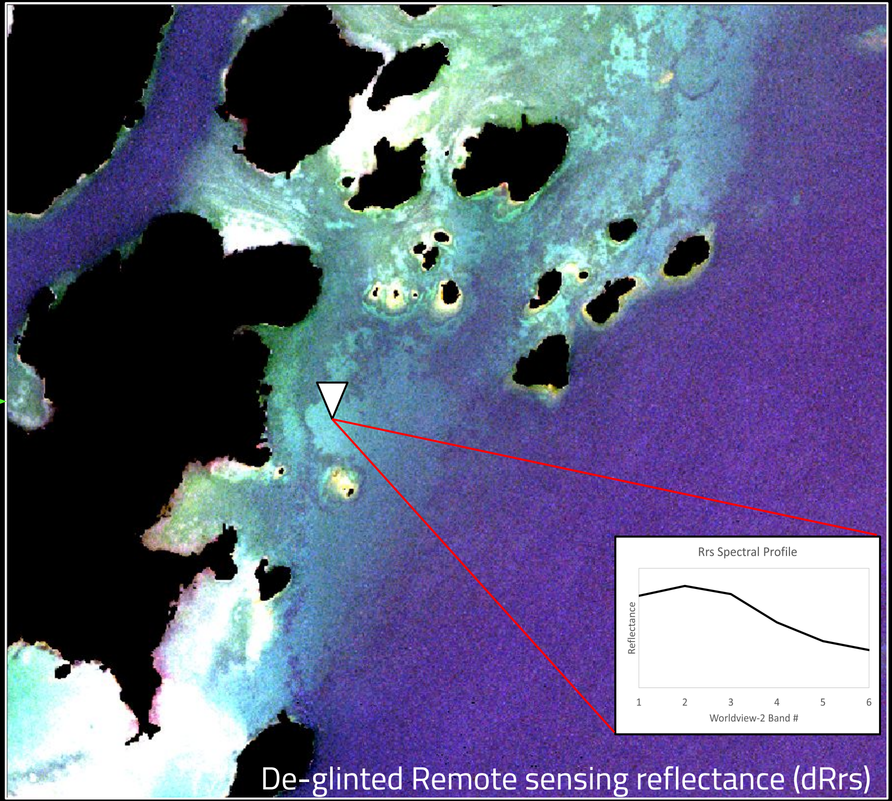


Figure: Fig. 2. Example at-sensor radiances L_u for different sensor altitudes. The water-leaving radiance and surface-reflected radiance (not shown) are the same in all cases.

Satellite-Derived Bathymetry: Atmospheric Correction/Compensation

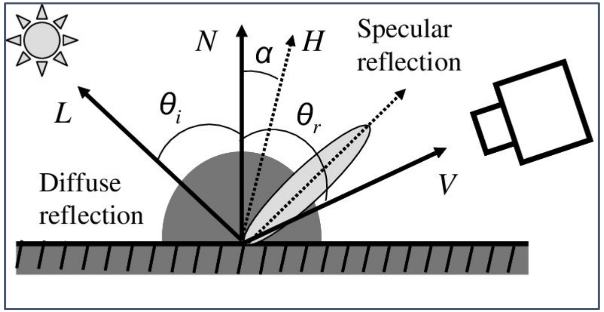


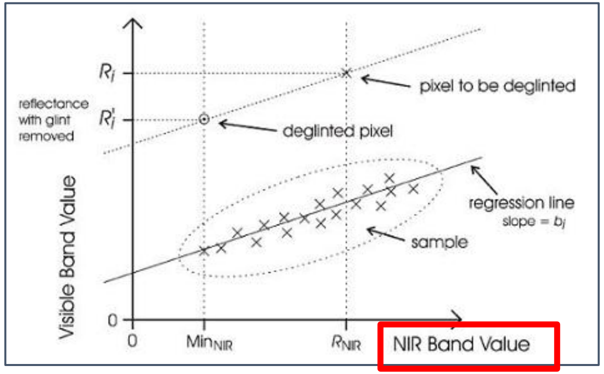


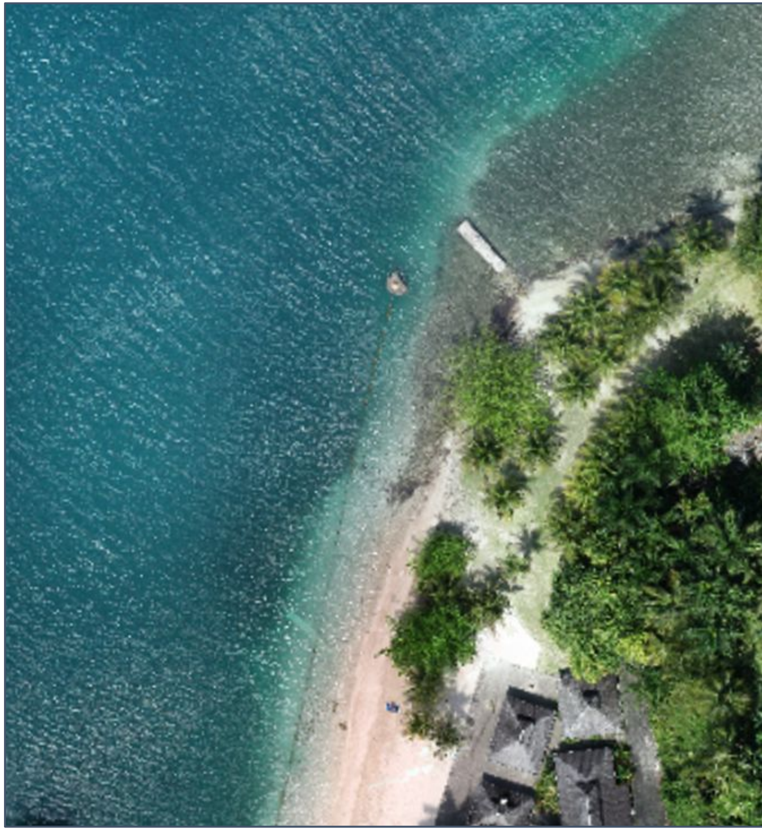
Satellite-Derived Bathymetry: Specular Reflection/Sun Glint

Sun-sensor geometry, spatial resolution, and sea-surface conditions all contribute to the likelihood of sun glint or specular reflection present in earth-observation imagery.

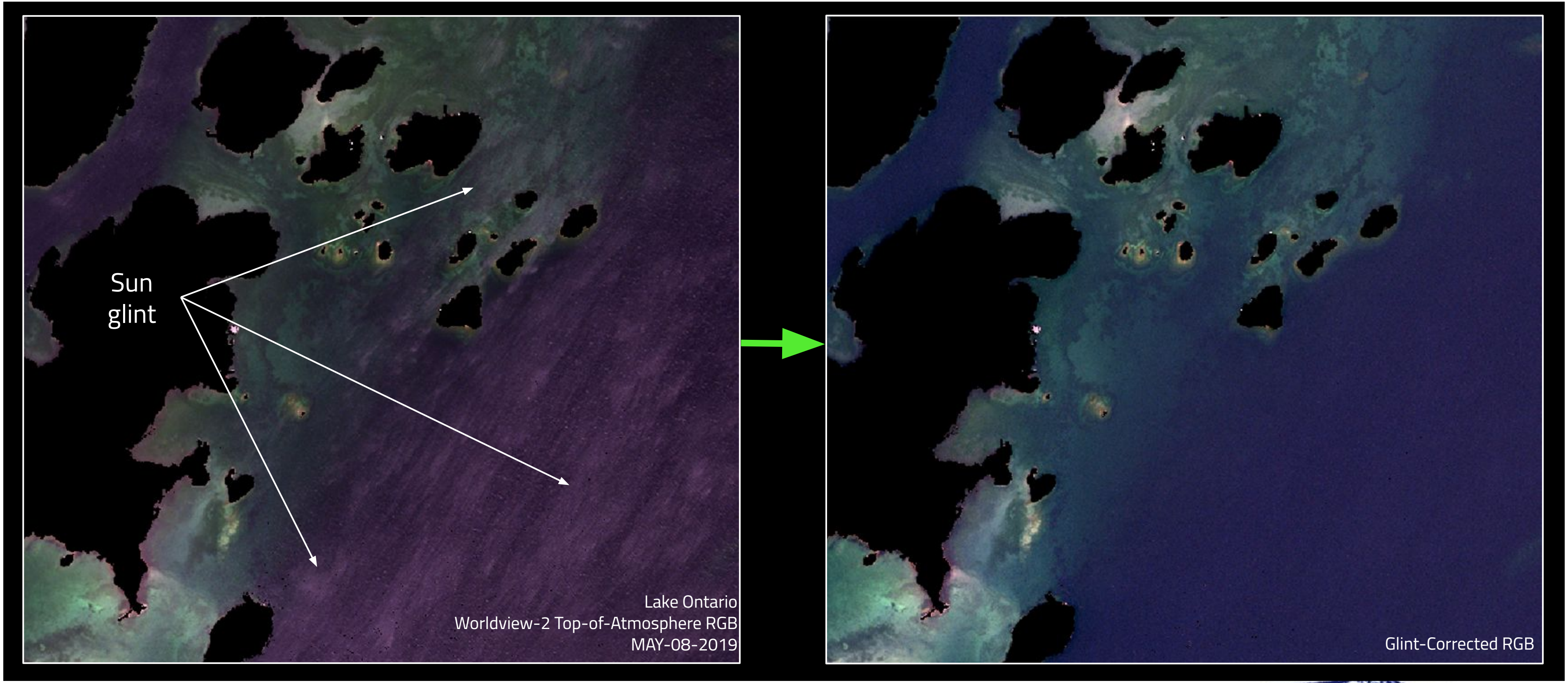
There are multiple methodologies for the correction or mitigation of sun glint. One of the more common algorithms is the Hedley Method, which models differences between visible and infrared wavelengths to correct for the contribution of specular reflection.



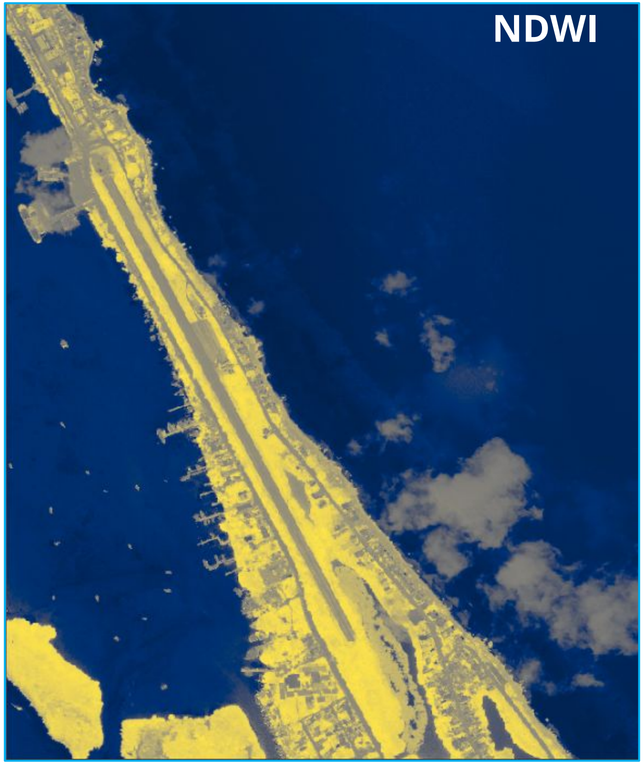


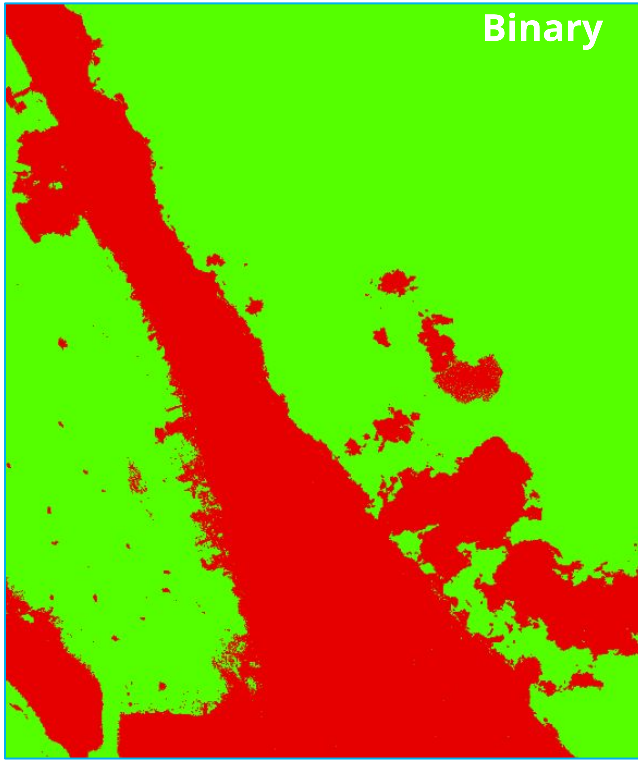


Satellite-Derived Bathymetry: Specular Reflection/Sun Glint



Satellite-Derived Bathymetry: Detractive High Reflectance Mitigation



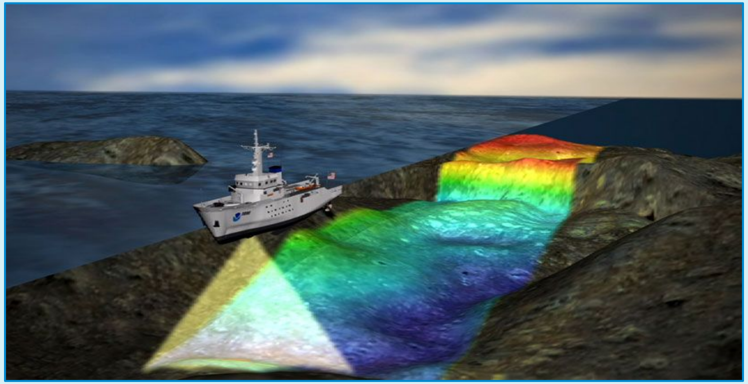


One method is the use of a normalized difference water index (NDWI) for extracting land and clouds.

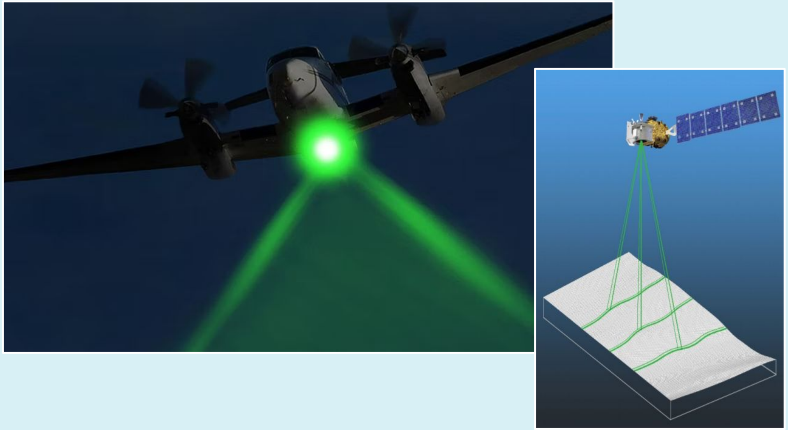
NDWI = (Green-NIR)/(Green+NIR)

Satellite-Derived Bathymetry: *In Situ / Ground Truth*

Traditional Sonar Surveys
(single-beam, multi-beam, sidescan, etc)



Airborne/Spaceborne Bathymetric Lidar
(~532nm laser altimeter)



Leadline/Nautical Charts

Uncrewed Underwater or Surface Vessels

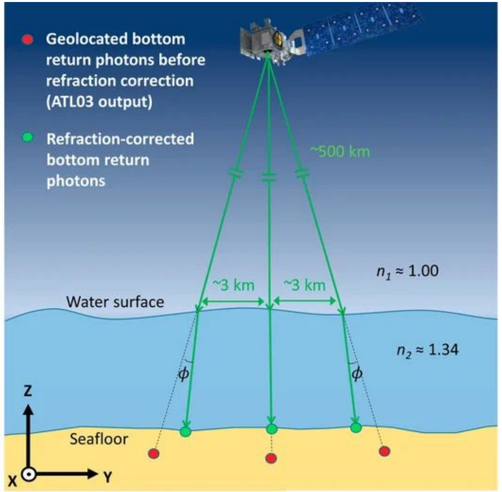
ICESat-2: Solution to the "*in situ*" problem

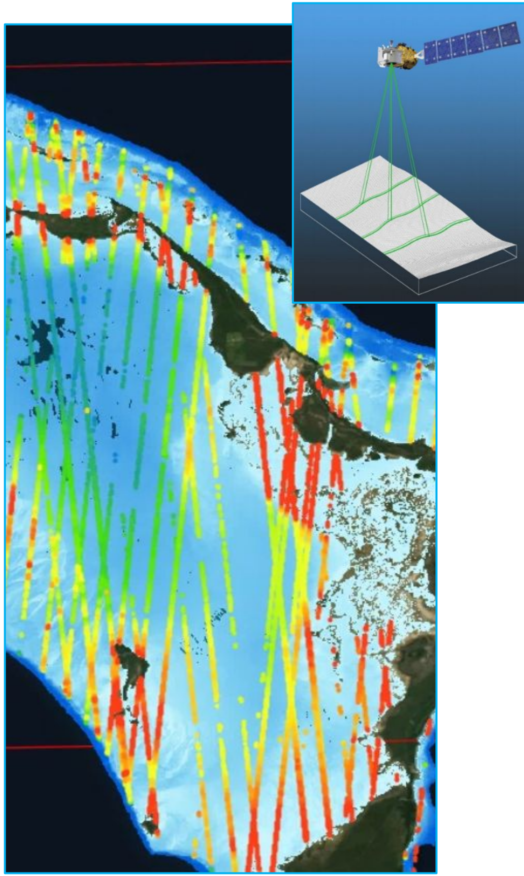
ICESat-2 carries a single instrument –
the **A**dvanced **T**opographic **L**aser **A**ltimeter **S**ystem, or ATLAS.

ATLAS measures the travel times of laser pulses to calculate the distance between the spacecraft and Earth's surface (https://icesat-2.gsfc.nasa.gov/space-lasers)

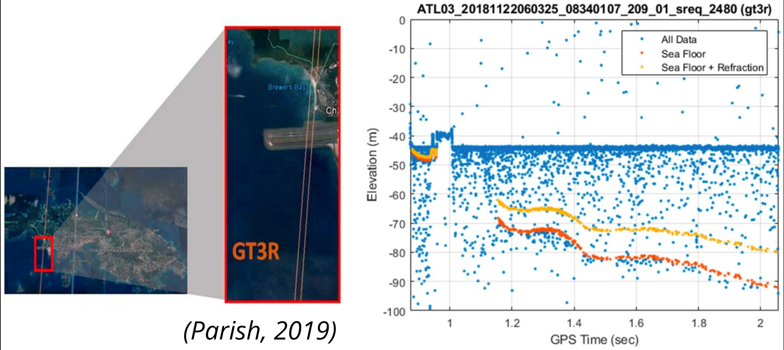
The ATL03 Geolocated Photon Data product is used to obtain space-based bathymetric measurements.

For bathymetric applications, ATL03 data is converted to orthometric heights. Bathymetric photon returns are corrected for water-column refraction and ocean tides





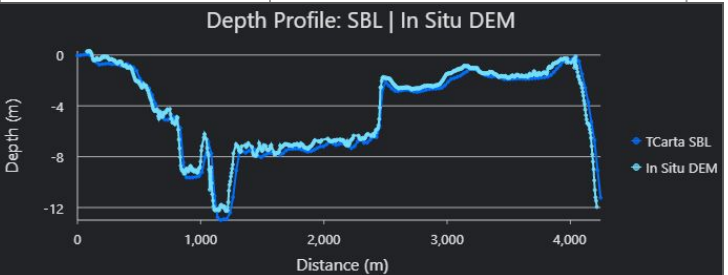
With a vertical RMSE of ~0.3m to ~0.5m, ICESat-2 is a beneficial tool for space-borne bathymetry modelling

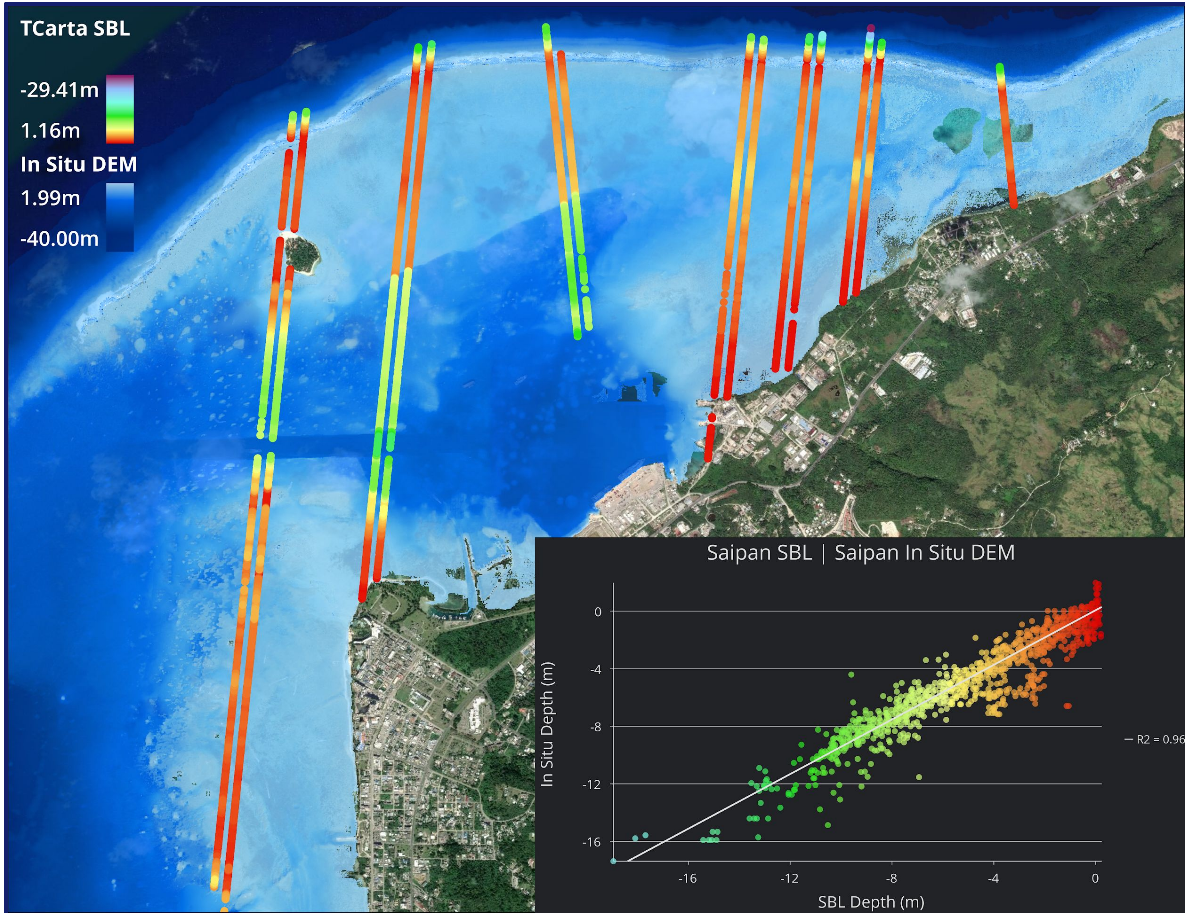


(Parish, 2019)

ICESat-2: Solution to the "*in situ*" problem

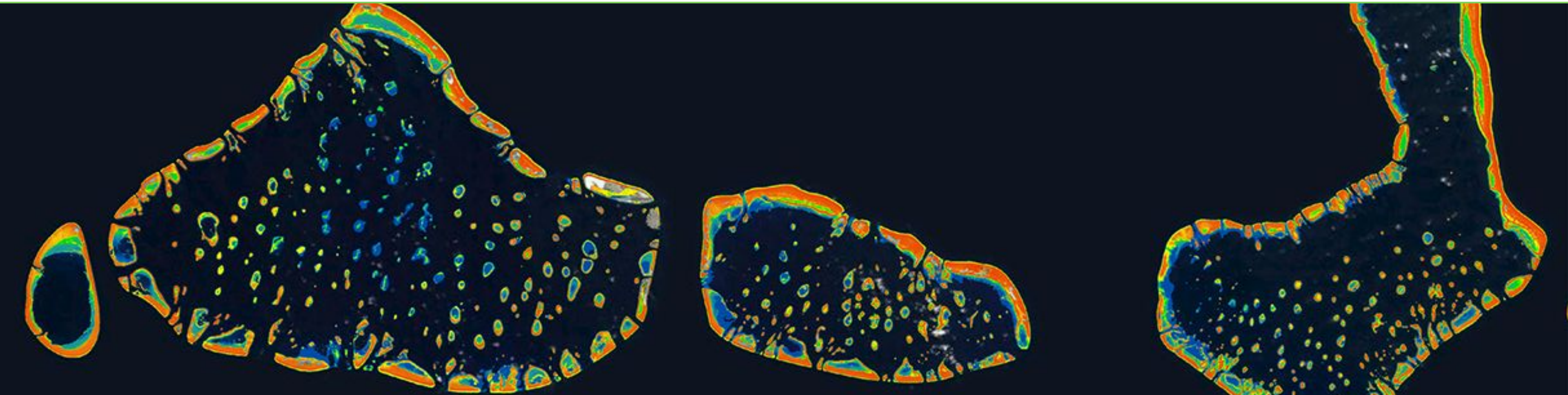
Depth Range	+1.16m - 29.41m
# Data Points	28,747
RMSE	**0.48m**
MAE	**0.33m**
DOI	29 Nov 2018, 28 Feb 2019, 29 Mar 2019, 30 May 2019
Vertical Datum	LAT | NOAA
In Situ Metadata	
Source	MBES/LiDAR | PIFSC, CRED, JIMAR, NAVO
DOI	2001-2007
Horizontal Resolution	5m
Vertical Datum	MLLW (Source) LAT (Converted)





ICESat-2: Use-Cases for Space-Based Hydrography

- Calibrate/train empirical regression models
- Validate or corroborate SDB results
  - Vertical uncertainty modelling
- Change detection/shoal detection
- Sea surface topography
- Adjustment/calibration of dependent variables
  - E.g. aerosol optical thickness/density
- Optically shallow water delineation
- Ocean Color measurements
- Shoreline delineation

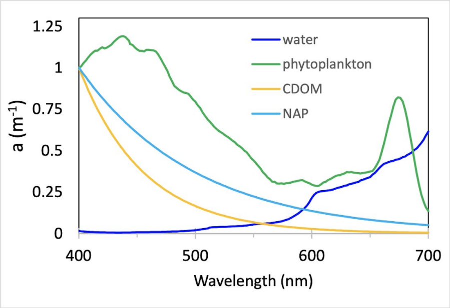


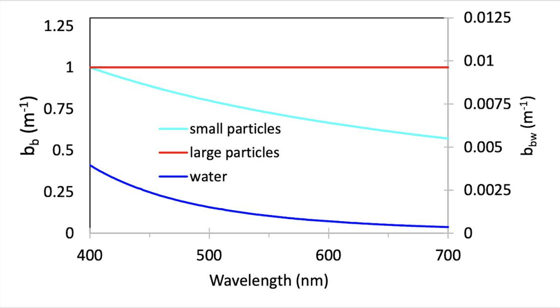
$$R_{rs}(\theta, \phi, \lambda) \equiv \frac{L_w(\text{in air}, \theta, \phi, \lambda)}{E_d(\text{in air}, \lambda)} \quad (\text{sr}^{-1}) .$$

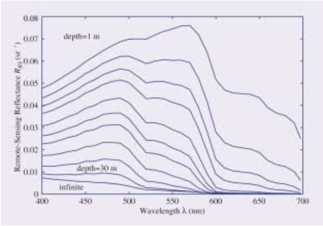
$$a(\lambda) = a_w(\lambda) + a_{phyt}(\lambda) + a_{NAP}(\lambda) + a_{CDOM}(\lambda)$$

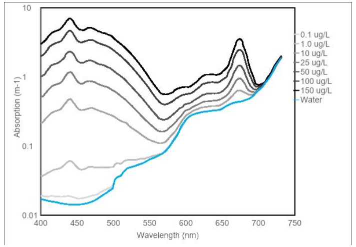
$$b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda)$$

$$R(\lambda) = f/Q \, \frac{b_b(\lambda)}{a(\lambda)+bb(\lambda)}$$









$$R(\lambda) = f/Q \, \frac{b_w(\lambda) + A_{bbp}\, b_{bp}^{*}(\lambda)}{a_w(\lambda) + A_{phyt}\, a_{phyt}^{*}(\lambda) + A_{NAP}\, a_{NAP}^{*}(\lambda) + A_{CDOM}\, a_{CDOM}^{*}(\lambda) + b_w(\lambda) + A_{bbp}\, b_{bp}^{*}(\lambda)}$$