Fundamentals of Aquatic Remote Sensing

Sherry L. Palacios, Ph.D.

Please note: slides have been expanded to remove animations. Slide numbers will match the script, but not the page numbers.
Course Objective

• Provide an overview of aquatic optics, the remote sensing of water targets, and NASA Earth observation resources available for aquatic applications.

Credit: NASA/USGS Landsat; Geoscience Australis
Agenda

• Light and Water
• Fundamentals of Remote Sensing
• Aquatic Remote Sensing Data Products and Their Uses
• Accessing NASA Satellite Imagery
• NASA Satellite Data Processing Tools

Phytoplankton Bloom in the Arabian Sea
Why Do We Observe from Space?
To Understand Earth’s Processes on a Global Scale
Advantages of Remote Sensing of Aquatic Environments

• Synoptic coverage
• Temporal frequency needed to capture dynamic aquatic processes
• Observations of remote ocean locations, infrequently accessed by sea-based platforms
Light and Water
Agenda

• Light and Water
  – How light propagates through the atmosphere and water column, and back to sensor
  – Constituents of the water column and their inherent optical properties

• Fundamentals of Remote Sensing

• Aquatic Remote Sensing Data Products and Their Uses

• Accessing NASA Satellite Imagery

• NASA Satellite Data Processing Tools

Phytoplankton Bloom in the Arabian Sea
First, an Aquatic Optics Primer…

The Electromagnetic Spectrum
How Light Interacts with Water

Defining Remote Sensing Reflectance (Rrs) – or ‘Ocean Color’

Inherent Optical Properties
\( a = \text{absorption by...} \)
- phytoplankton (ph)
- non-algal particles (nap)
- colored dissolved organic matter (CDOM)
- water (w)
How Light Interacts with Water
Defining Remote Sensing Reflectance (Rrs) – or ‘Ocean Color’

\[
Rrs(\lambda, 0^+) = C \frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)}
\]

**Inherent Optical Properties**
- \(a\) = absorption
- \(b\) = scattering in forward (f) and backward (b) directions
How Light Interacts with Water

Defining Remote Sensing Reflectance (Rrs) – or ‘Ocean Color’

\[
Rrs(\lambda, 0^+) \equiv C \frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)} = \frac{L_w(\lambda)}{E_d(\lambda, 0^+)}
\]

Inherent Optical Properties
\(a\) = absorption
\(b\) = scattering

Apparent Optical Properties
\(L_w\) = water leaving radiance
\(L_u\) = upwelling radiance
\(E_d\) = downwelling irradiance
\(R_{rs}\) = remote sensing (rs) reflectance
Inherent Optical Properties (IOPs) and the ‘Color’ of Water

\( \text{Rrs}(\lambda, 0^+) \equiv C \frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)} \)

Light absorption \((a)\) by photoplankton \((\text{ph})\), non-algal particles \((\text{nap})\), water \((\text{w})\), and colored dissolved organic matter \((\text{CDOM})\)

\[
a = a_{\text{ph}} + a_{\text{nap}} + a_{\text{CDOM}} + a_{\text{w}}
\]

Light scattering \((b)\) by particles in forward \((b_f)\) and backward \((b_b)\) direction

\[
b = b_f + b_b
\]
Inherent Optical Properties (IOPs) and the ‘Color’ of Water

- chlorophyll
- water
- CDOM
- nap/sediments
Inherent Optical Properties (IOPs) and the ‘Color’ of Water

- **chlorophyll**
- **water**
- **CDOM**
- **nap/ sediments**

The graph illustrates the reflectance (Rrs) of different water components across various wavelengths (nm):

- **Visible** range:
  - chlorophyll
  - sediments
- **Near IR** range:
  - CDOM
  - water

The x-axis represents wavelength (nm), and the y-axis represents Rrs (sr⁻¹).
Inherent Optical Properties (IOPs) and the ‘Color’ of Water

• The typical human eye has color-detecting receptors that sense light at:
  – 420-440 nm ‘blue’
  – 534-555 nm ‘green’
  – 564-580 nm ‘red’

• Water with high chlorophyll content looks green because it reflects strongly in the green part of the spectrum
Fundamentals of Remote Sensing
Agenda

• Light and Water
• Fundamentals of Remote Sensing
  – Spatial, Temporal, Spectral Resolution
  – NASA Satellites and Sensors for Aquatic Applications
  – Image “Correction”
  – Satellite Data Processing Levels
• Aquatic Remote Sensing Data Products and Their Uses
• Accessing NASA Satellite Imagery
• NASA Satellite Data Processing Tools

Phytoplankton Bloom in the Arabian Sea
## Types of Resolution

**Spatial Resolution**
- Decided by its pixel size
- Pixel: smallest unit measured by a sensor

**Temporal Resolution**
- How frequently a satellite observes the same area of the Earth

**Spectral Resolution**
- Ability of a sensor to define fine wavelength intervals
- Finer spectral channels enable remote sensing of different parts of the atmosphere

*Credit: Natural Resources Canada

<table>
<thead>
<tr>
<th>Satellite (Sensor)</th>
<th>Spatial Resolution</th>
<th>Temporal Resolution</th>
<th>Spectral Bands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landsat 8 (OLI)</td>
<td>15 m, 30 m</td>
<td>16 day revisit</td>
<td>9 bands (blue-green, green, red, near IR, shortwave and thermal IR)</td>
</tr>
<tr>
<td>Terra, Aqua (MODIS)</td>
<td>250 m – 1 km</td>
<td>2 times per day</td>
<td>36 bands (red, blue, IR, NIR, MIR)</td>
</tr>
</tbody>
</table>
How Do We Observe From Space?
Overview of Active & Passive Remote Sensing

• Satellites carry instruments and sensors to measure:
  – reflected solar radiation
  – emitted infrared and microwave radiation
Data Collection by Satellites

Atmosphere
- Clouds
- Aerosols
- Gases

Earth’s Surface
- Snow/Ice
- Land (land use, vegetation)
- Water
Remote Sensing of Water Bodies

**Reflected Solar Radiation** (~color of water)
- Measured by satellite sensors
- Used to derive the properties of optically-active water constituents

- Suspended Sediments
- Algae
- Colored Dissolved Organic Matter
- Detrital Organic Matter
- Submerged or floating vegetation
- Oil

- Contaminants
- Pathogens

Coccolithophore Bloom, Norway
Remote Sensing of Water Bodies

**Emitted Thermal Radiation**
- Used to derive the surface temperature of water bodies

![Diagram of sensor components](image)

8-day average SST

MARACOOS, ORB Lab, courtesy M. Oliver
NASA Satellites and Sensors for Aquatic Applications
Overview of NASA Satellites & Sensors for Water Quality Monitoring

- Currently several satellites observe water surface properties in:
  - the open ocean
  - coastal oceans and estuaries
  - many inland lakes
- A number of water quality parameters are operationally available from these satellites
  - e.g. temperature, chlorophyll-a
<table>
<thead>
<tr>
<th>Satellite</th>
<th>Sensor</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landsat Series</td>
<td>• Thematic Mapper (TM)</td>
<td>• Spectral Reflectance</td>
</tr>
<tr>
<td>(7/1972 - present)</td>
<td>• Enhanced Thematic Mapper (ETM+)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Operational Land Imager (OLI)</td>
<td></td>
</tr>
<tr>
<td>Terra</td>
<td>Moderate Resolution Imaging Spectroradiometer (MODIS)</td>
<td></td>
</tr>
<tr>
<td>(12/1999 - present)</td>
<td></td>
<td>• Spectral Reflectance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Chlorophyll-a Concentration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Colored Dissolved Organic Matter (CDOM)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Turbidity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Euphotic Depth</td>
</tr>
<tr>
<td>Aqua</td>
<td>Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)</td>
<td></td>
</tr>
<tr>
<td>(5/2002 - present)</td>
<td></td>
<td>• Spectral Reflectance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Temperature</td>
</tr>
<tr>
<td>Terra</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(12/1999 – present)</td>
<td></td>
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</tr>
</tbody>
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## NASA Satellites & Sensors for Ocean and Coastal Systems

<table>
<thead>
<tr>
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<th>Sensor</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>• Chlorophyll Concentration</td>
</tr>
<tr>
<td>International Space Station</td>
<td>Hyperspectral Imager for the Coastal Ocean (HICO) (2009 – 2014)</td>
<td>• Spectral Radiance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Spectral Remote Sensing Reflectance</td>
</tr>
<tr>
<td>Plankton, Aerosols, Clouds, ocean Ecosystems (PACE) (proposed for 2022 or 2023)</td>
<td>Ocean Color Instrument</td>
<td>• Spectral Reflectance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Optional Polarimeter being considered</td>
</tr>
</tbody>
</table>
Landsat Satellites and Sensors

http://landsat.gsfc.nasa.gov/

- Near-polar orbit
- 10 a.m. equator crossing time
- Global coverage
- July 1972 – present
- 16 day revisit time
- Sensors:
  - MSS
  - TM
  - ETM+
  - OLI
  - TIRS
Landsat-7 Enhanced Thematic Mapper (ETM+)

http://geo.arc.nasa.gov/sge/landsat/l7.html

- Flying on-board Landsat 7 polar orbiting satellites
- Spatial Coverage and Resolution:
  - Global, swath 185 km
  - Spatial Resolution: 15 m, 30 m, 60 m
- Temporal Coverage and Resolution
  - April 15, 1999 – present
  - 16 day revisit time
- Spectral Bands
  - 8 bands (major bands include: blue-green, green, red, reflected and thermal IR, and panchromatic)

- Spectral Bands
  - Bands 1-5, 7: 30 m
  - Band 6: 60 m
  - Band 8: 15 m
Landsat-8 Operational Land Imager (OLI)


- Flying on-board Landsat 8 (Landsat Data Continuity Mission – LDCM) polar orbiting satellite
- Spatial Coverage & Resolution:
  - Global, Swath 185 km
  - Spatial Resolution: 15 m, 30 m
- Temporal Coverage & Resolution:
  - February 11, 2013 – present
  - 16 day revisit time
- Spectral Bands
  - 9 bands (major bands include blue-green, red, near IR, shortwave and thermal IR, panchromatic)
Terra and Aqua


Terra
• Polar orbit, 10:30 a.m. equator crossing time
• Global Coverage
• December 18, 1999 – present
• 1-2 observations per day
• Sensors:
  – ASTER, CERES, MISR, MODIS, MOPITT

Aqua
• Polar orbit, 1:30 p.m. equator crossing time
• Global Coverage
• May 4, 2002 – present
• 1-2 observations per day
• Sensors:
  – AIRS, AMSU, CERES, MODIS, AMSR-E
MODerate Resolution Imaging Spectroradiometer (MODIS)

http://modis.gsfc.nasa.gov

- On board Terra and Aqua
- Designed for land, atmosphere, ocean, and cryosphere observations
- Spatial Coverage and Resolution:
  - Global, Swath: 2,330 km
  - Spatial Resolution Varies: 250 m, 500 m, 1 km
- Temporal Coverage and Resolution:
  - 2000 – present
  - 2 times per day

Spectral Bands

- 36 bands (red, blue, IR, NIR, MIR)
  - Bands 1-2: 250 m
  - Bands 3-7: 500 m
  - Bands 8-16: 1000 m

Image Credit: http://cimss.ssec.wisc.edu/
National Polar Partnership (NPP)

http://www.nasa.gov/mission_pages/NPP

- Polar orbit
- 1:30 p.m. equator crossing time
- Global coverage
- November 21, 2011 – present
- 1-2 observations per day

- Sensors:
  - VIIRS
  - ATMS
  - CrIS
  - OMPS
  - CERCES
Visible Infrared Imaging Radiometer Suite (VIIRS)

http://npp.gsfc.nasa.gov/viirs.html

- Flying on-board NPP, polar-orbiting satellite
- Designed to collect measurements of clouds, aerosols, ocean color, surface temperature, fires, and albedo
- Spatial Coverage and Resolution:
  - Global, swath width: 3,040 km
  - Spatial resolution: 375 m – 750 m
- Temporal Coverage
  - October 2011 – present
  - 2 times per day

- Spectral Bands
  - 15 bands (major bands include visible, red, blue, green, short, middle, and long-wave IR)
  - Ocean Color Bands 1-7: 0.402 - 0.682 μm
  - Sea Surface Temperature Bands 12-13: 3.660 - 4.128 μm
Hyperspectral Imager for the Coastal Ocean (HICO)


- Partnership with U.S. Naval Research Lab, Office of Naval Research, Oregon State University, and NASA
- Active 2009 – 2014 aboard the International Space Station (ISS)
- 380 nm to 960 nm at 5.7 nm spectral resolution
- 90 m² spatial resolution
- Targeted data collection

Plankton, Aerosol, Clouds, Ocean Ecosystem (PACE)

http://pace.gsfc.nasa.gov/

• Polar orbiting, 2-day revisit
• High spectral resolution
• 1 km ground sample distance
• Optional polarimeter being considered for cloud and aerosol study and to aid in atmospheric correction
• Anticipated launch 2022
Image “Correction”
Remote Sensing of Water Bodies

Phytoplankton

Colored Dissolved Organic Matter

Detrital particles

Suspended sediments

Remote sensing reflectance ($R_{rs}$) vs. wavelength (nm)

Near IR
Atmospheric Correction

\[
L_t(\lambda) = L_r(\lambda) + L_a(\lambda) + L_{ra}(\lambda) + T(\lambda, \theta) L_g(\lambda) + t(\lambda, \theta) L_{wc}(\lambda) + t(\lambda, \theta) L_w(\lambda)
\]

>90%

<10%

Figure 2.4: Contributions of all radiances to the total top-of-atmosphere radiance measured by the sensor. Radiance originating from the Rayleigh scattering in the atmosphere accounts for a large portion of the signal but its contribution can be estimated accurately. The radiance attributable to scattering by aerosols is variable and is the most difficult term to constrain. \(L_r(\varpi)\) is responsible in many cases for failure of the atmospheric correction procedure. An overestimation of the contribution by aerosols often results in the computation of underestimated or negative radiances in the coastal zone. Here, \(L_{ra}(\varpi)\) was not included in the processing. The water-leaving radiance itself only accounts for a moderate amount of the signal, particularly in coastal waters. The effects of whitecaps, \(L_{wc}(\varpi)\), and of sun glint, \(L_g(\varpi)\), are generally small.

Normalized water-leaving radiances

The primary objective of ocean color missions is to provide remote measurements of water-leaving radiances that are independent of the measurement conditions. The magnitude and spectral shape of \(L_w(\varpi)\) are directly dependent on the illumination conditions. Although the extraction of the signal required to remove the effects
Water-leaving radiance

\[ R_{rs}(\lambda, 0^+) = \frac{L_w(\lambda)}{E_d(\lambda, 0^+)} \]

Downwelling Irradiance
Atmospheric Correction

\[ L_t(\lambda) = L_r(\lambda) + L_a(\lambda) + L_{ra}(\lambda) + T(\lambda, \theta) L_g(\lambda) + t(\lambda, \theta) L_{wc}(\lambda) + t(\lambda, \theta) L_w(\lambda) \]

- >90%
- <10%

Atmospheric correction
Satellite Data Processing Levels
Levels of Data Processing

http://oceancolor.gsfc.nasa.gov/cms/products

- Level 0: unprocessed instrument data at full resolution, rawest format available
- Level 1A: reconstructed and unprocessed instrument data at full resolution
- Level 1B: L1A data with instrument/radiometric calibrations applied
- Level 2: Derived geophysical variables at same resolution as L1 data
- Level 3: L2 projected onto a well defined spatial grid over a well-defined time period
- Level 4: model output or results from analyses of lower level data
  - e.g., Primary Productivity
Data Processing Levels

- **L0**: Raw instrument data
- **L1**: Geolocated and calibrated
- **L2**: Products derived from L1B
- **L3**: Gridded and quality controlled
- **L4**: Model output: derived variables

**Harder to Use**

**Easier to Use**
Aquatic Remote Sensing
Data Products and Their Uses
Agenda

- Light and Water
- Fundamentals of Remote Sensing
- Aquatic Remote Sensing Data Products and Their Uses
- Accessing NASA Satellite Imagery
- NASA Satellite Data Processing Tools

Phytoplankton Bloom in the Arabian Sea
## What Can We Observe from Space?
Ocean Properties Derived from Remote Sensing Imagery

<table>
<thead>
<tr>
<th>Observation</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorophyll-a</td>
<td>Phytoplankton biomass, primary productivity, biogeochemical cycling</td>
</tr>
<tr>
<td>Water Turbidity</td>
<td>Water quality, human and ecosystem health</td>
</tr>
<tr>
<td>Colored Dissolved Organic Matter (CDOM)</td>
<td>Water quality, biogeochemical cycling, human and ecosystem health</td>
</tr>
<tr>
<td>Sea Surface Temperature (SST)</td>
<td>Currents, primary productivity, climate studies, biogeochemistry, temperature flux</td>
</tr>
<tr>
<td>Surface winds</td>
<td>Currents, mixing, air-sea flux of gases</td>
</tr>
<tr>
<td>Salinity</td>
<td>Mixing, air-sea flux of gases, geostrophic currents, salt flux</td>
</tr>
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Chlorophyll-a from Remote Sensing Reflectance (Rrs)
Rrs at Different Chlorophyll-a Concentrations

Surface Remote Sensing Reflectance

$R_{rs}$ (sr$^{-1}$)

Wavelength (nm)

1

2

3

4

1

2

3

4
Chlorophyll-a Estimates

Estimations are a function of the ratios of Rrs values

Algorithm description: [http://oceancolor.gsfc.nasa.gov/cms/atbd/chlor_a](http://oceancolor.gsfc.nasa.gov/cms/atbd/chlor_a)
Chlorophyll-a from Space

MODIS chlorophyll-a Northern Hemisphere Spring 2014
Accessing NASA Satellite Imagery
Agenda

- Light and Water
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- Aquatic Remote Sensing Data Products and Their Uses
- Accessing NASA Satellite Imagery
  - Worldview
  - OceanColor Web Data Browsers
  - Other Data Access Tools
- NASA Satellite Data Processing Tools
NASA Worldview

https://worldview.earthdata.nasa.gov/

- Interactive web-based tool for browsing satellite imagery
- Imagery is generally available within four hours of observation
- Daily imagery from May 2012 to present
- Data can be downloaded
- Image output in JPEG, PNG, GeoTIFF, and KML formats
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NASA OceanColor Web – Data Access

http://oceancolor.gsfc.nasa.gov/cms/dataaccess

• Level 1 & 2 Browser
• Level 3 Browser
• Direct Data Access
• Data File Search
• SeaBASS Field Data
NASA OceanColor Web – Level 1 & 2 Browser
http://oceancolor.gsfc.nasa.gov/cgi/browse.pl
Some Other Data Access Tools

- NOAA CoastWatch
  - http://coastwatch.noaa.gov/
- NASA Giovanni
  - http://giovanni.gsfc.nasa.gov/giovanni/
- USGS Earth Explorer
  - http://earthexplorer.usgs.gov/
NASA Satellite Data Processing Tools
NASA OceanColor Web
http://oceancolor.gsfc.nasa.gov/

• OceanColor Web is supported by the Ocean Biology Processing Group (OBPG) at NASA Goddard

• OBPG’s duties include collection, processing, calibration, validation, archive, and distribution of ocean-related data products from a large number of satellite missions
SeaWiFS Data Analysis System (SeaDAS)

http://seadas.gsfc.nasa.gov/

- Image analysis package for the processing, display, analysis, & quality control of ocean color data
- Originally developed for SeaWiFS, but supports most U.S. and international ocean color missions
- Online tutorials, help pages, and an active user community in the Ocean Color Forum
- Attentive & friendly support team based at NASA Goddard
Online Tutorials and Webinars for SeaDAS

http://seadas.gsfc.nasa.gov/tutorial/

- Strongly recommend completing all of the on-demand tutorials listed on this webpage
- SeaDAS supports a wide variety of satellite sensors so your investment in learning it will be time well spent
- Check out this SeaDAS webinar from June 15, 2016:
  - https://earthdata.nasa.gov/user-resources/webinars-and-tutorials
Interested in a More In-Depth Understanding of Aquatic Optics and Remote Sensing Imagery?

• For a more solid foundation in aquatic optics:
  – Ocean Optics Web Book: http://www.oceanopticsbook.info/
  

• For remote sensing imagery information, data access, and processing tools:
  – NASA’s OceanColor Web: http://oceancolor.gsfc.nasa.gov/cms
Summary

• Light and Water
  – How light propagates through the atmosphere and water column, and back to sensor
  – Constituents of the water column and their inherent optical properties

• Fundamentals of Remote Sensing
  – Spatial, Temporal, Spectral Resolution
  – NASA Satellites and Sensors for Aquatic Applications
  – Image “Correction”
  – Satellite Data Processing Levels

• Aquatic Remote Sensing Data Products and Their Uses

• Accessing NASA Satellite Imagery
  – Worldview
  – OceanColor Web
  – Other Data Access Tools

• NASA Satellite Data Processing Tools
  – SeaDAS
Thank you!

http://arset.gsfc.nasa.gov/webinars/fundamentals-remote-sensing