EBS 566/666
Lecture 8: (i) Energy flow, (ii) food webs

Topics

- Light in the aquatic environment
- Energy transfer and food webs

Algal bloom as seen from space (NASA)

Requirements for plant growth

(1) Energy in the form of solar radiation (light)

(2) Inorganic carbon (*from EOS-I*)

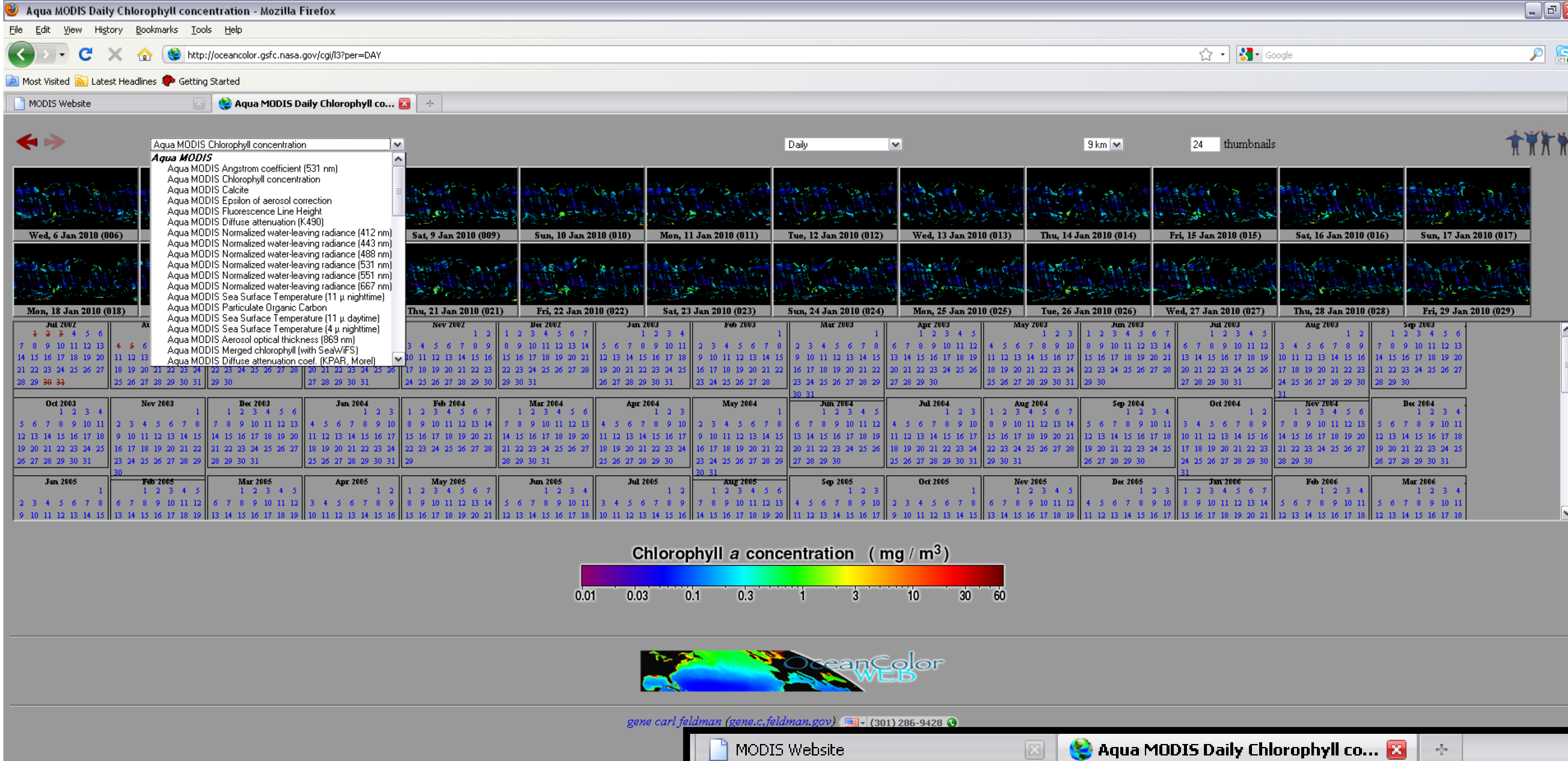
(3) Mineral nutrients (*from EOS-I*)

(4) Water

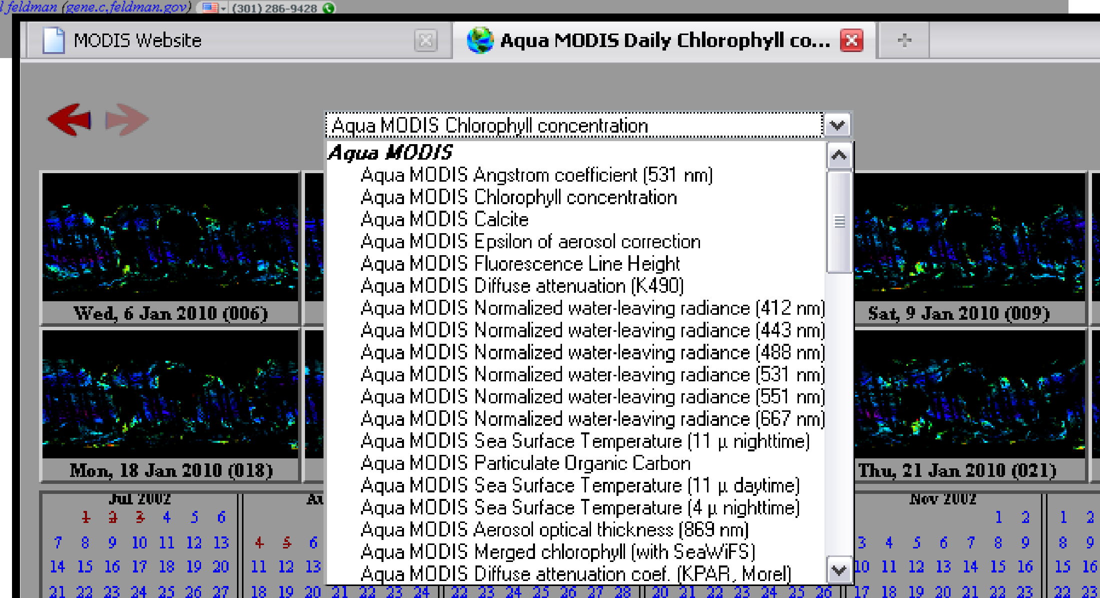
Goal: learn the properties of light in aquatic environments to understand and predict how light influences the distribution of organisms

Relevance for oceanography

- Light fuels photosynthesis (carbon fixation)
- Fixation of carbon through photosynthesis forms the base of most aquatic food webs
- ‘Plant’ growth alters chemical composition of atmosphere and ocean (local and global scales)
- Properties of light exploited for remote sensing of primary production, terrestrial inputs to coastal oceans, etc.


Aqua MODIS Daily Chlorophyll concentration - Mozilla Firefox
File Edit View History Bookmarks Tools Help
http://oceancolor.gsfc.nasa.gov/cgi/l3?per=DAY
Most Visited Latest Headlines Getting Started
MODIS Website
Aqua MODIS Daily Chlorophyll co...
Aqua MODIS Chlorophyll concentration
Daily
9 km
24 thumbnails
Aqua MODIS
Aqua MODIS Angstrom coefficient (531 nm)
Aqua MODIS Chlorophyll concentration
Aqua MODIS Calcite
Aqua MODIS Epsilon of aerosol correction
Aqua MODIS Fluorescence Line Height
Aqua MODIS Diffuse attenuation (K490)
Aqua MODIS Normalized water-leaving radiance (412 nm)
Aqua MODIS Normalized water-leaving radiance (443 nm)
Aqua MODIS Normalized water-leaving radiance (488 nm)
Aqua MODIS Normalized water-leaving radiance (531 nm)
Aqua MODIS Normalized water-leaving radiance (551 nm)
Aqua MODIS Normalized water-leaving radiance (667 nm)
Aqua MODIS Sea Surface Temperature (11 µ nighttime)
Aqua MODIS Particulate Organic Carbon
Aqua MODIS Sea Surface Temperature (11 µ daytime)
Aqua MODIS Sea Surface Temperature (4 µ nighttime)
Aqua MODIS Aerosol optical thickness (869 nm)
Aqua MODIS Merged chlorophyll (with SeaWiFS)
Aqua MODIS Diffuse attenuation coef. (KPAR, Morel)
Wed, 6 Jan 2010 (006)
Sat, 9 Jan 2010 (009)
Sun, 10 Jan 2010 (010)
Mon, 11 Jan 2010 (011)
Tue, 12 Jan 2010 (012)
Wed, 13 Jan 2010 (013)
Thu, 14 Jan 2010 (014)
Fri, 15 Jan 2010 (015)
Sat, 16 Jan 2010 (016)
Sun, 17 Jan 2010 (017)
Mon, 18 Jan 2010 (018)
Thu, 21 Jan 2010 (021)
Fri, 22 Jan 2010 (022)
Sat, 23 Jan 2010 (023)
Sun, 24 Jan 2010 (024)
Mon, 25 Jan 2010 (025)
Tue, 26 Jan 2010 (026)
Wed, 27 Jan 2010 (027)
Thu, 28 Jan 2010 (028)
Fri, 29 Jan 2010 (029)
Chlorophyll a concentration (mg / m3)
0.01 0.03 0.1 0.3 1 3 10 30 60
OceanColor WEB
gene carl feldman (gene.c.feldman.gov) (301) 286-9428


2005-01-12

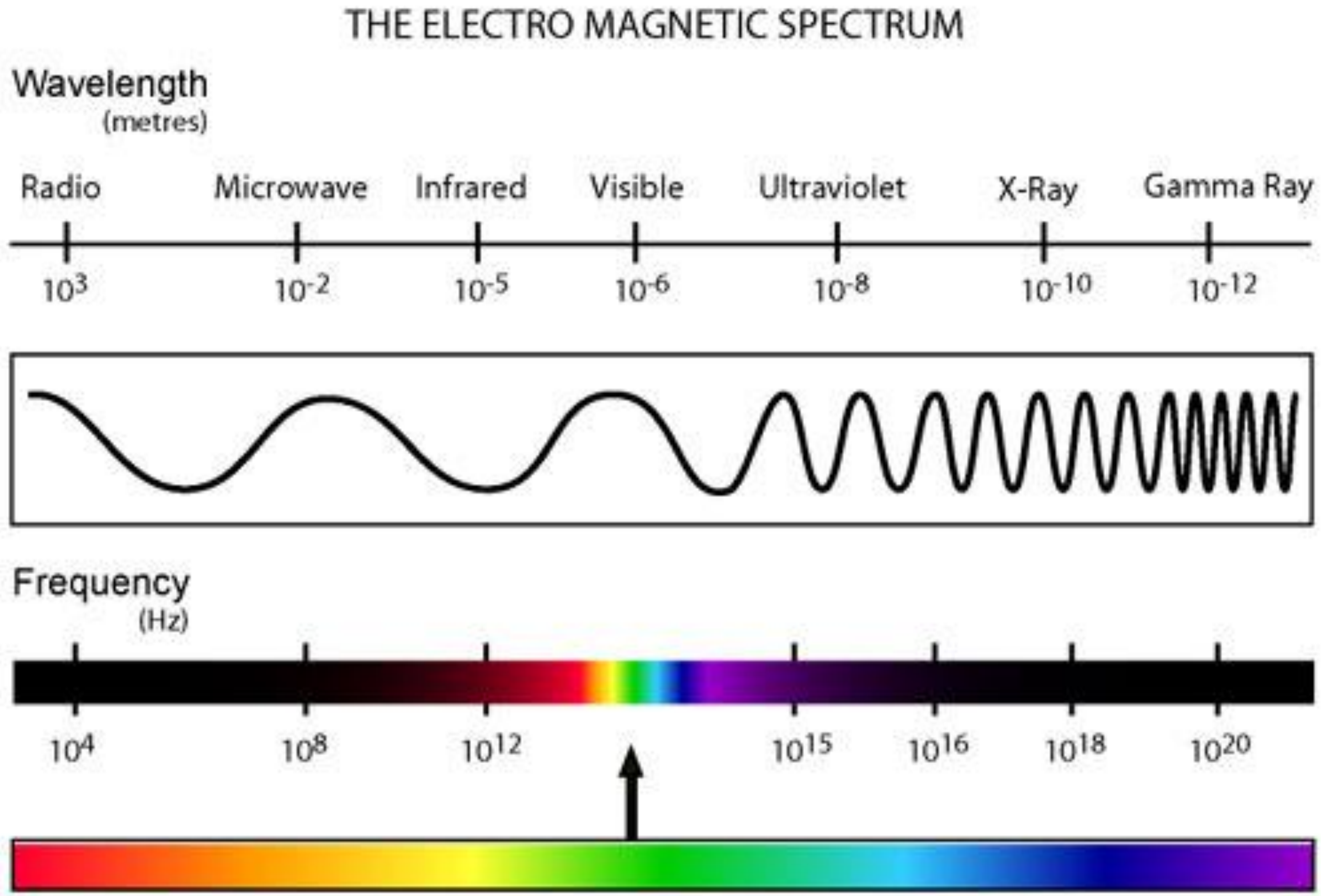

MODIS Website
Aqua MODIS Daily Chlorophyll co...
Aqua MODIS Chlorophyll concentration
Aqua MODIS
Aqua MODIS Angstrom coefficient (531 nm)
Aqua MODIS Chlorophyll concentration
Aqua MODIS Calcite
Aqua MODIS Epsilon of aerosol correction
Aqua MODIS Fluorescence Line Height
Aqua MODIS Diffuse attenuation (K490)
Aqua MODIS Normalized water-leaving radiance (412 nm)
Aqua MODIS Normalized water-leaving radiance (443 nm)
Aqua MODIS Normalized water-leaving radiance (488 nm)
Aqua MODIS Normalized water-leaving radiance (531 nm)
Aqua MODIS Normalized water-leaving radiance (551 nm)
Aqua MODIS Normalized water-leaving radiance (667 nm)
Aqua MODIS Sea Surface Temperature (11 µ nighttime)
Aqua MODIS Particulate Organic Carbon
Aqua MODIS Sea Surface Temperature (11 µ daytime)
Aqua MODIS Sea Surface Temperature (4 µ nighttime)
Aqua MODIS Aerosol optical thickness (869 nm)
Aqua MODIS Merged chlorophyll (with SeaWiFS)
Aqua MODIS Diffuse attenuation coef. (KPAR, Morel)
Wed, 6 Jan 2010 (006)
Sat, 9 Jan 2010 (009)
Mon, 18 Jan 2010 (018)
Thu, 21 Jan 2010 (021)
Jul 2002
Nov 2002

Some definitions

- Light:

- Optics:

- Hydrologic optics:



Photosynthetically Active Radiation (PAR) = 400 – 700 nm

The nature of light

- Units of light are photons, the quantum (minimum indivisible unit) of the electromagnetic field
  - Each photon has a wavelength (λ) and a frequency (ν)
  - λ =
  - c = speed of light (   )
- Energy (ε) in a photon varies with frequency (ν):
  - ε =
  - h = Planck's constant (   )
  - ε = (/λ) x 10^{-19} J (if λ is given in nm)

400 nm provides more energy than 700 nm light

- $\varepsilon = (1989/\lambda) \times 10^{-19}$ J
  - 400: 4.97 x 10-19 J
  - 700: 2.84 x 10-19 J
- 1.75 times more energy provided by 400 nm wavelength energy (700 is 57% of energy at 400 nm)

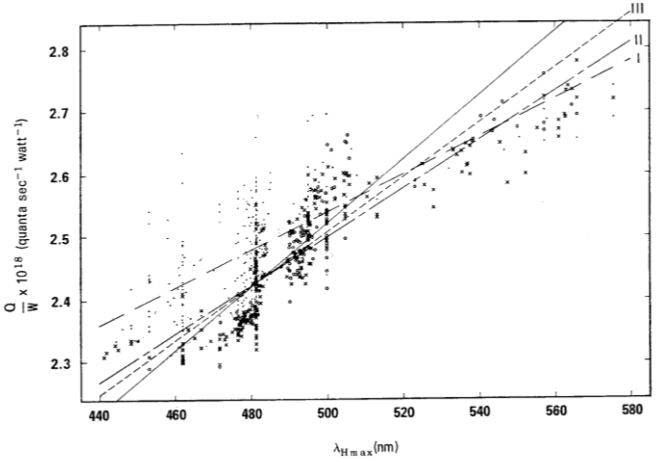
- Radiant flux (Φ): the time rate of flow of radiant energy expressed in W (J s^{-1}) or quanta s^{-1}
- For a single wavelength (monochromatic light), radiant flux (Φ) expressed in quanta s^{-1} (photons s^{-1}) can be converted to J s^{-1} (ie, watts)
  - More commonly, radiant flux is expressed in energy units (watts)
- To convert radiant flux (Φ) from W to quanta s^{-1}, use the relation:

$$\text{quanta } s^{-1} = 5.03\ \Phi\ \lambda \times 10^{15}$$

  - Φ is radiation flux in W (J s^{-1})
  - λ is wavelength ($\lambda = 1989 * 10^{-19}/\varepsilon$, ε in J)
  - Applies to **monochromatic** light only

For broad spectrum radiation (e.g. PAR) an accurate conversion from quanta s^{-1} to W is not possible since λ varies across the spectral band

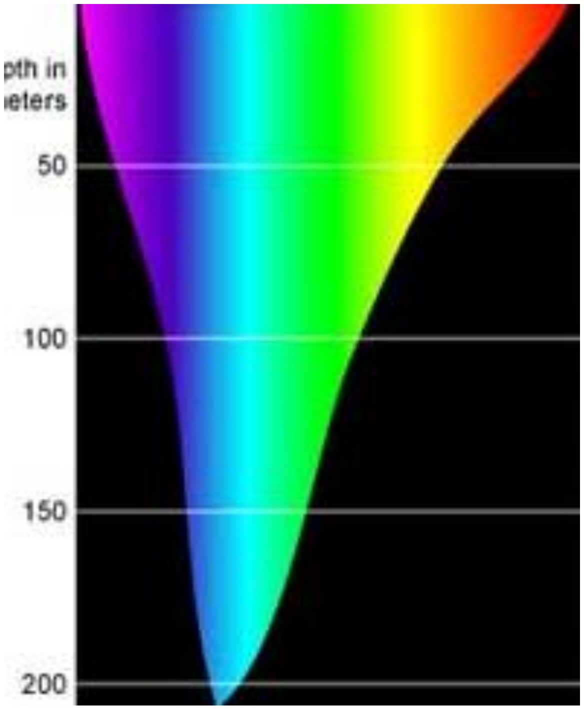
- Photons (quanta) have different energy depending on frequency
- To convert between W and quanta s^{-1}, assume a quanta: energy (Q:W) ratio of 2.77 x 10^{18} (quanta s^{-1} W^{-1}) in air (± 1-3%) – essentially, 'average energy'
- In water, spectral distribution of solar radiation changes with depth; Q:W varies by only ± 10% from a mean of 2.5x10^{18} quanta s^{-1} W^{-1}

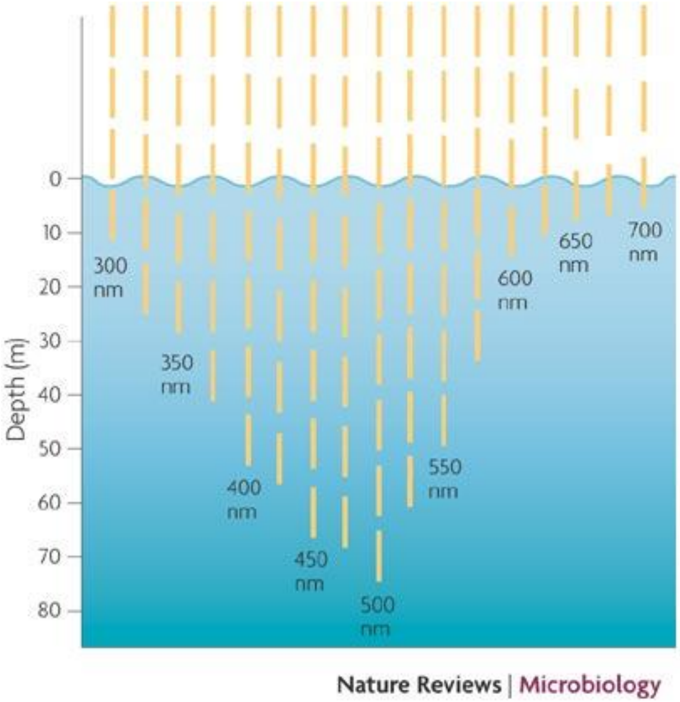


Morel & Smith (1974)

Light penetration is wavelength-dependent

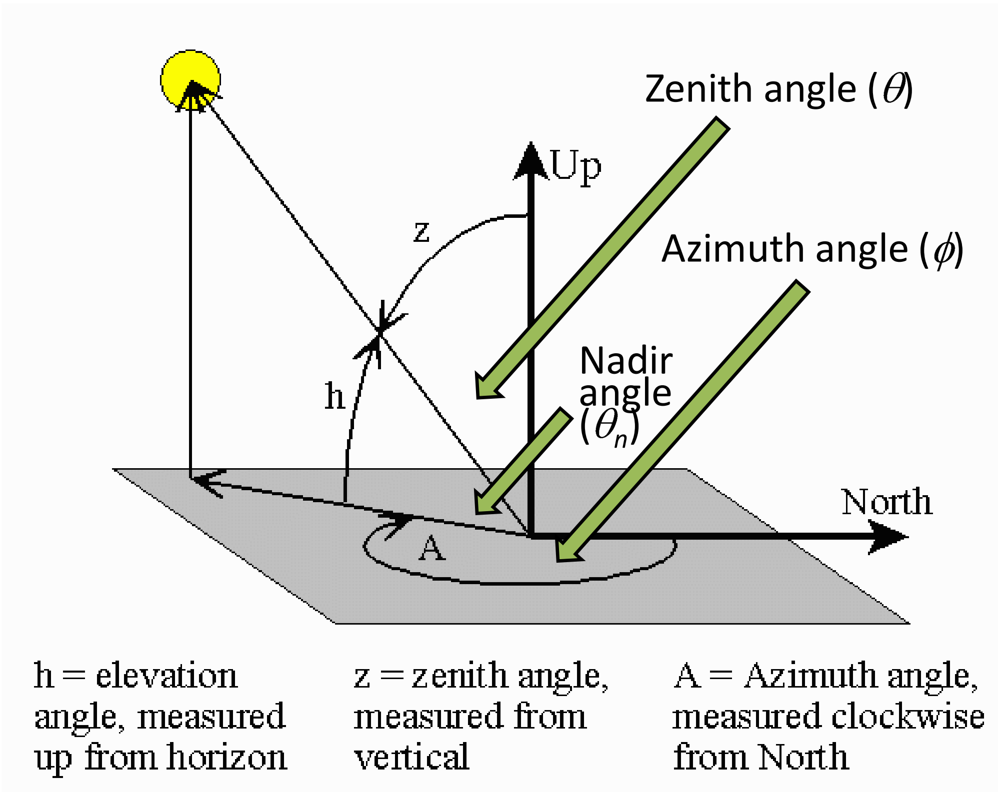
- In any medium, light travels more slowly than it does in a vacuum
- Velocity of light in a medium ≈ velocity of light in a vacuum/refractive index of the medium
- Refractive index of air = 1.00028 (air ≈ vacuum); refractive index of water = 1.33
- Recall: $\lambda = c/\nu$; therefore, as c decreases, λ decreases (ν doesn't change)





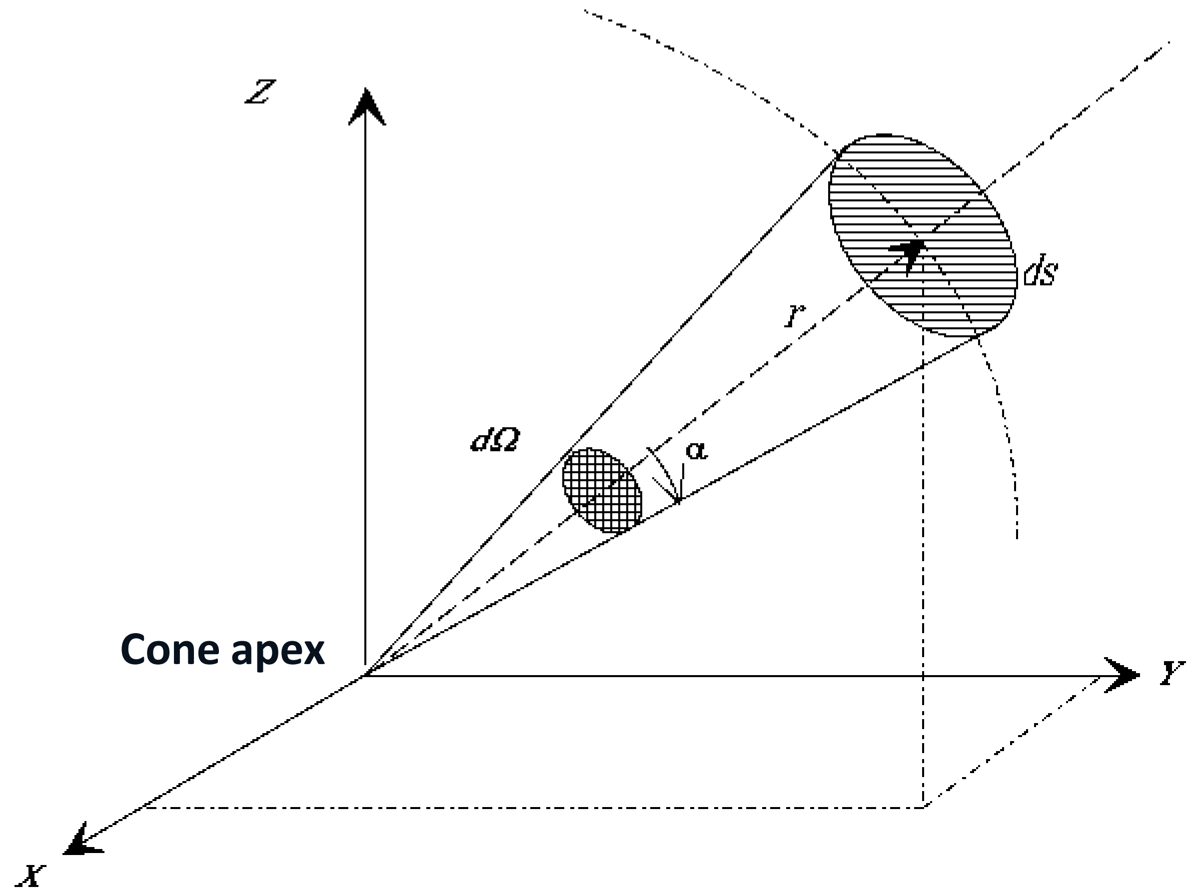
Characteristics of the light field

Direction given in terms of zenith angle, θ, and the azimuth angle, ϕ



Zenith angle (θ) varies from 0 – 90°
Azimuth angle (ϕ) varies from 0 – 360°

Solid angle: a solid angle, $d\Omega$, delimits a cone in space: $d\Omega = dS/r^2$ (in steradians, Sr) where dS is the area cut by the cone over a sphere of radius r, the center of which is at the apex of the cone.



Radiance (L)

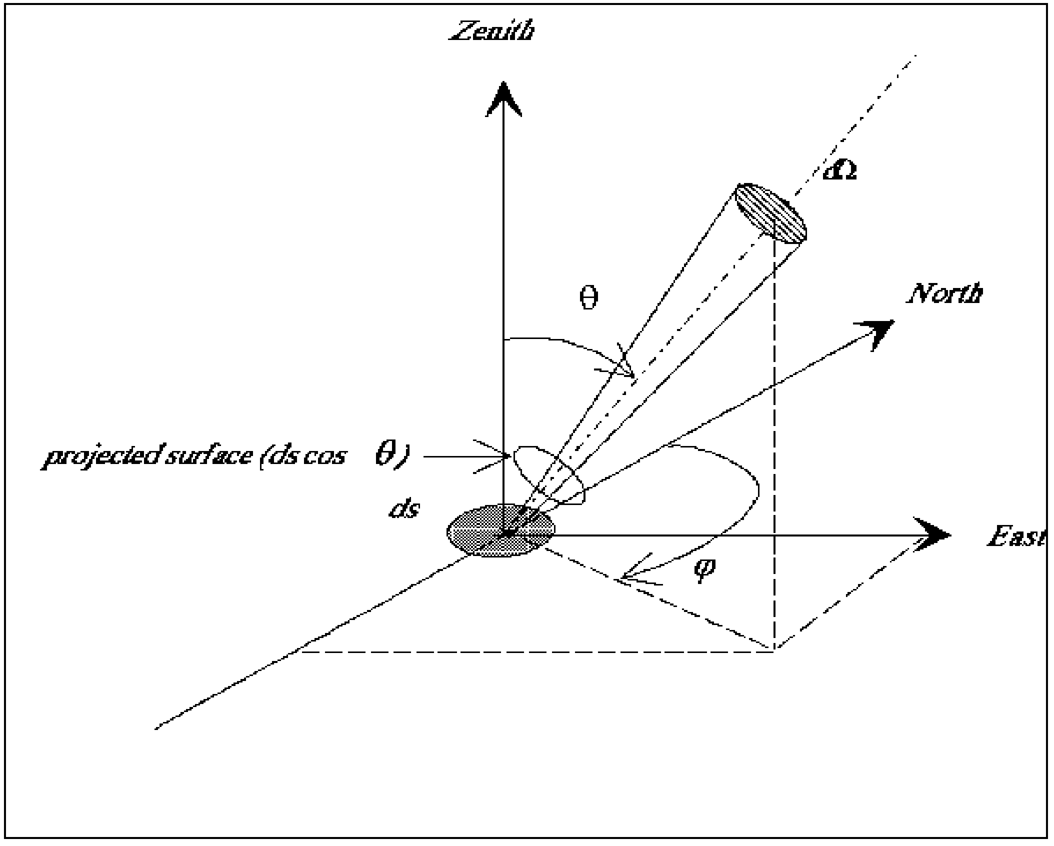
- *Radiant flux* (*Φ*): *the time rate of flow of radiant energy expressed in W (J s^{-1}) or quanta s^{-1}*

- Radiant intensity (I): measure of the radiant flux per unit solid angle in a specific direction (W $steradian^{-1}$):
  - $I = d\Phi / d\Omega$

- Radiance (L): radiant flux (Φ) per unit solid angle per unit area of a plane at right angles to the direction of flow (W $steradian^{-1}$ m^{-2})
  - L is a function of direction (both zenith and azimuth angles) and is generally expressed as $L(\theta,\phi)$:
    - $L(\theta, \phi) = d^2 \Phi / dS \cos\theta \, d\Omega$

- *Surface* radiance (L_s): radiant flux emitted in a given direction per unit solid angle per unit projected area (seen from viewing direction)

Radiance (L): radiant flux (Φ) emitted in a given direction (θ,ϕ) per unit solid angle ($d\Omega$) per unit area ($dS\cos\theta$)



$$L(\theta, \phi) = d^2\,\Phi\,/dS\cos\theta\,d\Omega$$

Irradiance (E)

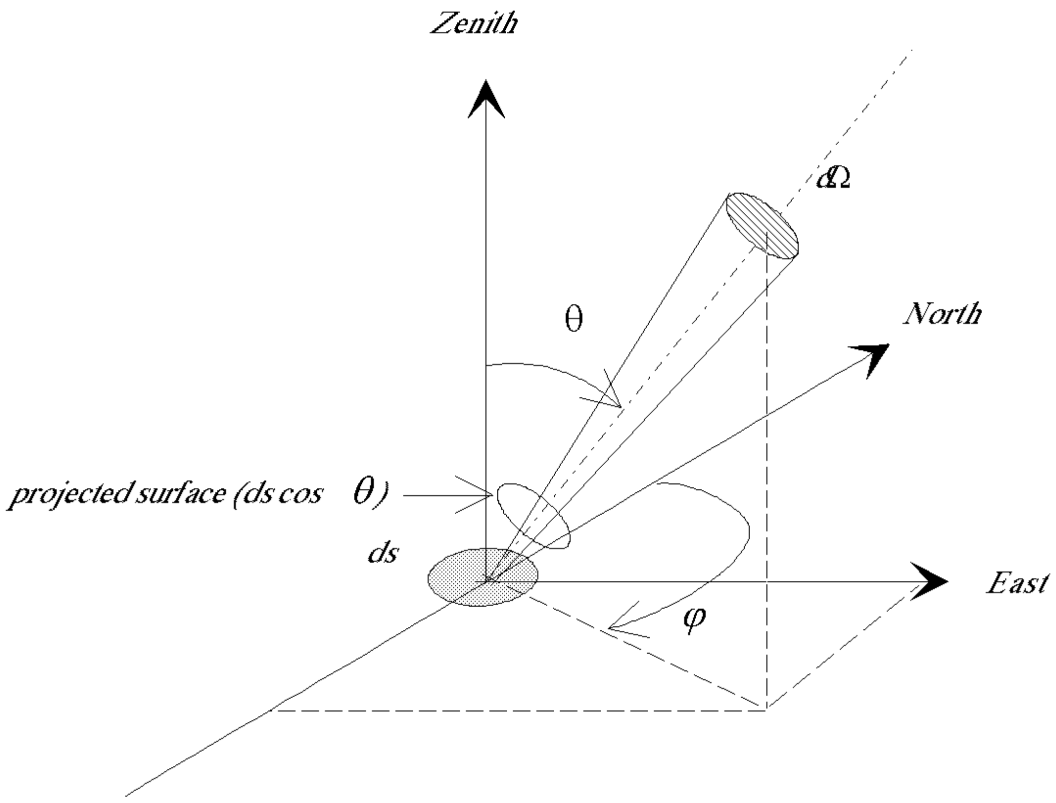
- E = radiant flux (Φ) incident on an infinitesimal element of a surface containing the point under consideration, divided by the area of that element ($\cong$ radiant flux per unit area of a surface)
  - W m^{-2} or quanta (or photons) m^{-2} s^{-1}, or mol quanta (or photons) m^{-2} s^{-1}
  - $E = d\Phi/dS$
  - Total solar irradiance = 1373 W m^{-2} (solar constant)
- 1 mol of photons is 6.02×10^{23} photons (Avogadro's number); one mole of photons is frequently referred to as an <u>einstein</u>

Quantity	Symbol	SI unit	Abbr.
Radiant energy	Q	joule	J
Radiant flux	Φ	watt	W
Radiant intensity	I	watt steradian^{-1}	W sr^{-1}
Radiance	L	watt steradian^{-1} m^{-2}	W sr^{-1} m^{-2}
Irradiance	E	watt m^{-2}	W m^{-2}
Radiant emittance	M	watt m^{-2}	W m^{-2}

Speak of *radiance* (emission, L) of a source and *irradiance* (E) at an object

$L(\theta,\phi) = d^2\Phi/dS \cos\theta \, d\Omega$

$E = L(\theta,\phi) \cos\theta \, d\Omega$

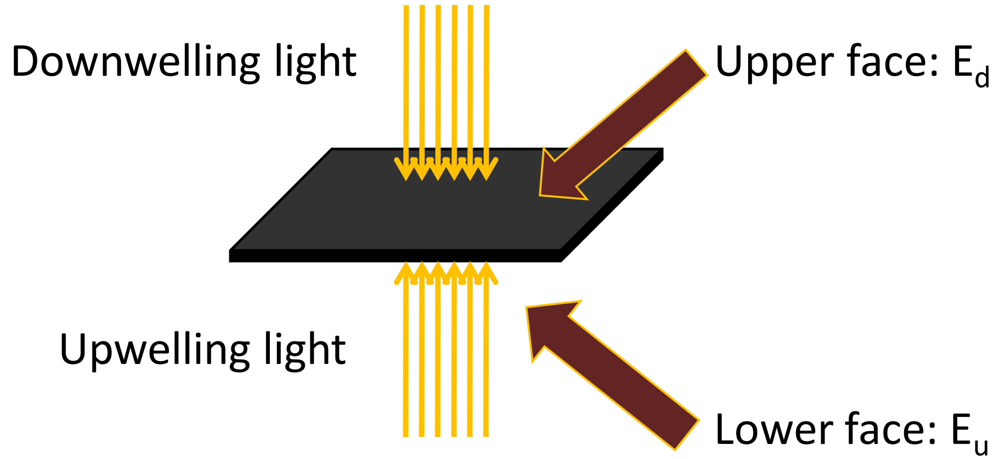


Radiance of a widespread source ds.

http://ceos.cnes.fr:8100/cdrom-00/ceos1/science/baphygb/chap2/chap2.htm

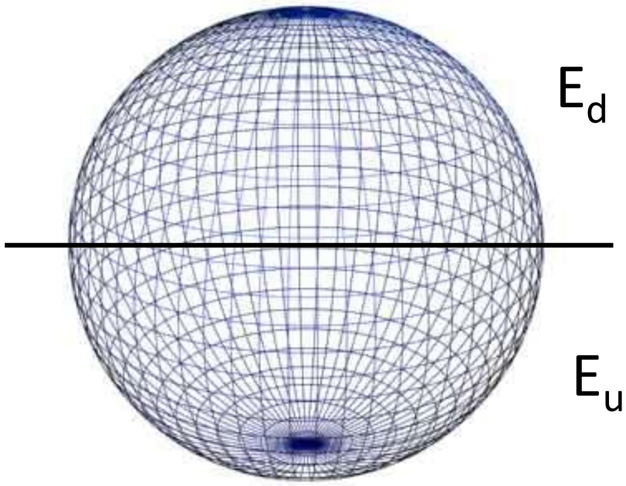
Downward vs upward irradiance

- E_d and E_u refer to value of irradiance on the upper and lower faces, respectively, of a horizontal surface
- E_d is the irradiance due to the *downwelling* light stream and E_u is that due to the *upwelling* light stream



- Total downward irradiance: $E_d = \int_{2\pi} L(\theta,\phi) \cos\theta \, d\Omega$
- Total upward irradiance: $E_u = -\int_{2\pi} L(\theta,\phi) \cos\theta \, d\Omega$
- Net downward irradiance: $E = E_d - E_u$
- $E = \int_{4\pi} L(\theta,\phi) \cos\theta \, d\Omega$ (net downward irradiance)

- Scalar irradiance, E_0, is the integral of the radiance distribution at a point over all directions about the point:
  - $E_0 = \int_{4\pi} L(\theta,\phi) \, d\Omega$ (total irradiance)



Inherent Optical Properties (IOP)

- **Definition**: properties that depend only on the water and other substances that are dissolved or suspended in it, not on the geometric structure of the light field
- Fate of photons entering water:
  - Absorption
  - Scattering
- Two IOPs: absorption coefficient (a), volume scattering function (β)
  - Scattering coefficient (b) and beam attenuation coefficient (c) derived from these
- **Absorption coefficient** (a): fraction of incident light that is absorbed divided by the thickness of the layer over which it is absorbed
- **Volume Scattering Function** (β): characterizes intensity of scattering as a function of angle.
  - β is the ratio of the intensity of scattered light (in W/sr) to the incident irradiance (in W/m^2), per unit volume (in m^3) at each angle from 0° (the original angle of the incident light) to 180° (units are (W/sr) / (W/m^2 m^3) = sr^{-1} m^{-1})

Inherent Optical Properties (IOP)

- **Scattering coefficient** (b): fraction of incident light that is scattered divided by the thickness of the layer
- **Beam Attenuation Coefficient** (c): The attenuation experienced by a hypothetical perfectly collimated beam of light ($c = a+b$)

- *Absorptance* (A) and *scatterance* (B) are the fractions of the radiant flux **lost** from the incident beam by absorption and scattering, respectively.

Quantitative expressions for absorptance and scatterance:

- Absorptance (A) = Φ_a / Φ_0
- Scatterance (B) = Φ_b / Φ_0
  - Where Φ_0 is the incident radiant flux (energy or quanta per unit time), Φ_a is the absorbed radiant flux, and Φ_b is the radiant flux scattered by the system
- Sum of absorptance (A) and scatterance (B) = attenuance (C)

  $C = A+B$

Inherent Optical Properties (IOP)

- For an infinitesimally thin layer with thickness Δr, incident flux lost by absorption and scattering are ΔA and ΔB, respectively, and:
  - $a = \Delta A/\Delta r$
  - $b = \Delta B/\Delta r$
- c is the fraction of incident flux which is absorbed and scattered, divided by the thickness of the layer, r ($c = \Delta C/\Delta r$)
- The *change* in radiant flux (Φ) in passing through a layer Δr is $\Delta\Phi$. The attenuance of the thin layer is:

$\Delta C = -\Delta\Phi/\Phi$; and $\Delta\Phi/\Phi = -c\Delta r$

Attenuation coefficient, c

$\Delta\Phi/\Phi = -c\Delta r$

- Integrating between 0 and r we obtain:

  $\ln \Phi/\Phi_0 = -cr$, or $\mathbf{\Phi = \Phi_0 e^{-cr}}$

- This may be written as:

  $c = 1/r \ln \Phi_0/\Phi$

  or

  $c = -1/r \ln (1-C)$

- Therefore, *c* can be obtained from measurements of the diminution in intensity of a parallel beam passing through a known pathlength of medium, r.

Apparent Optical Properties (AOP)

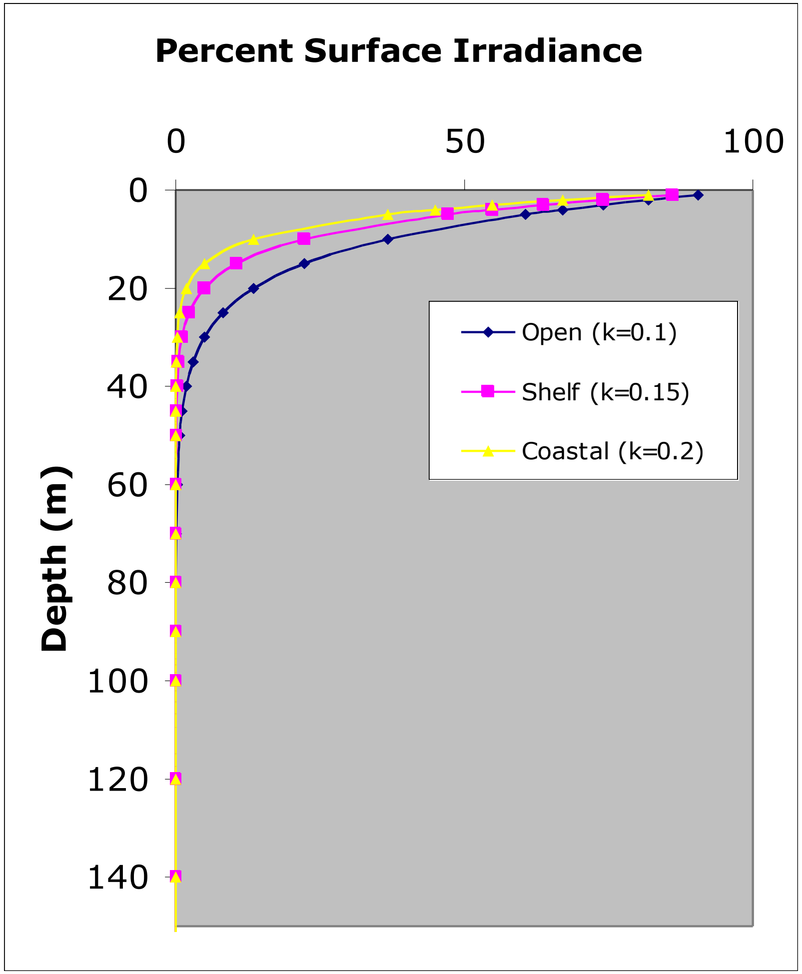
- Definition: properties that depend both on inherent optical properties (IOPs) and on the light field in which they are measured

- Vertical attenuation coefficients (K) for radiance, irradiance, and scalar irradiance are referred to as *Apparent Optical Properties*; reflectance (R) is also considered an AOP

- In practice, every optical measurement is dependent on the light field used for the measurement, but instruments for IOP measurements provide their own controlled light field rather than relying on ambient light. In contrast, AOPs are typically derived from measurements of ambient light

Light attenuation

- Light attenuation is a function of depth (z)
- $I_z = I_0 e^{-kz}$
  - z = depth (m)
  - I_0= light at surface (e.g. 100%)
  - I_z = light that penetrates to depth z
  - k_d = diffuse attenuation coefficient (m^{-1})
    - Function of how "clear" the water is
    - Open ocean, k_d=0.10
    - Coastal ocean, k_d=0.20



Practical application: measuring light

- Instruments to measure IOP
  - a and β, scattering (b_b, b_f) (e.g. HydroScat series, HOBI labs)
  - Transmissometer (attenuation, beam-c)
  - Absorption (a) and attenuation (c) (AC-meters, AC-S, AC-9, WetLabs)
- Light sensors/radiometers
  - Integrated (e.g. PAR) BioSpherical light meter (quantum scalar irradiance, QSL, meter)
  - Multispectral (Satlantic)
  - Hyperspectral (Satlantic)

THE AC-SPECTRA, AN INSTRUMENT FOR HYPERSPECTRAL CHARACTERIZATION OF INHERENT OPTICAL PROPERTIES IN NATURAL WATERS

www.wetlabs.com

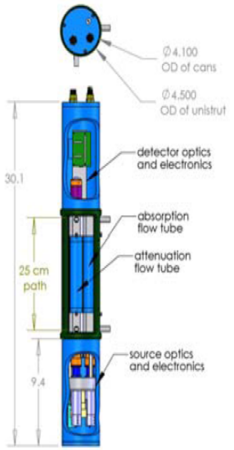
RHOADES, BRUCE
Derr, Alex; Moore, Casey; Zaneveld, Jacques Ronald
WET Labs Inc, PO Box 518, Philomath, OR USA



A newly designed instrument couples a high spectral resolution scanning spectral source with proven sampling optics to provide in situ beam attenuation and absorption coefficients at 4 nm resolution from 400 nm to 720 nm. The dual path instrument incorporates two Argon filled incandescent bulbs that are spectrally dispersed by a rotationally scanning linear variable filter. Light propagates through the water via separate 25 cm length optical paths. The attenuation measurement employs a collimated beam within the optical path that is refocused upon a narrow aperture receiver. The absorption measurement also uses a collimated beam propagated through a reflective tube onto a large area detector.

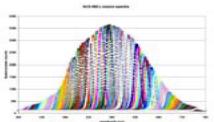
DESCRIPTION

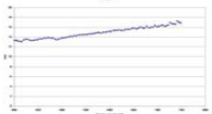
The ac-s is composed of two pressure housings separated by a unistrut frame. The lower housing holds the source optics which include two incandescent lamps that couple into a single scanning filter spectrometer. Light output from the spectrometer is collimated and then propagates into the volume separating the two housings. Within this volume two continuous flow cells surround the optical paths. The absorption path is surrounded by a reflective quartz tube which constrains scattered light within the diameter of the tube. The attenuation path tube has blackened walls which absorbs scattered light from the attenuation beam path. Light reaching the end of the absorption tube is collected by a large area detector. Light reaching the end of the attenuation path propagates into the second receiver housing and is refocused upon a small aperture and detector. The receiver housing also holds the acquisition and control electronics for the sensor.



SOURCE SPECTROMETER

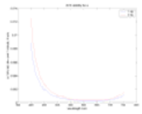
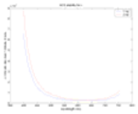
The ac-s uses a linear variable filter (LVF) scanning spectrometer to provide its spectral output. The scanning spectrometer provides a minimum resolution of approximately 3 nm although the spot size of the beam creates an effective 4-5 nm resolution for the instrument. Center wavelength bands and FWHM resolution of the source spectrometer were determined by projection of a white-light source through the scanning filter upon a calibrated grating spectrometer and determining wavelength as a function of encoder position.



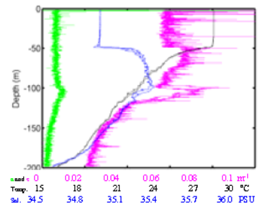


For the beam spot size used, the LVF filter demonstrated effective full-width-half-maximum (FWHM) bandwidths ranging from 13 to 17 nm.

PERFORMANCE

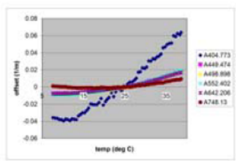



Noise and temperature performance are two of the most defining aspects of ac-s sensor behavior. Noise performance ultimately limits the meter's ability to resolve signals in the water. In very approximate terms an attenuation signal resolvable to 0.001/m represents the ability to see changes in total suspended mass levels on the order of 1 part per billion (Howard, 1979). The above plots show the average noise (standard deviation in inverse meters) in the ac-s as a function of wavelength.

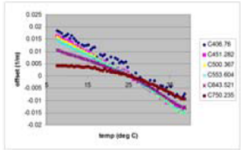


In-situ measurements demonstrate instrument stability and precision. Absorption (673nm, green line), Beam attenuation (650nm, magenta line), Temperature (black line) and Salinity (blue line) profiles taken at the Hawaii Ocean Time Series (HOTS) Aloha site near 22.75°N, 158°W (approximately 100 km north of Oahu, Hawaii) on August 11, 2004. The data were obtained during one down and up profile.

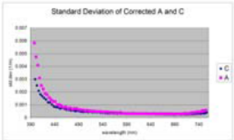
A



B

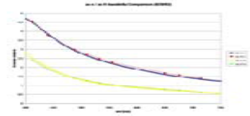


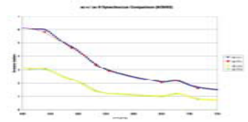
C



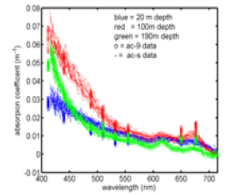
The sensor's response to temperature is critical in defining its over all stability. Plots A and B show uncorrected attenuation and absorption values of selected wavelengths subjected to a 30 degree C temperature change. Plot C demonstrates net change after temperature correction through the entire 30 degree temperature cycle.

AC-S - AC-9 COMPARISON





The ac-s underwent extensive evaluation in comparison with an ac-9. The ac-9 response is well understood, and has been proven effective in measurement of natural waters. It thus serves as a viable platform for comparison. Basic comparison tests proved critical even during prototyping of the instrument. These were the defining litmus tests in pursuing the described design path.



Data obtained at near the HOTS Aloha site show multiple spectra obtained at three depths, by an ac-s and co-located ac-9. The data, which has been corrected for water temperature and salinity values shows that ac-s and ac-9 measurements agree to within 0.005 m^{-1}.

DISCUSSION

The ac-s represents both a logical evolution of a proven design and a significant departure from the original effort. While the fundamental optical design is largely preserved with respect to the ac-9, the meter holds new solutions for the scanning spectrometer, the control and acquisition electronics and other critical system components. As a result the instrument offers ac-9 measurement performance with improved spectral discrimination, and is in many respects simpler to build, easier to tune, and simpler to characterize than its predecessor.

Critical development tasks remain. Presently optical throughput below 450 nm limits sensor precision. Efforts are currently underway to improve this performance. Additionally, new software will provide more completely processed data. Our goal is to automate the application of temperature, salinity, and scattering corrections to *in situ* absorption measurements. The ac-s was designed as part of a larger platform for providing a multi-parametric determination of specific biogenics in the water. Another component yet to be implemented on this device will be an in-line spectral fluorescence measurement concurrent with the attenuation and absorption coefficient determinations.

ACKNOWLEDGEMENTS

Primary efforts for this project were carried out under the auspices of NASA SBIR contract # NAS13-02055 through Stennis Space Center.

The National Oceanographic Partnership Program (NOPP) helped support conceptual groundwork, testing and validation of the ac-s.

Special thanks to Tommy Dickey, Grace Chang, Victor Kuwahara, and Derek Manov, UCSB for assistance in collection and analysis of data.

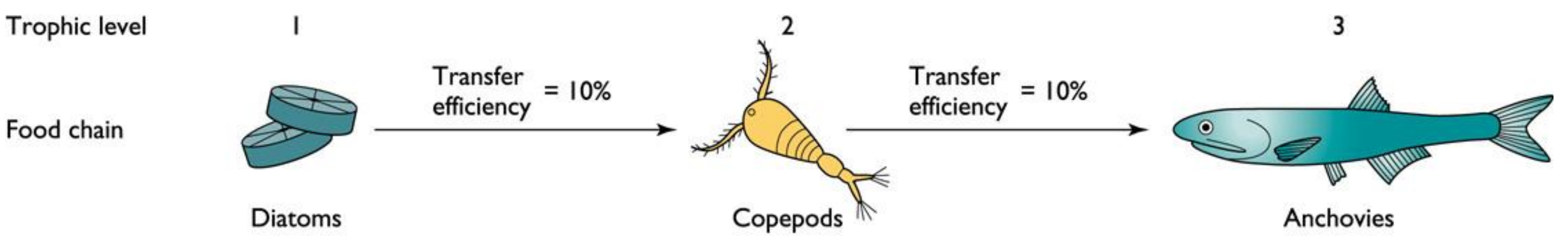
Energy fixation

- Energy from sunlight is fixed through photosynthesis:

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

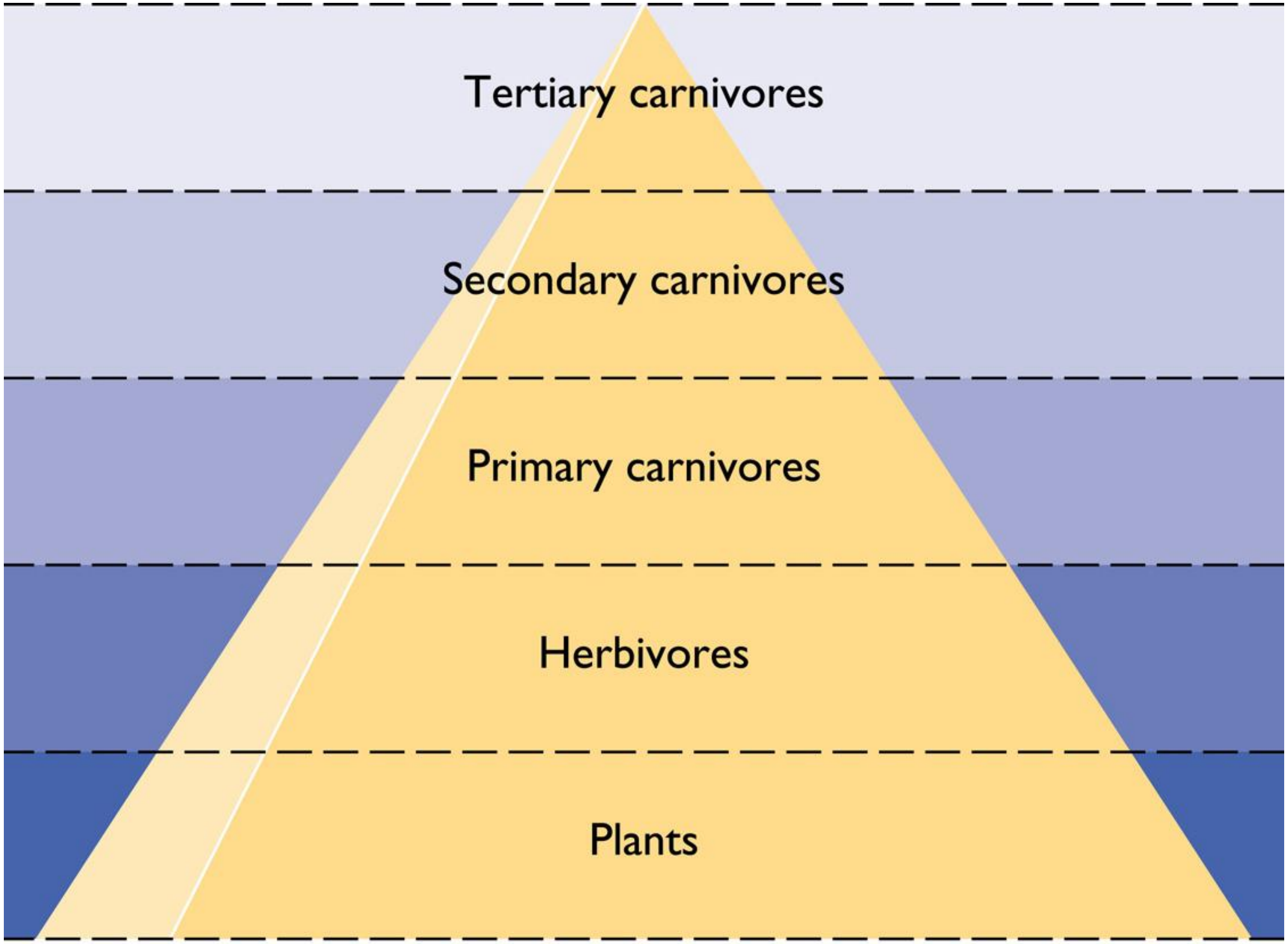
- This energy is used to fuel cell metabolism and growth; approximately 10% is converted to higher trophic levels through grazing of plant material

High Latitude "Food Chain"



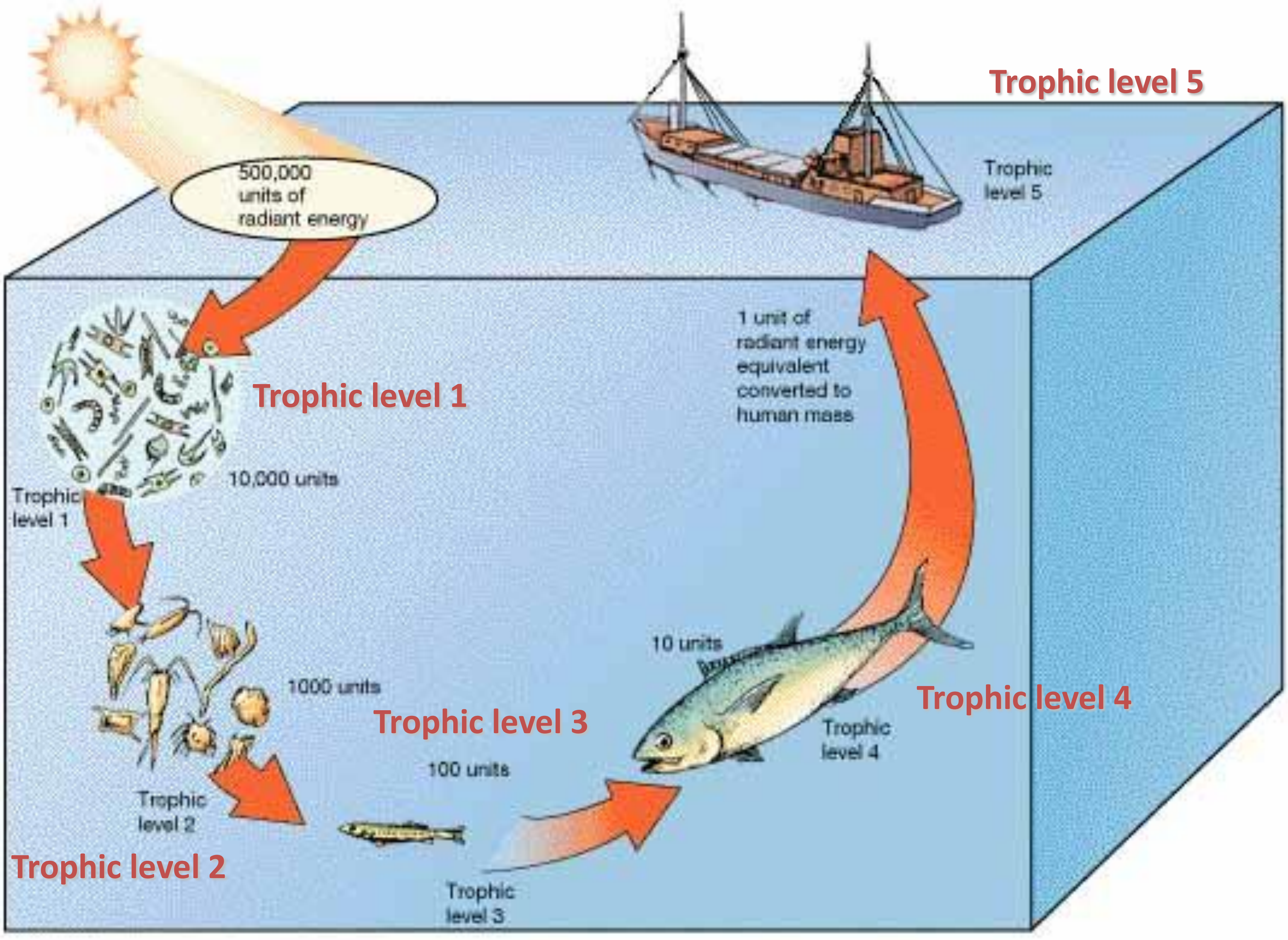
- Successive trophic levels
  - Larger, fewer organisms with longer generation times
- Time lag as move up the chain

“Trophic Pyramid”



(c) ENERGY PYRAMID

Plankton to Tuna (to Humans)

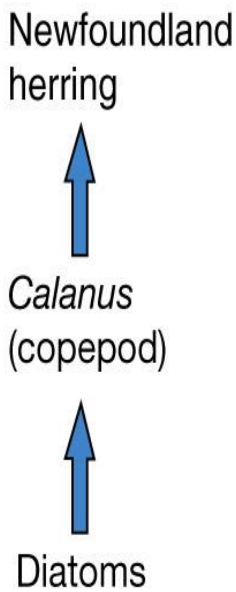


Trophic Levels

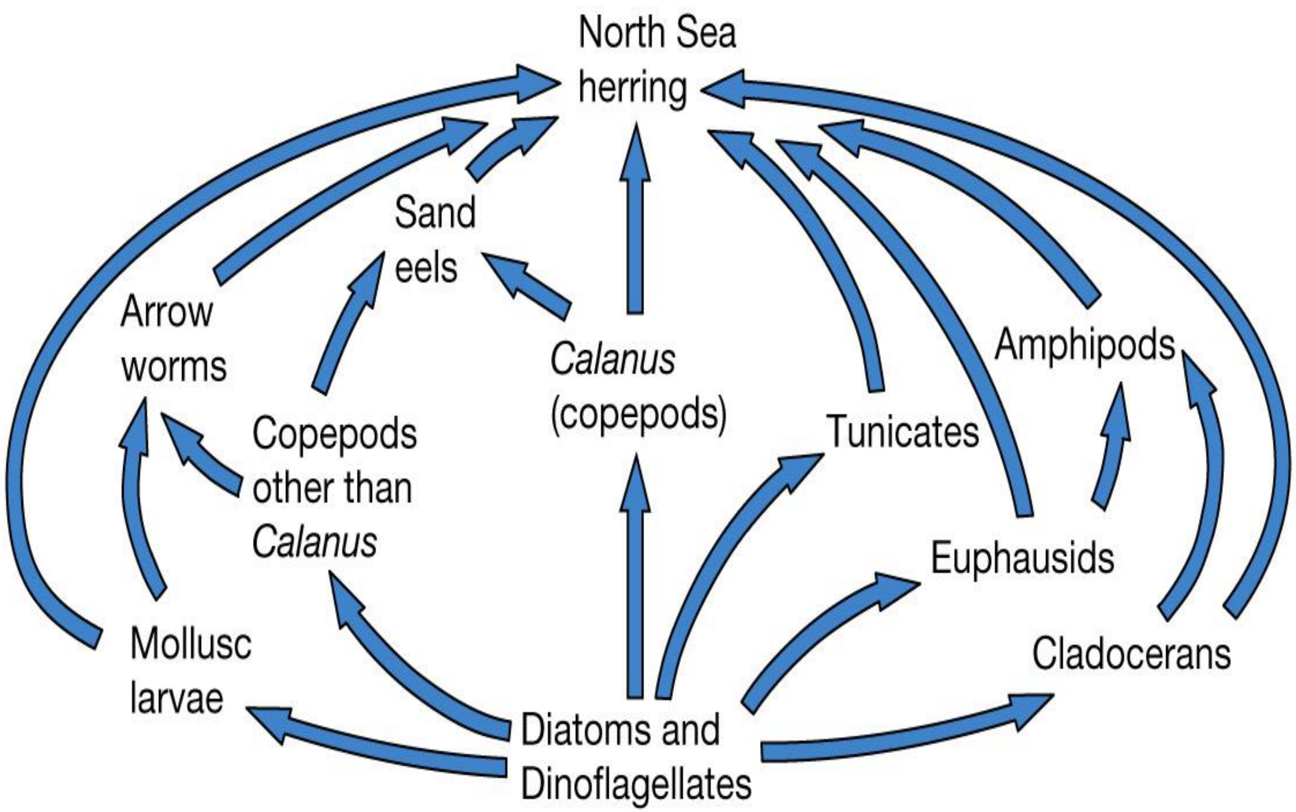
- Total # of levels depends on
  - Energy available
  - Recycling efficiency
    - Eventually, not enough energy for another level
- Successive trophic levels
  - Larger, fewer organisms with longer generation times
- Complication: the microbial loop & viral shunt

Trophic transfer efficiency

- 90% energy lost at each level
  - Where does it go?
    - Respiration
    - Movement
    - Thermoregulation
    - Reproduction
      - Broadcast spawners



(a) Three-level food chain of Newfoundland herring



(b) Food web of North Sea herring containing many food chains

Big Picture

- What factors influence the amount of photosynthesis on Earth? How are these factors influenced by climate change and anthropogenic activities?
  - Mixed layer depth (Behrenfeld et al., 2007)
    - River flow
  - Coastal run-off
  - Upwelling
- What changes can we expect in the California Current system?
  - Kahru et al., 2009; DiLorenzo et al., 2008