海洋光学仪器简介

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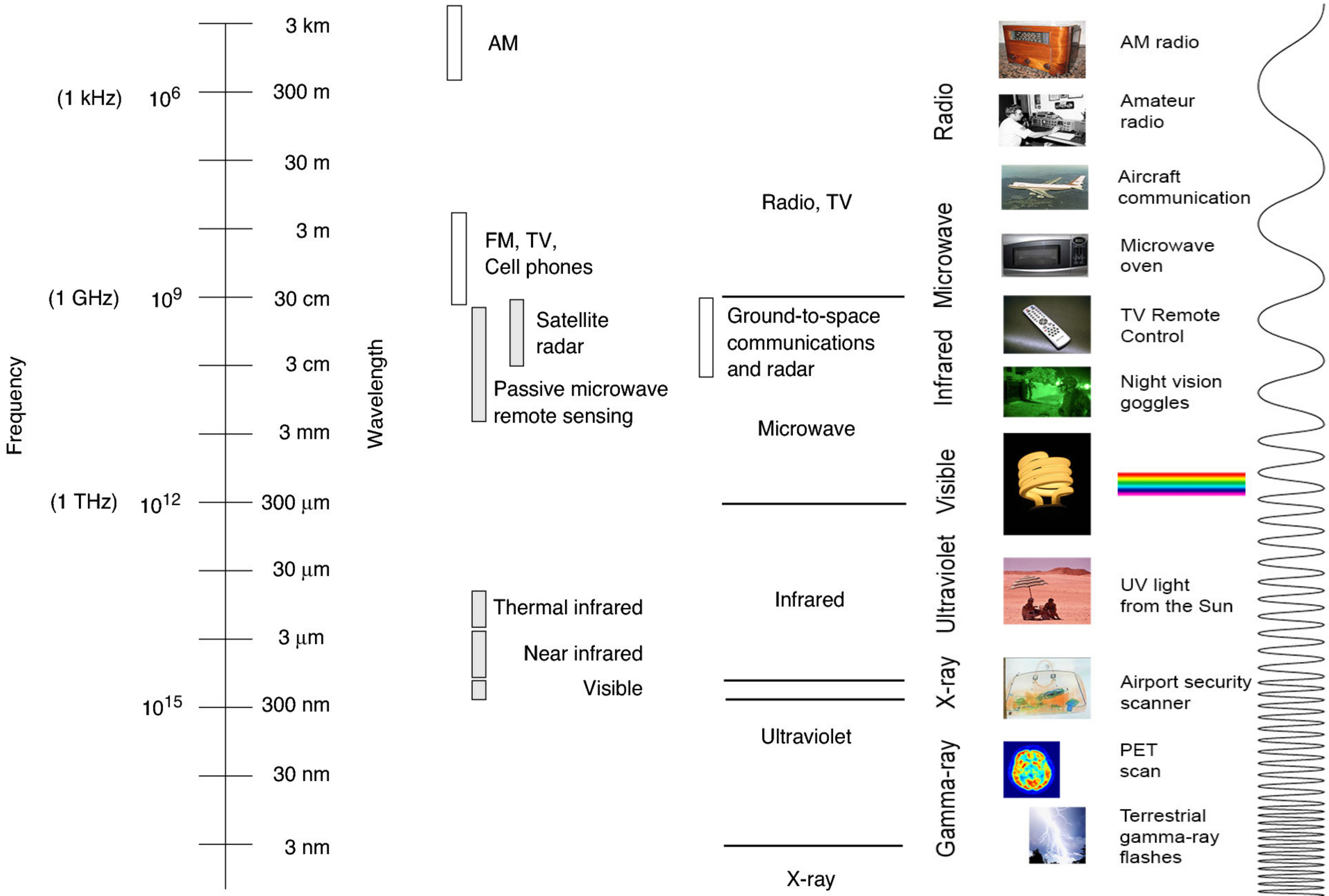
电磁波的波段 (Bands of Electro-Magnetic Waves)



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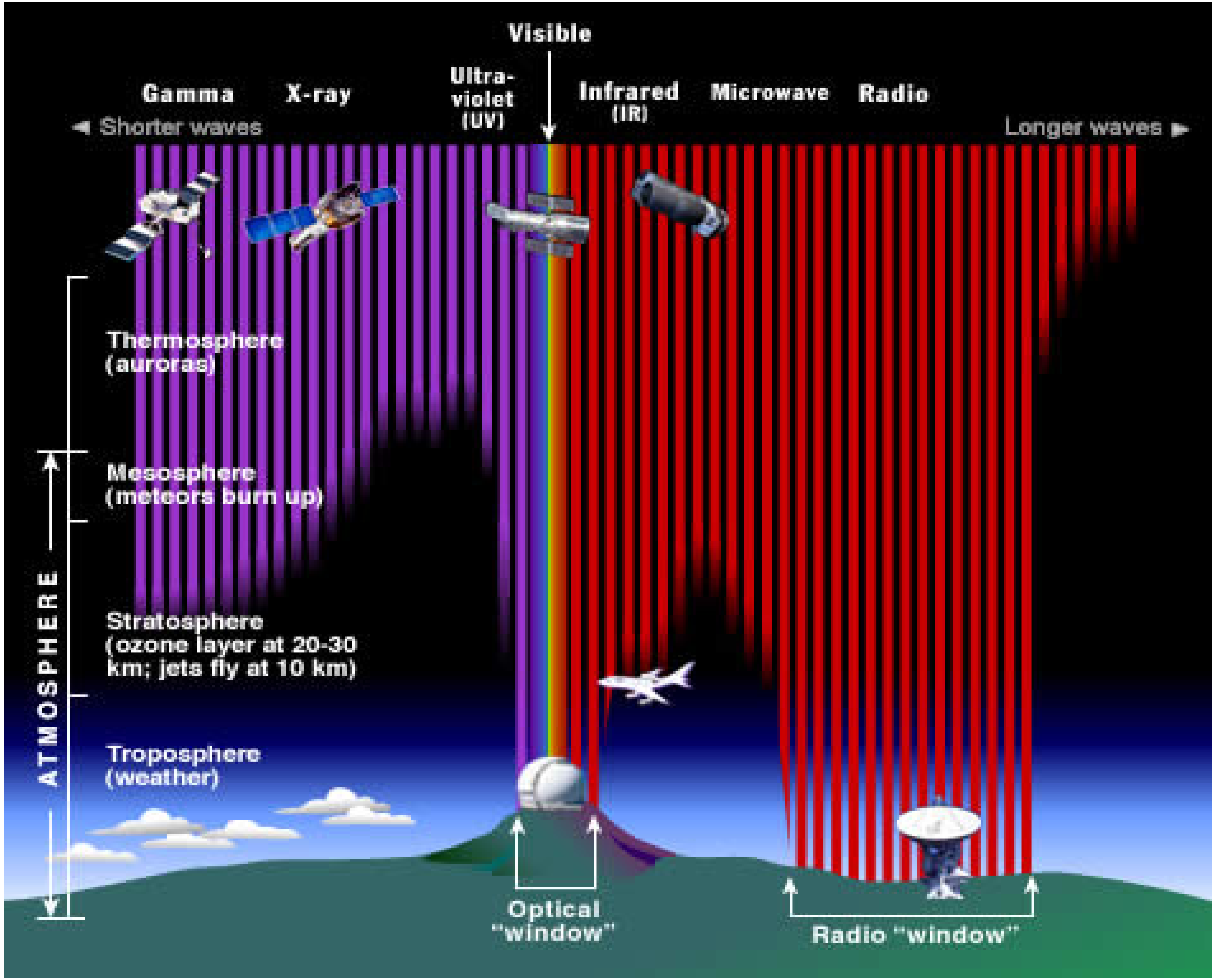
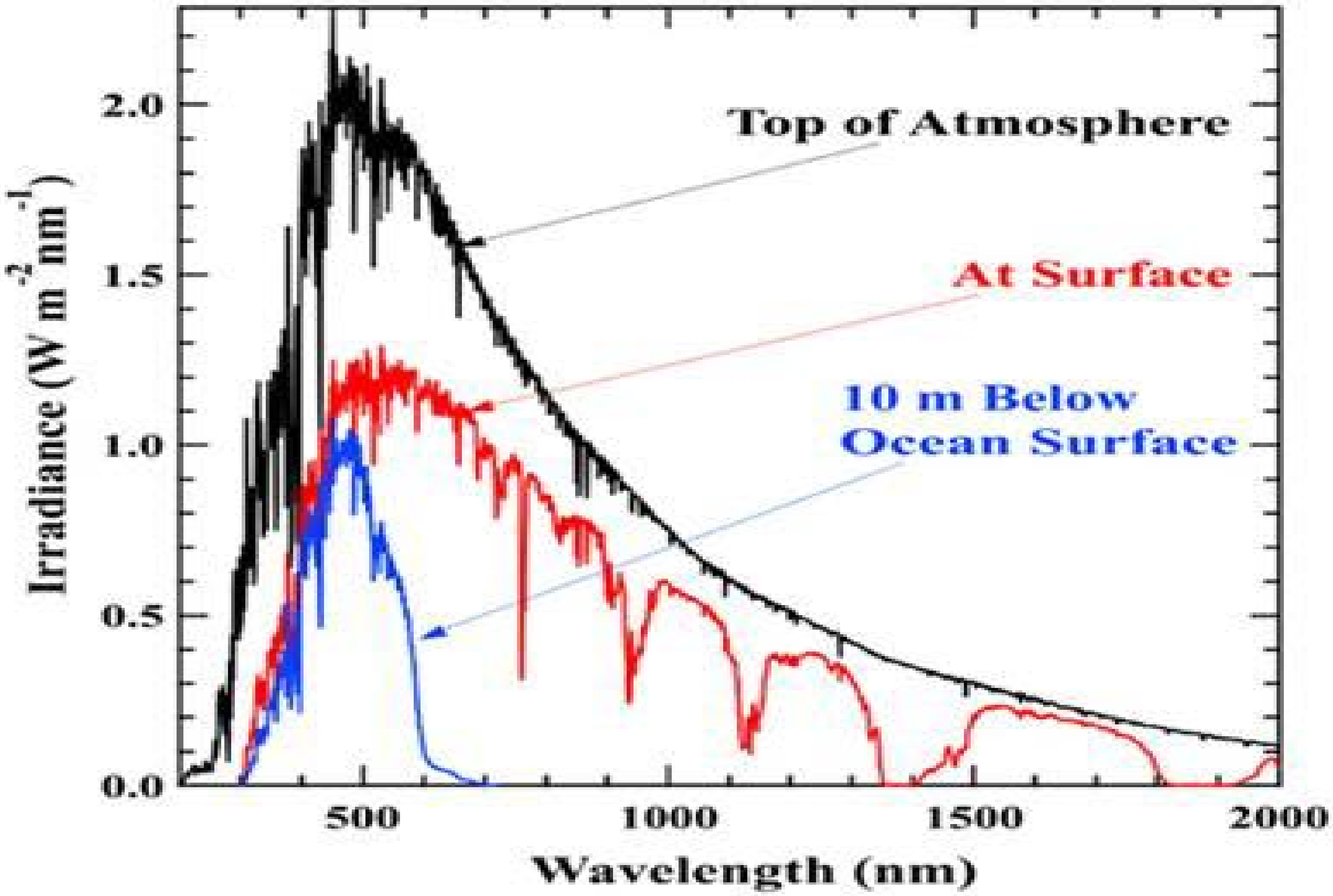
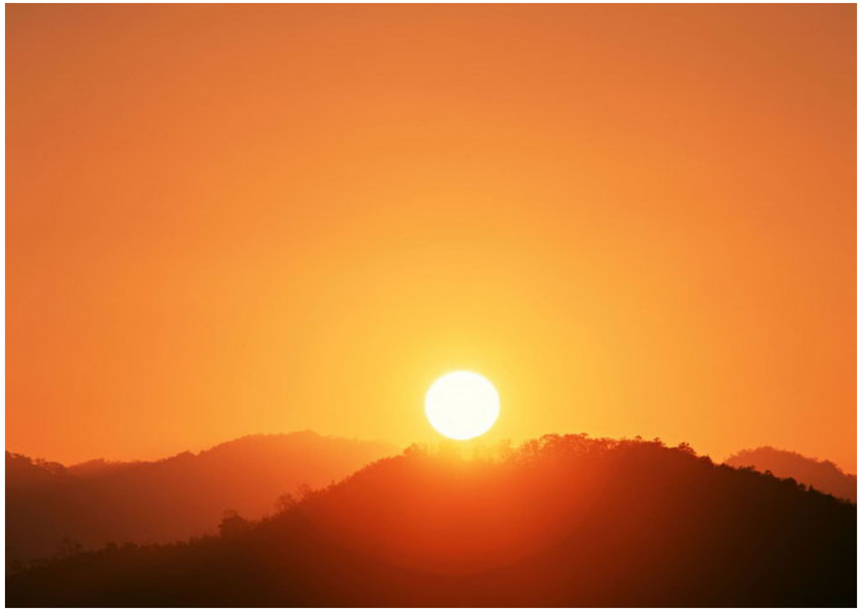




- 大气
  - ✓ 大气分子
  - ✓ 气溶胶
  - ✓ 云
- 海洋水体
  - ✓ 纯海水
  - ✓ 颗粒物
  - ✓ 可溶物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问 题

如果地球表面没有大气层：

- 太阳是什么颜色的？
- 天空是什么颜色的？
- 入射光线角度是多少？

问 题

如果地球表面没有大气层：

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- 天空是什么颜色的?
- 入射光线角度是多少?

大气改变了入射太阳光的强度、颜色、传播方向

问 题

如果海洋中没有吸收只有散射作用：

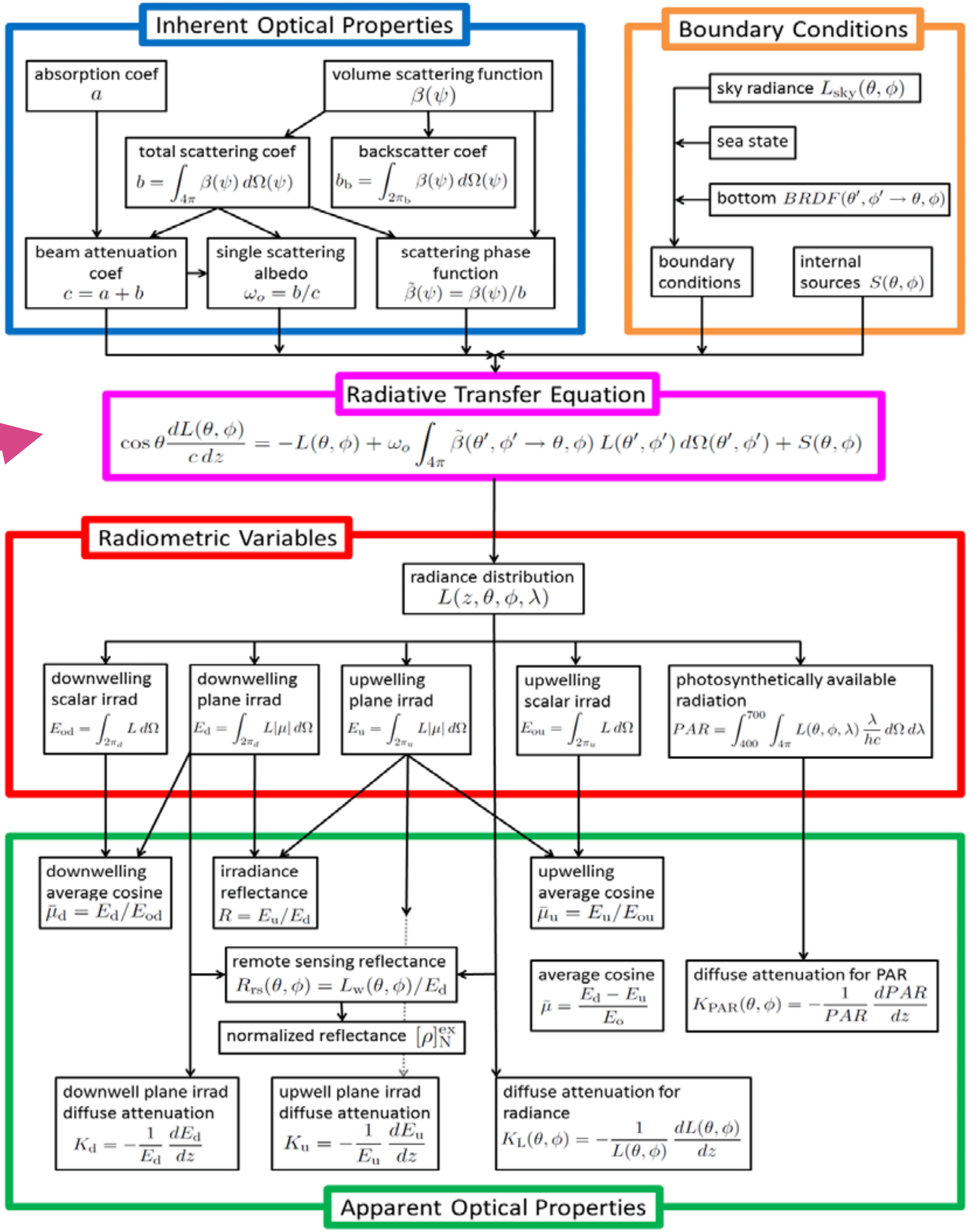
如果海洋中没有散射只有吸收作用：

- 海洋是什么颜色的?

固有光学性质

辐射传输模拟

表观光学性质



http://www.oceanopticsbook.info/view/radiative_transfer_theory/radiative_transfer_equations

辐射术语

辐射能 Q (Radiant Energy)：表示辐射能量的多少，单位是J（焦耳）

辐射通量 Φ (Radiant Flux)：单位时间里接收的辐射能量，单位是W（瓦特，1W=1J·s^{-1}）

辐射强度 I (Radiant Intensity)：点光源在特定方向上单位立体角的辐射通量

$$\Phi = \frac{dQ}{dt} \qquad I = d\Phi / d\Omega \, [W \cdot sr^{-1}]$$

辐射术语

辐亮度L （Radiance）：沿辐射方向单位面积和单位立体角的辐射通量。单位[$Wm^{-2}sr^{-1}$]

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

光谱辐亮度L(λ)（Spectral Radiance）：单位波段（波长或频率）内沿辐射方向单位面积和单位立体角的辐射通量。

$$L(\lambda,\theta,\phi)=\frac{dL(\theta,\varphi)}{d\lambda}\quad[W\cdot m^{-2}\cdot sr^{-1}\cdot\mu m^{-1}]$$

辐射术语

辐照度E（Irradiance）：表示通过单位面积的辐射通量．单位是[W．m^{-2}]

光谱辐照度E(λ)（Spectral Irradiance）：辐照度相对于频率或波长的能量分布．单位是[W．m^{-2}．μm^{-1}]

$$
\begin{aligned}
E &= \frac{d\Phi}{dA} \\
&= \int_{\Omega} L(\theta,\varphi)\cos\theta d\Omega \\
&= \int_0^{2\pi} d\varphi \int_0^{\frac{\pi}{2}} L(\theta,\varphi)\cos\theta\sin\theta d\theta
\end{aligned}
$$

$$E(\lambda) = dE / d\lambda$$

辐射术语

海洋水色遥感中，又分为海水内垂直剖面的上行辐照度（upwelling/upward irradiance）和下行辐照度（downwelling/downward irradiance）

$$E_u(z,\lambda)=\frac{d^2\Phi_u(z,\lambda)}{dAd\lambda}=\int_0^{2\pi}d\varphi\int_0^{-\frac{\pi}{2}}L(z,\lambda,\theta,\varphi)\cos\theta\sin\theta d\theta$$

$$E_d(z,\lambda)=\frac{d^2\Phi_d(z,\lambda)}{dAd\lambda}=\int_0^{2\pi}d\varphi\int_0^{\frac{\pi}{2}}L(z,\lambda,\theta,\varphi)\cos\theta\sin\theta d\theta$$

辐射术语

Energy from the Earth & Atmosphere Q

over time is

Flux Φ

which strikes the detector area

Irradiance E

at a given wavelength interval

Monochromatic Irradiance E(λ)

over a solid angle on the Earth

Radiance observed by satellite radiometer L(λ)

is described by

The Planck function

can be inverted to

Brightness temperature

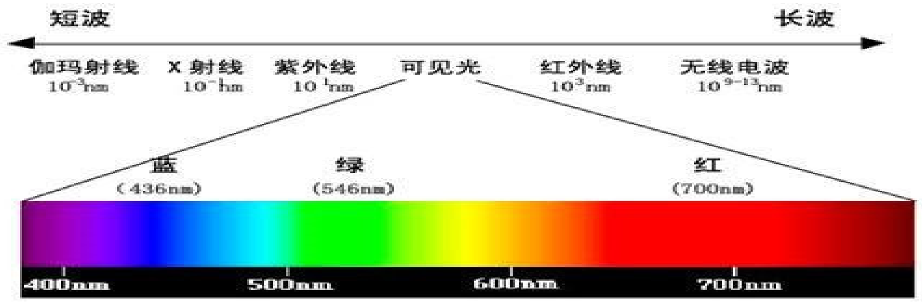
辐射术语

海洋水色遥感中，又定义了离水辐亮度(Water-Leaving Radiance) $L_w(\lambda,0)$，与海面下的向上辐亮度的关系是

$$L_w(\lambda,0)=\frac{t_i L_u(\lambda,0^-)}{(n')^2}$$

- 式中L_u（λ,0^-）代表海面下的向上辐亮度，
- 自变量“0^-”表示表示刚好处于水表面以下下角标“u”表示向上辐亮度。
- n′ 是海-气界面复折射率的实部，也称为折射率。
- $(n')^2$表明光由海水到大气传播时光束立体角变化带来辐亮度的变化。
- 水-气界面透射率t_i与菲涅耳反射率的关系是 $t_i=1-\rho$
- 式中ρ是在太阳光垂直入射条件下水-气界面的菲涅耳反射率；在可见光和近红外波段，ρ ≈ 0.02，t_i = 1- ρ ≈ 0.98。

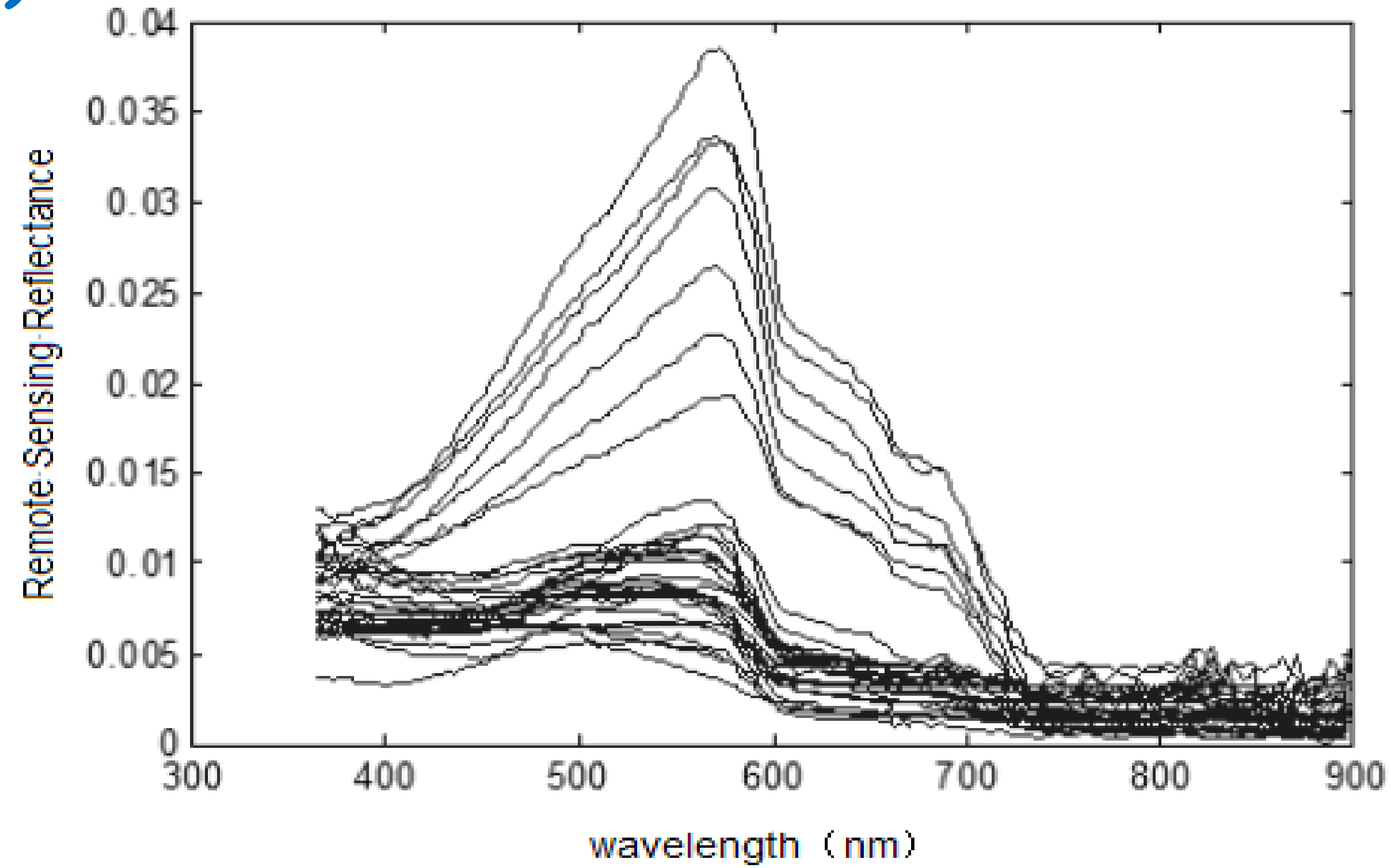
辐射术语



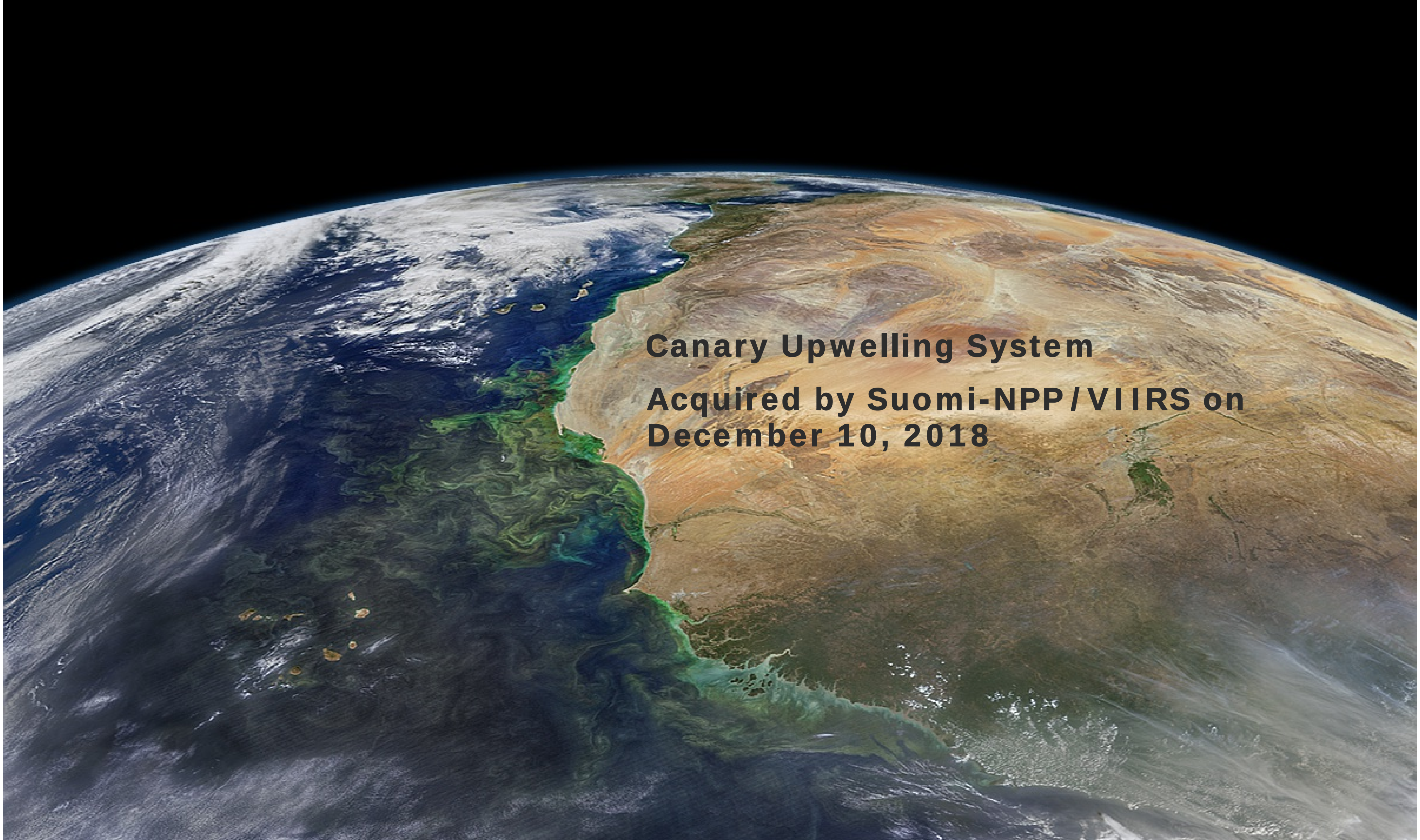
海洋水色遥感中，定义了遥感反射比 (Remote-sensing Reflectance) $R_{rs}(\lambda,0)$

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

$$=\frac{L_w(\lambda)}{F_s(\lambda)\cos\theta_s t(\lambda,\theta_s)}$$



https://oceancolor.gsfc.nasa.gov/gallery/614/



表观光学性质

- 遥感反射比测量方法

✓ 水上测量法

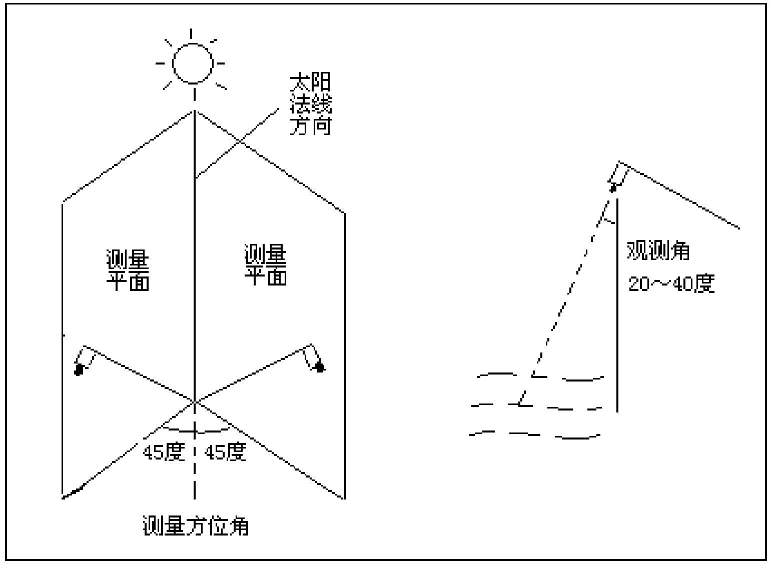
✓ 水下测量法

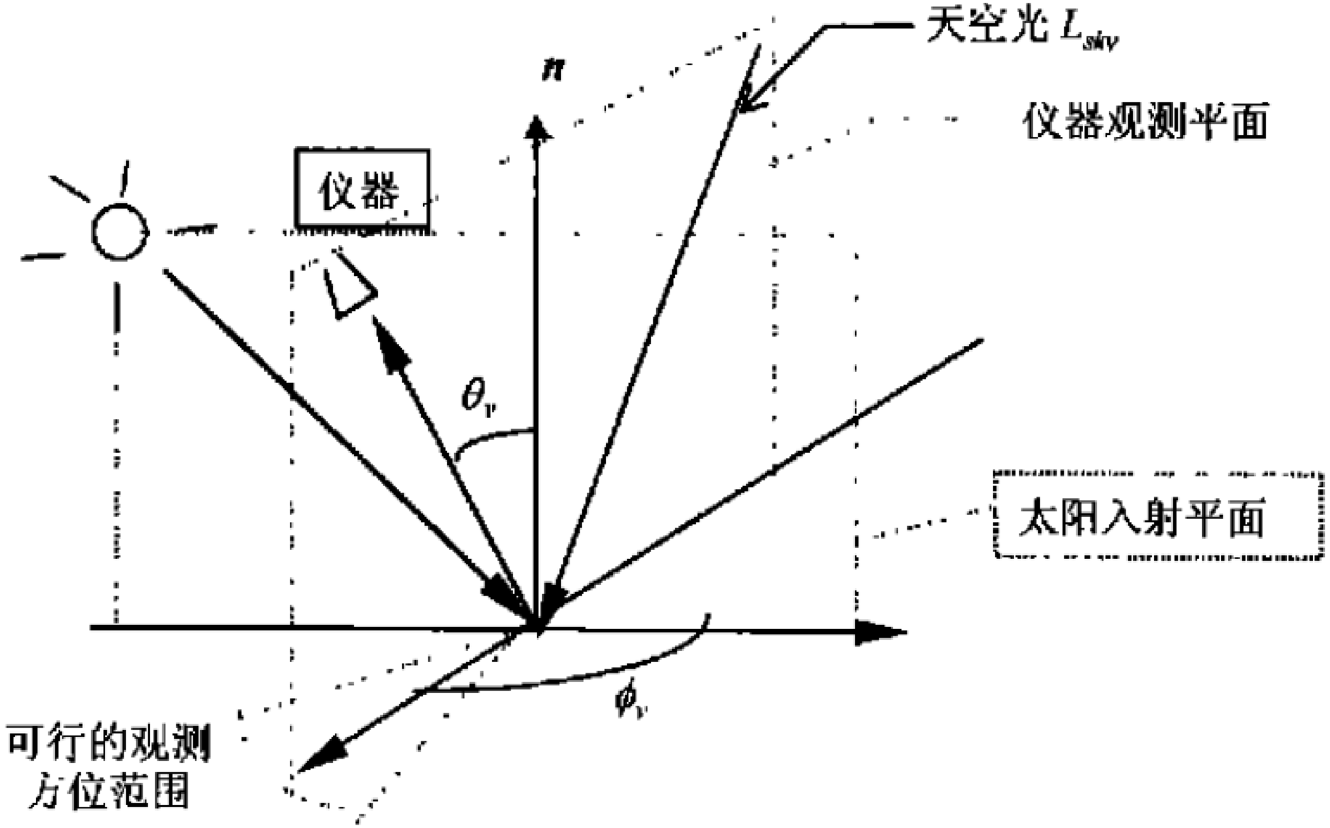
✓ 水面测量法

● 遥感反射比测量方法

表观光学性质

✓ 水上测量法





避免绝大部分的太阳直射反射

• 遥感反射比测量方法 水上测量法

表观光学性质

离水辐亮度L_w为

$$L_w(\lambda,\varphi,\theta) = L_{sea}(\lambda,\varphi,\theta) - rL_{sky}(\lambda,\varphi,\theta)$$

遥感反射比R_{rs}为

$$R_{rs} = \frac{L_w}{E_s}$$

归一化离水辐亮度为 $L_{wn} = \dfrac{\overline{F}_0}{E_s} L_w$

• 遥感反射比测量方法　水上测量法

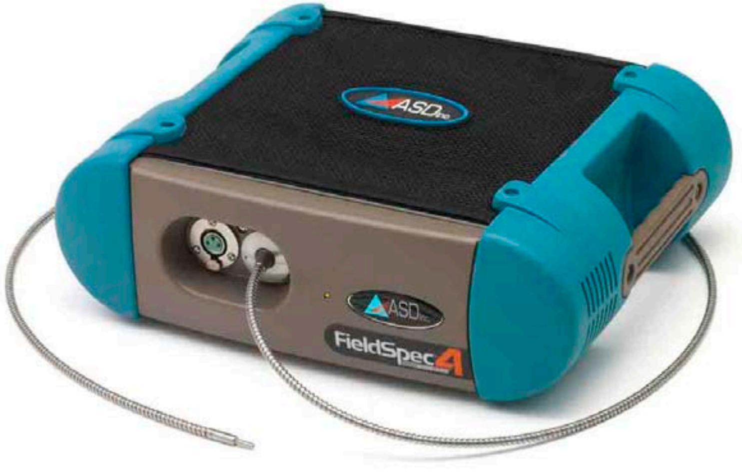
海面高光谱测量仪HYPERSPECTRAL SURFACE ACQUISITION SYSTEM (HYPERSAS)

- HyperSAS可沿着船舶的航迹对水色进行连续观测，也可安装在海上测量平台上进行长时间连续观测，或安装在航空器上遥测水色。
- 136个通道的辐亮度和辐照度传感器，可同时对空中和海面进行测量。
- 此外，HyperSAS可以选配GPS设备和Satlantic倾斜和方向传感器，为所获得的光学数据提供精确定位、地理参考资料和准确的时间标注。

	空气中的辐照度	空气中的辐亮度
视野:	余弦 ±3% 0 - 60° 10% 60° - 85° (350 – 800 nm)	3° (FOV 加大光圈)
典型饱和度:	9 W cm-2nm-1	0.5 W cm-2nm-1
信噪比:	1.6×10^4	1.6×10^4
尺寸:	高39.9 (cm) 直径6.0 (cm) 重量1.0 (kg)	高36.2 (cm) 直径6.0 (cm) 重量1.0 (kg)
工作环境温度:	-10 to +50 °C	-10 to +50 °C

• 遥感反射比测量方法 水上测量法

表观光学性质



太阳光在海面上的入射辐照度为

$$E_s(\lambda,\varphi_0,\theta_0)=\pi\frac{L_p(\lambda,\varphi_0,\theta_0)}{\rho_p(\lambda)}$$

离水辐亮度L_w为

$$L_w(\lambda,\varphi,\theta)=L_{sea}(\lambda,\varphi,\theta)-rL_{sky}(\lambda,\varphi,\theta)$$

遥感反射比R_{rs}为

$$R_{rs}=\frac{L_w}{E_s}$$

表观光学性质

- **遥感反射比测量方法**

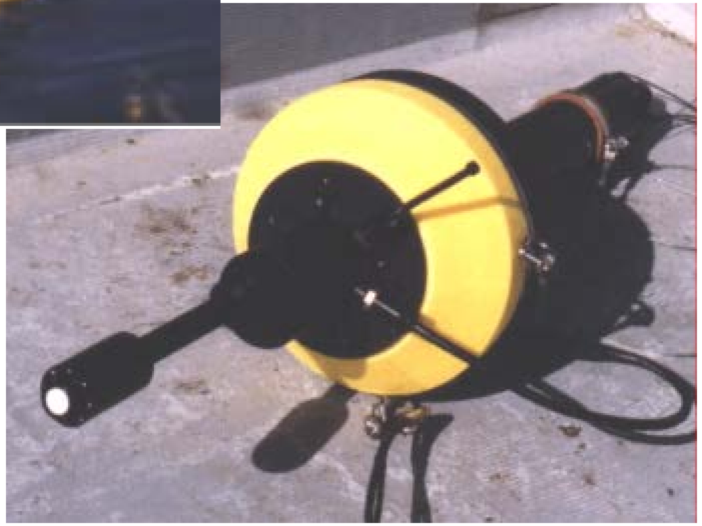
ASD(Analytica Spectra Devices., Inc)地物光谱分析仪FieldSpec 4

波长范围	350-2500 nm
光谱分辨率	3 nm @ 700 nm 10 nm @ 1400/2100 nm
光谱宽度	1.4 nm @ 350-1000 nm 1.1 nm @ 1001-2500 nm
通道数	2151
探测器	VNIR (350-1000 nm): 512 element silicon array SWIR 1 (1001-1800 nm): Graded Index InGaAs Photodiode, Two Stage TE Cooled SWIR 2 (1801-2500 nm): Graded Index InGaAs Photodiode, Two Stage TE Cooled
光纤光学探头	1.5 m fiber optic (25° field of view). Optional narrower field of view fiber optics available.
重量	5.44 kg (12 lbs)
测量参数	反射率、辐亮度

- **遥感反射比测量方法**

✓ **水下测量法**

自由落体式的水色剖面测量



浮标式测量

• 遥感反射比测量方法

Satlantic公司Profiler II自由落体式水下光谱剖面仪

- Profiler II可做自由落体式的水色剖面测量，也可以连接一个分离式的浮筒对海水近表面水层进行测量(HyperTSRB)。
- 可以提供的数据有：离水辐亮度、遥感反射比、能量通量、有效光合辐射和漫衰减系数等。
- **自由落体式的剖面测量模式：**
  Profiler II的最大优势是可以远离船体并作自由落体式剖面测量，避免了船体阴影的干扰。
  Profiler II配备压力传感器和倾斜度传感器，剖面测量时监测下降速度和角度。
- **水面测量模式：**
  Profiler II系统可以通过连接一个浮球立即将剖面仪改装为近水面观测装置，提供实时观测数据。

遥感反射比测量方法

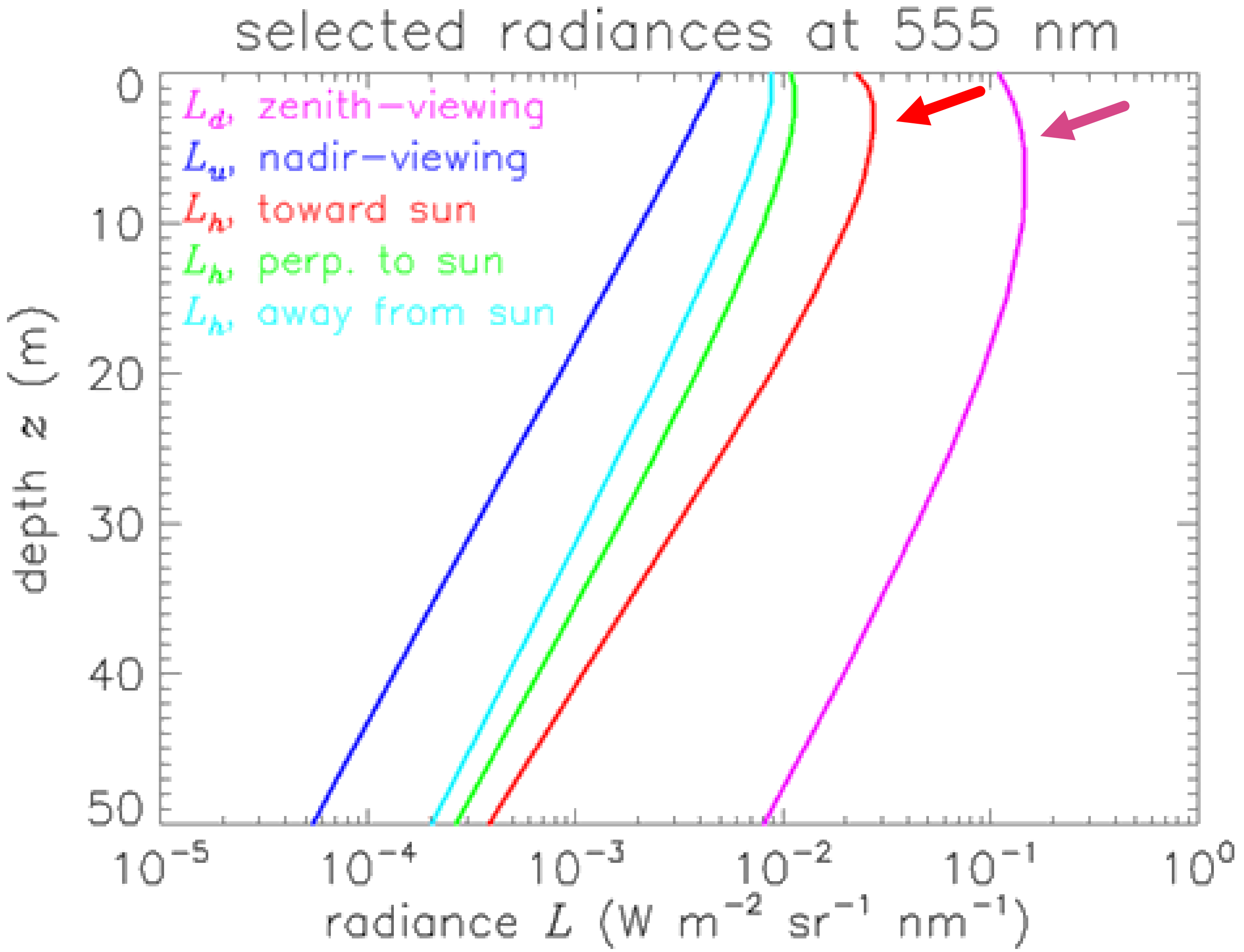
Satlantic公司Profiler II自由落体式水下光谱剖面仪

Radiometer	Distance to Surface	Distance to Pressure
HyperOCR ICSW (as Ed)	0	0.786 m
HyperOCR ICSW (as Lu)	0.316	0
HyperOCR ICSW (as Eu if in profiler mode – RECOMMENDED)	1.068 m	0
HyperOCR ICSW (as Eu if in surface mode as reference – NOT RECOMMENDED)	0.200 m	0.470 m
HyperOCR R08W	0.316 m	0
HyperOCR R08W (if Eu present in surface mode as reference)	0.200 m	0

L_u 向上或天底观测

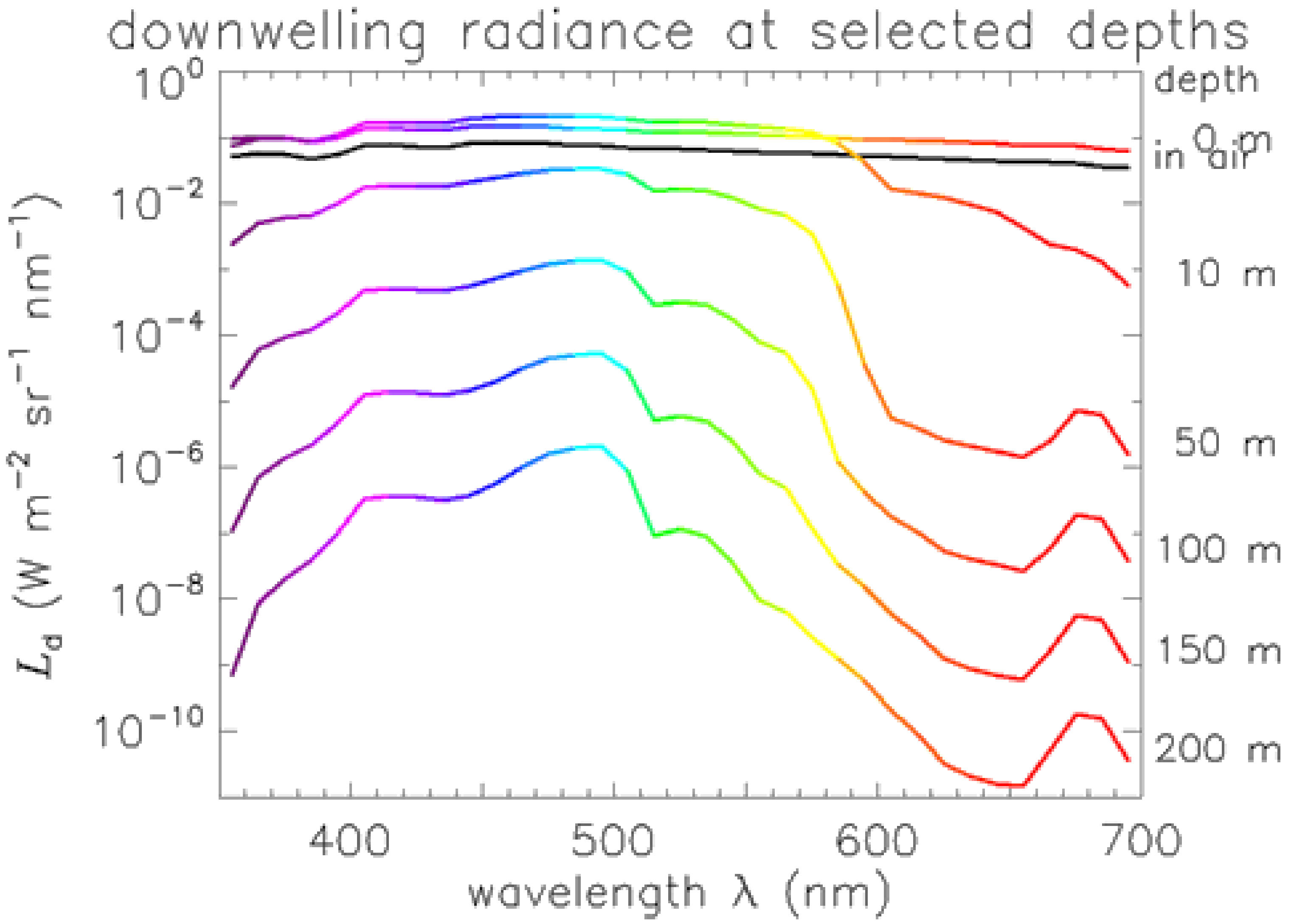
L_d 向下或天顶观测

L_h 水平观测，观测方位角面向、背对偏离太阳平面一个角度、垂直太阳平面。



555nm波段的在几个观测方向上的辐亮度随深度变化

http://www.oceanopticsbook.info/view/light_and_radiometry/visualizing_radiances



向下辐亮度光谱随深度变化

http://www.oceanopticsbook.info/view/light_and_radiometry/visualizing_radiances

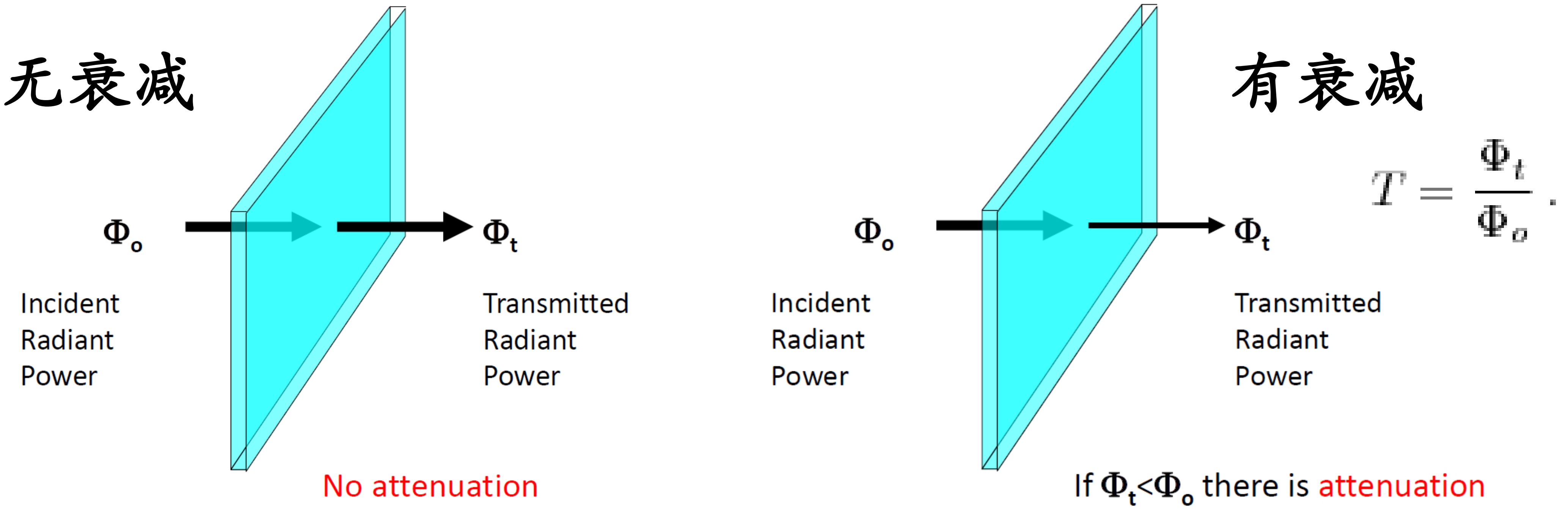
固有光学性质

海洋水体对太阳光的吸收和散射作用

- 衰减系数
- 吸收系数
- 散射系数（前向、后向）、体散射函数

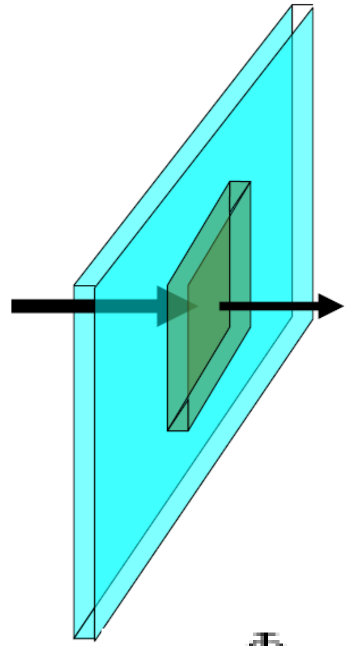
固有光学性质

海洋水体对太阳光的衰减（吸收+散射）作用



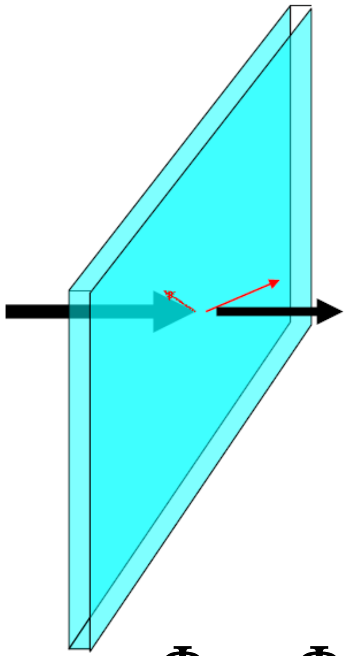
固有光学性质

只有吸收作用



$$A = \frac{\Phi_a}{\Phi_o} = \frac{\Phi_o - \Phi_t}{\Phi_o}.$$

只有散射作用



$$B = \frac{\Phi_b}{\Phi_o} = \frac{\Phi_o - \Phi_t}{\Phi_o}$$

固有光学性质

吸收作用

吸收率 $A=\frac{\Phi_a}{\Phi_o}=\frac{\Phi_o-\Phi_t}{\Phi_o}$.

吸收系数 $a=\frac{A}{\Delta x}$

单位距离的吸收率

$$a\Delta x=\lim_{\Delta x\to 0}\left(\frac{\Delta\Phi}{\Phi}\right)$$

$$\int_0^x a\,dx=-\int_{\Phi_o}^{\Phi_t}\frac{d\Phi}{\Phi}$$

$$ax\big|_0^x=-\ln\Phi\big|_{\Phi_o}^{\Phi_t}$$

$$ax=-[\ln(\Phi_t)-\ln(\Phi_o)]=-\ln\left(\frac{\Phi_t}{\Phi_o}\right)$$

$$a=-\frac{1}{x}\ln\left(\frac{\Phi_t}{\Phi_o}\right)$$

该式提供了测量吸收系数的仪器设计思路

固有光学性质

吸收和衰减系数的测量

现场测量

- ✓ ac-s高光谱吸收衰减仪 Spectral Absorption and Attenuation Meter
- ✓ ICAM (integrating cavity absorption meters)积分空腔吸收仪

实验室采样测量

- ✓ 过滤+分光光度计

固有光学性质

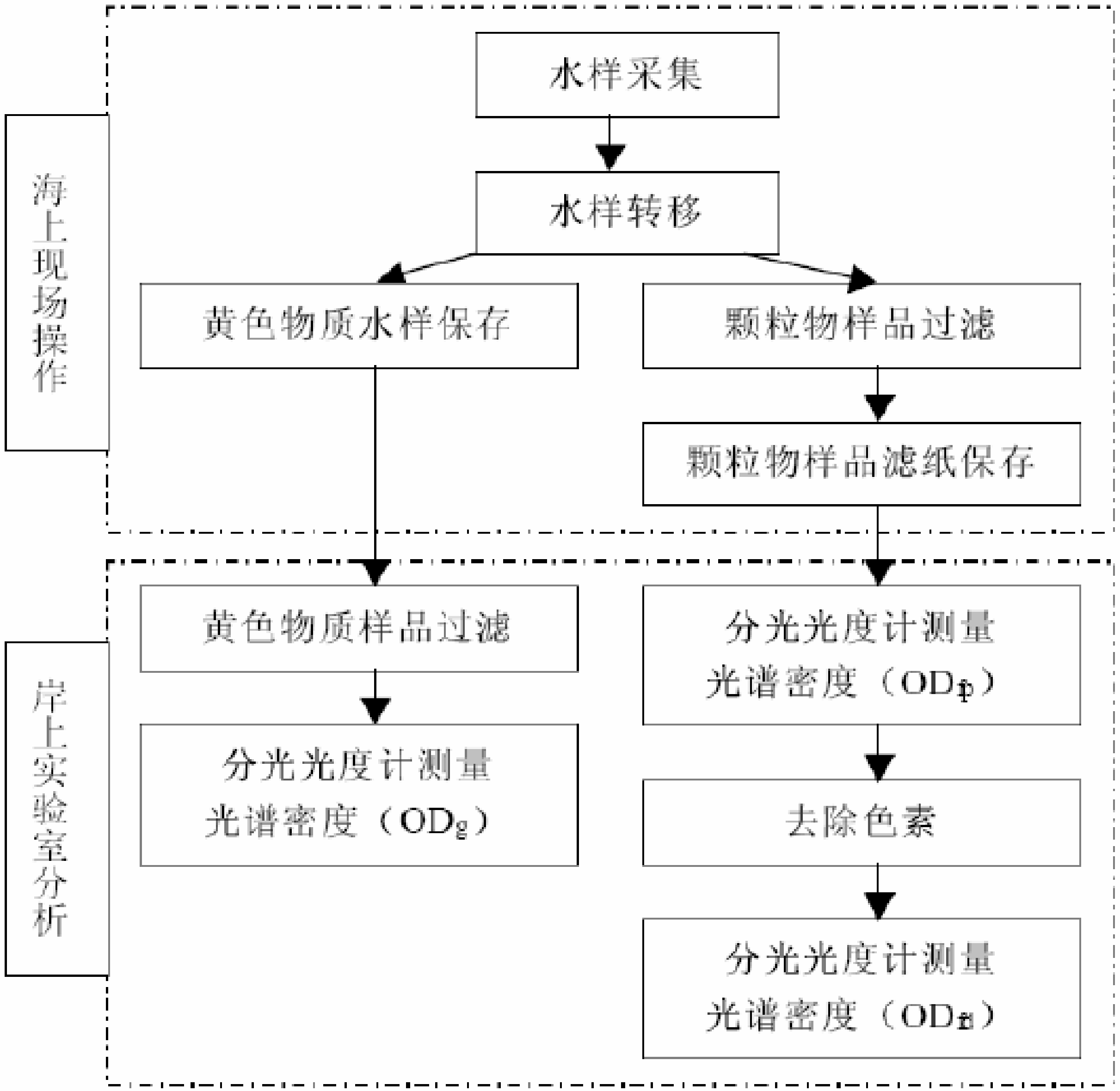
吸收和衰减系数的测量

现场测量

- ✓ ac-s高光谱吸收衰减仪 Sp
- ✓ ICAM (integrating cavity absorpt

实验室采样测量

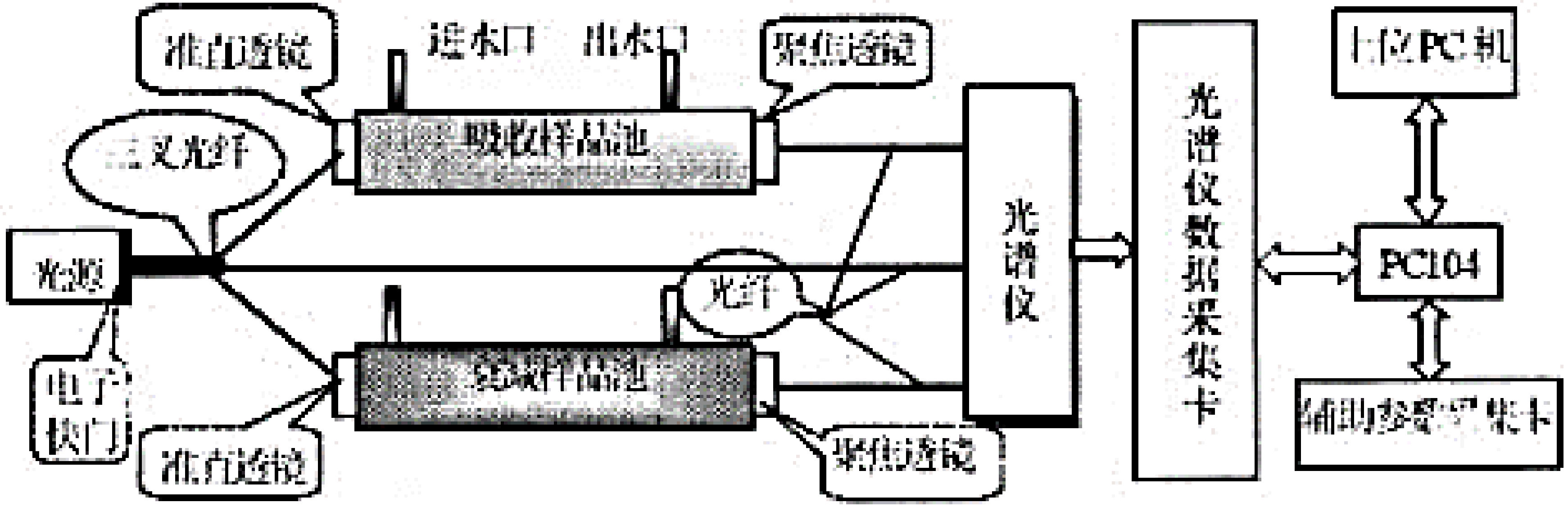
- ✓ 过滤+分光光度计



固有光学性质

吸收和衰减系数的测量

ac-s



光源发出的光经三叉光纤分光后输出，其中的两路光束由透镜准直成平行光束，分别射入吸收系数测量池和衰减系数测量池，吸收池采用全反射石英管，衰减池采用全吸收管，在吸收池和衰减池的另一端由光纤收集透射光，并分别输入到光谱仪中进行测量，吸收和衰减测量池均为全封闭的流通管；另一路作为参考光信号，该信号直接由光纤送入光谱仪进行测量（用于光源补偿和输入光信号的探测）。

吸收和衰减系数的测量

- ac-s

Mechanical Parameters

Size	79 x 10.4 cm diameter
Weight (in air)	5.9 kg
(in water)	0.8 kg

Electrical Parameters

Input	10–35 VDC
Current draw	0.83 Amps @ 12 V nominal
Serial output	RS-232, -422, or -485
Connector	MCBH6M
Sample rate	4 scans/sec., nominal

Environmental Parameters

Temperature range	0–30 deg C
Rated depth	500 m

Optical Parameters

Spectral range	400–730 nm
Band pass	15 nm/channel
Pathlength	25 cm (10 cm available)
Beam cross-section	8 mm dia. (nominal)
Linearity	$\geq$ 99% R^2
Output wavelengths	80–90
Resolution	4 nm
Precision (450–750nm)	+/-0.001 m^{-1} typ., 0.003 max @ 4 Hz
	+/-0.0005 m^{-1} typ., 0.0015 max @ 1 Hz
Precision (400–449 nm)	+/-0.005 m^{-1} typ., 0.0012 max @ 4 Hz
	+/-0.003 m^{-1} typ., 0.006 max @ 1 Hz
Accuracy	+/- 0.01 m^{-1}
Dynamic range	0.001–10 m^{-1}

固有光学性质

吸收和衰减系数的测量

- ac-s
- 可测量吸收系数、衰减系数。
- 仪器使用前需用纯水进行校正(定标)，获得校正(定标)文件。
- 数据校正
  - ✓温度和盐度校正
  - ✓不理想的吸收和散射测量装置

固有光学性质

吸收和衰减系数的测量

- ac-s
- 仪器使用前需用纯水进行校正，获得校正文件。
- 采用超纯水，且应与环境条件达到平衡状态。定标时，仪器和纯水的温度应与环境温度接近一致，测量时要避免产生气泡。

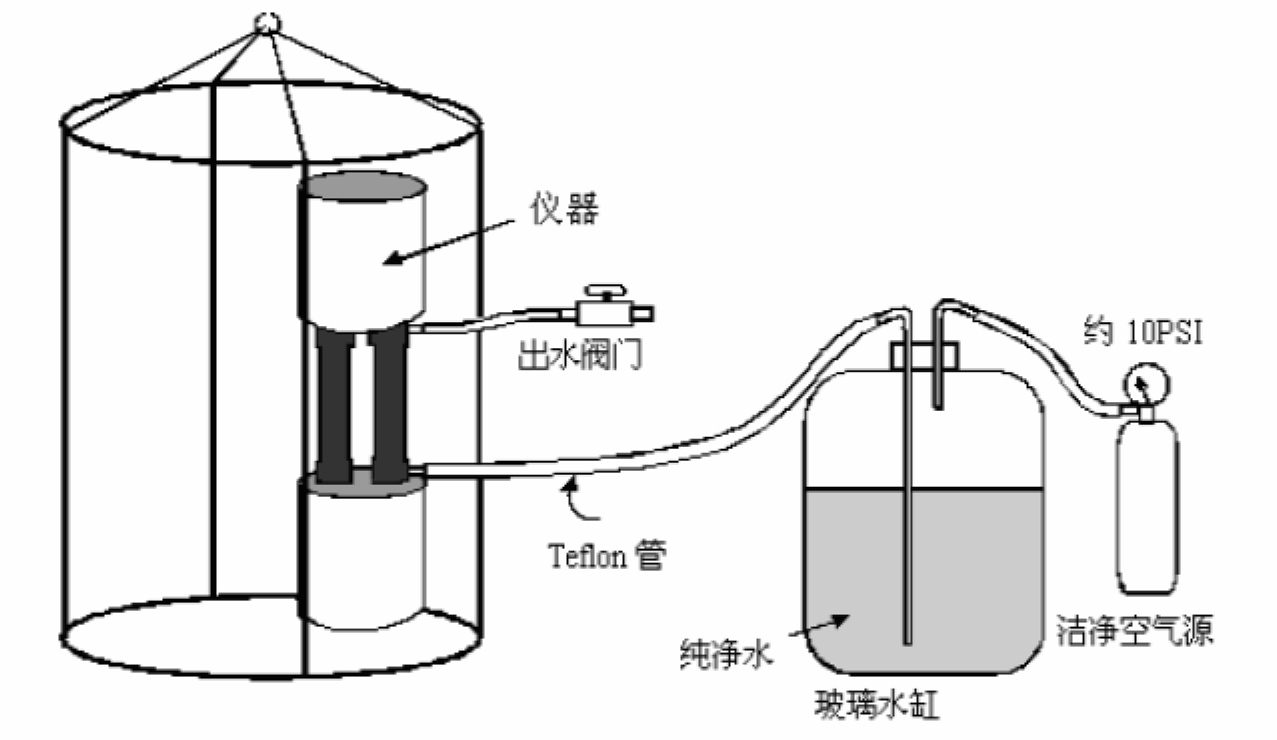


图6 现场水定标系统结构图

固有光学

吸收和衰减系数的测量

- **ac-s**

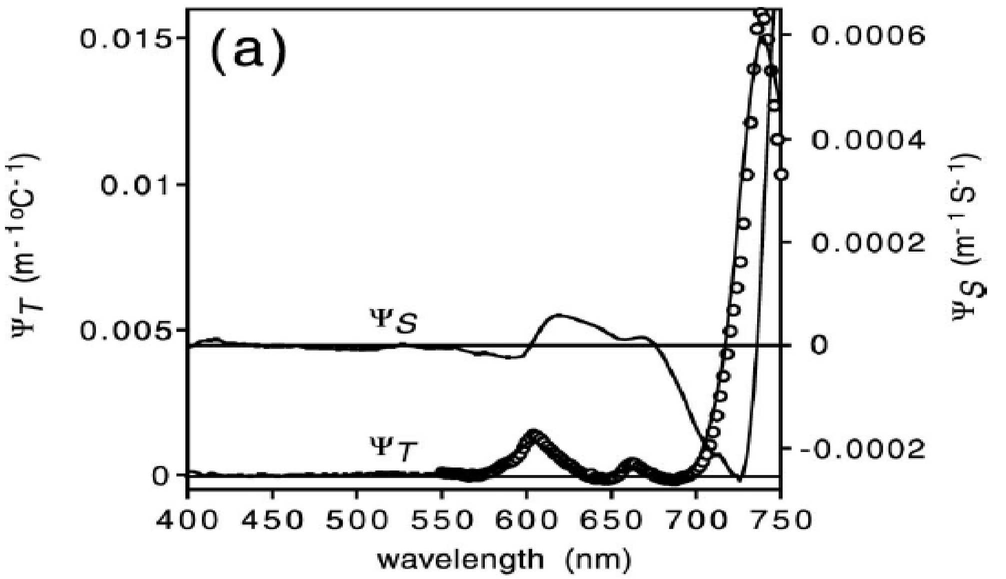
✓ 温度和盐度校正

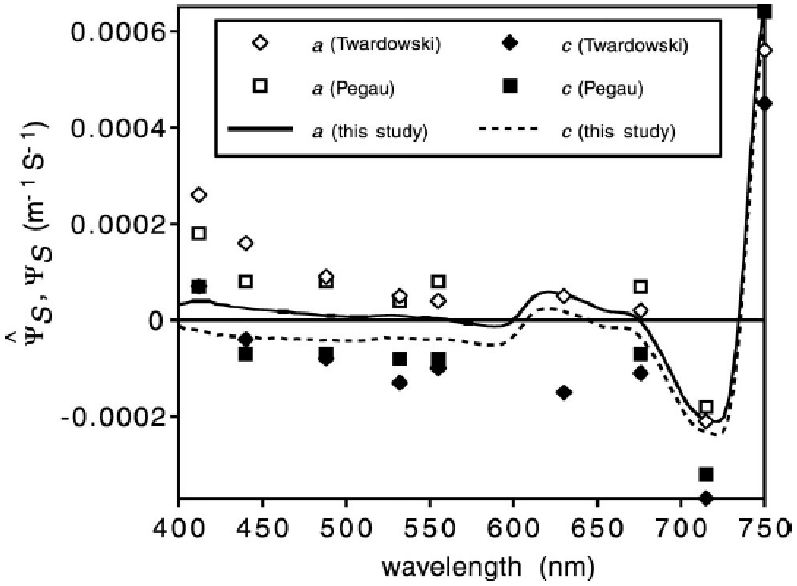
$$a_{\mathrm{tcorr}}(\lambda) = a_{\mathrm{meas}}(\lambda) - (T_i - T_{\mathrm{norm}})^* \Psi_T(\lambda),$$

$$c_{\mathrm{tcorr}}(\lambda) = c_{\mathrm{meas}}(\lambda) - (T_i - T_{\mathrm{norm}})^* \Psi_T(\lambda),$$

$$a_{\mathrm{scorr}}(\lambda) = a_{\mathrm{meas}}(\lambda) - S_i^* \, \hat{\Psi}_{s,a}(\lambda),$$

$$c_{\mathrm{scorr}}(\lambda) = c_{\mathrm{meas}}(\lambda) - S_i^* \, \hat{\Psi}_{s,c}(\lambda),$$





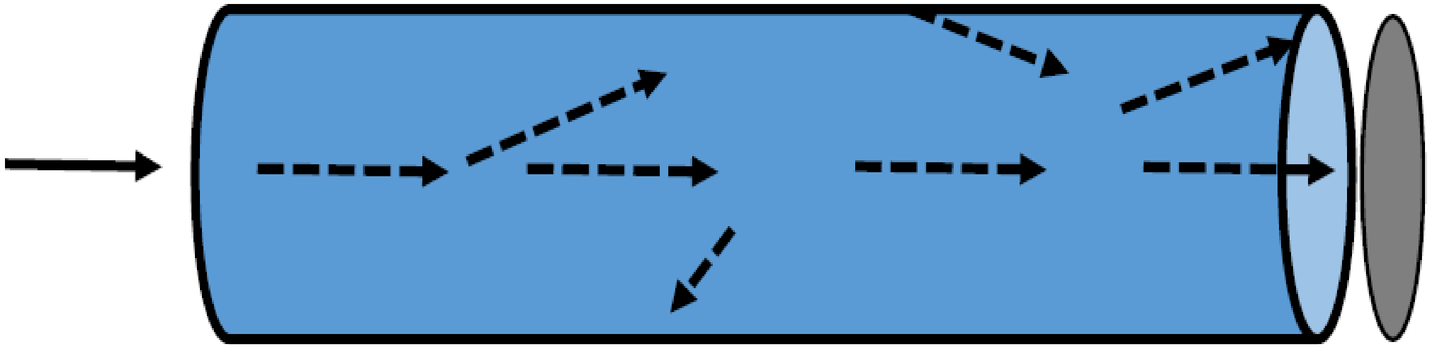
Sullivan et al., 2006, AO

吸收和衰减系数的测量

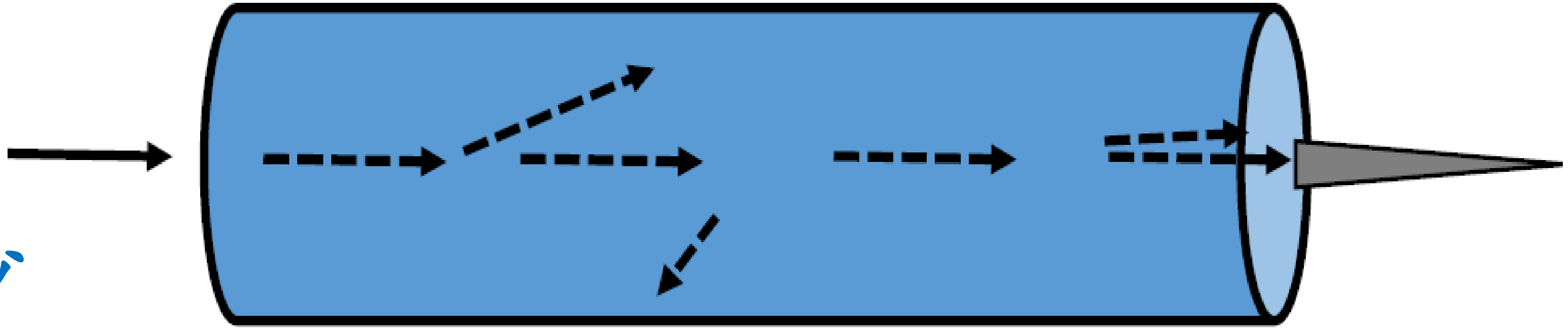
不理想的吸收和散射测量装置

- ac-s 散射b如何得?

- 测量吸收系数a
- 全反射管
- 在接收端尽量收集散射的所有能量



- 测量衰减系数c
- 全吸收管
- 在接收端尽量减少散射能量的收集



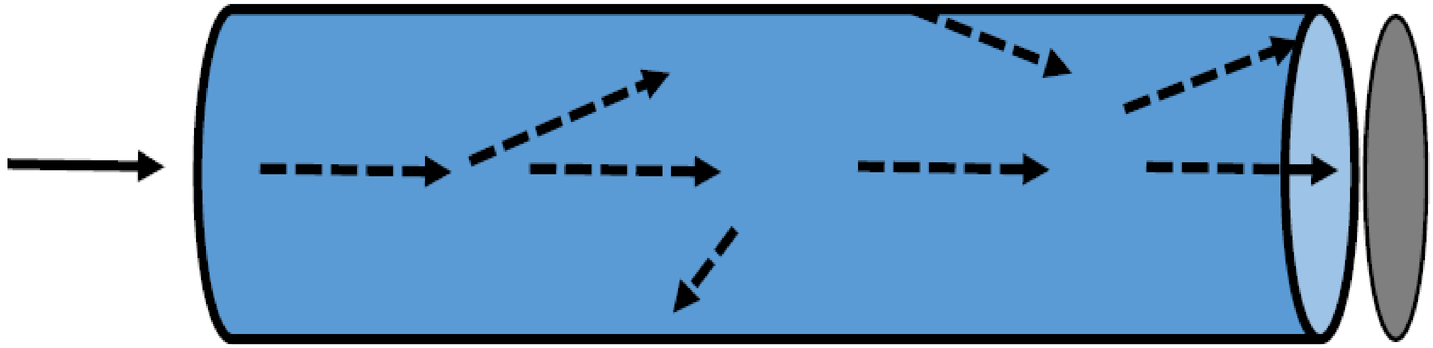
固有光学性质

吸收和衰减系数的测量

- ac-s　散射b如何得?

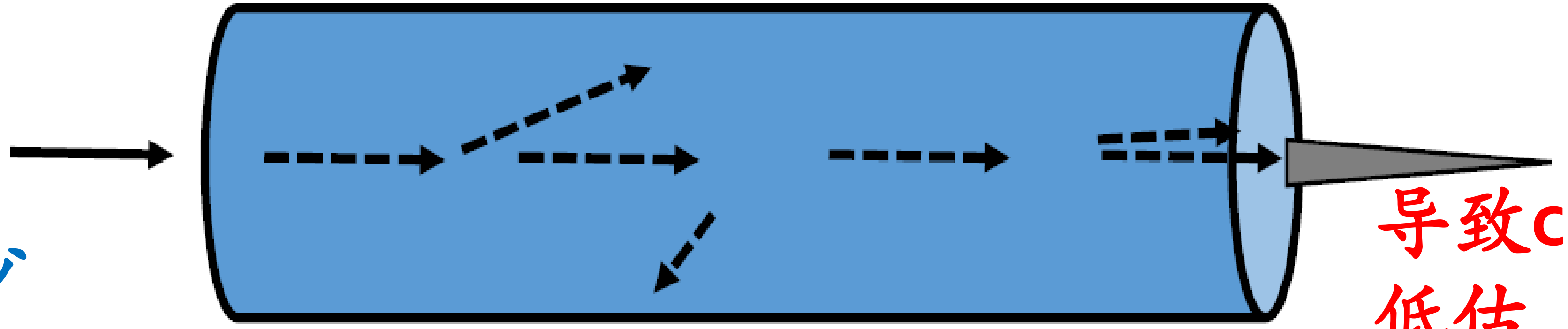
- 测量吸收系数a
- 全反射管
- 在接收端尽量收集散射的所有能量

一些散射的光能量在接收端难以收集到，



导致a高估

- 测量衰减系数c
- 全吸收管
- 在接收端尽量减少散射能量的收集



导致c低估

一些散射的光能量在接收端被收集到，

固有光学性质

吸收和衰减系数的测量

- ac-s

✓ 散射校正

反射管式吸收系数测量方法，设计原理是在光的传输过程中，光滑内壁反射了所有的散射光到收集器中，实际是这是无法达到的理想情况，离光学主轴大于41.7°的光都未收集到，因此要对吸收系数数据进行散射校正。

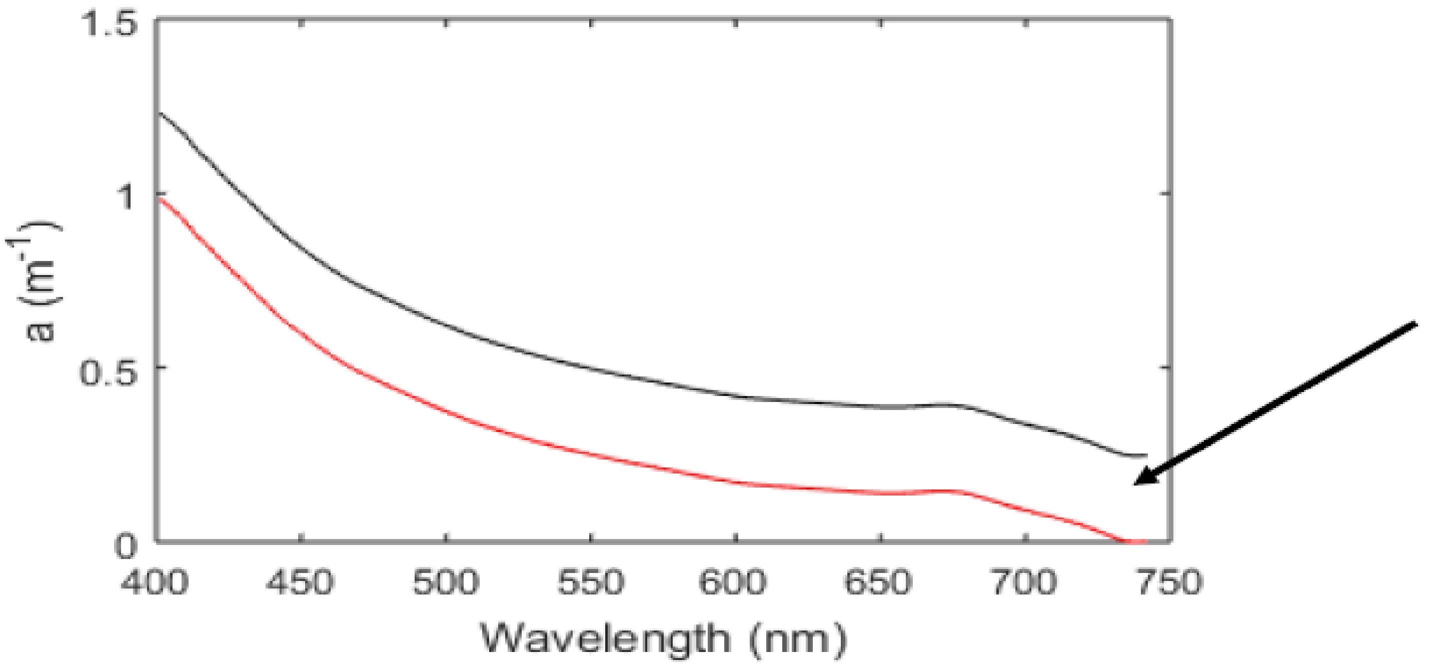
固有光学性质

吸收和衰减系数的测量

3. Scattering correct the absorption spectra
   a. Subtract a_m(NIR)
      "b not a function of λ"
      spectrophotometric approach

- **ac-s**

✓ 散射校正



Stramski and Babin 2002

吸收和衰减系数的测量

固有光学性质

3. Scattering correct the absorption spectra

b. Subtract spectral scattering contribution, fraction of b(λ)

- **ac-s**

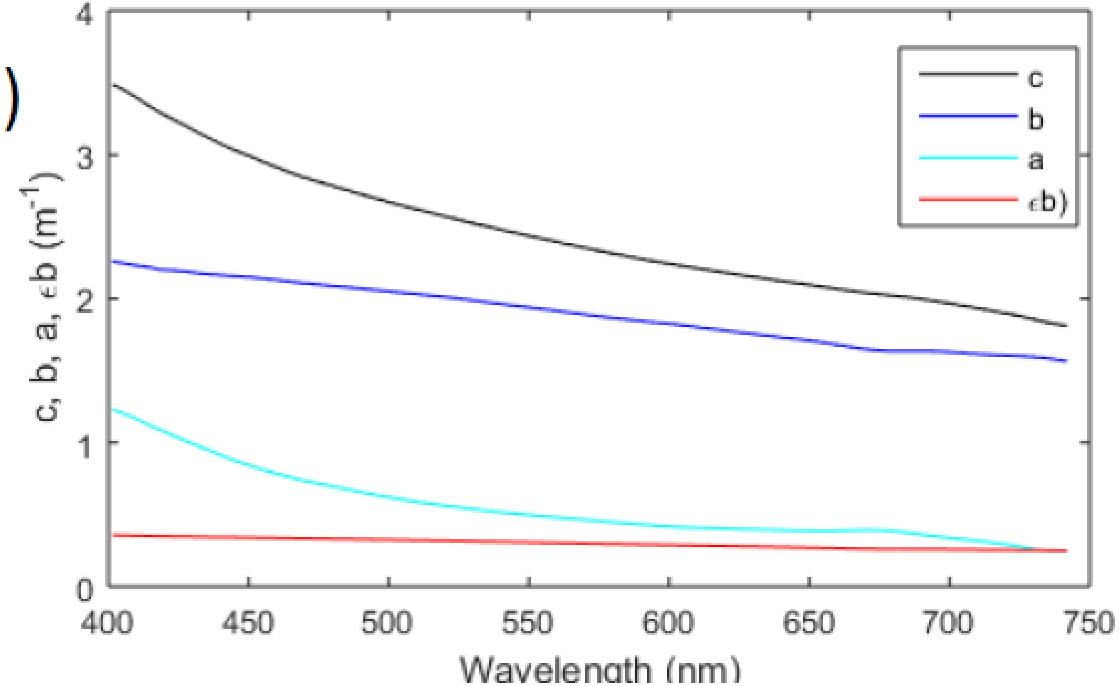
✓ 散射校正

$b(\lambda) = c(\lambda) - a(\lambda)$

if $a(NIR) = 0$ signal is due to scattering

$fb(\lambda) = a(NIR)/b(NIR)$

$$a_{corr}(\lambda) = a(\lambda) - (fb(\lambda) * b(\lambda))$$



Roesler and Zaneveld 1993

固有光学性质

吸收和衰减系数的测量

- ac-s

衰减系数测量中的接收角影响

Table 1. Collimated commercial beam transmissometers whose measurements we compare in this study. For the ac meters we only display information for the wavelength used here. For reference the common Sea Tech transmissometer had an acceptance angle of 1.03° [4], a 660nm wavelength and a pathlength of 25cm.

Instrument	Manufacturer	Acceptance Angle (degrees, in-water)	Pathlength	Wavelength (bandwidth)	Beam Diameter
C-STAR-10	WETLabs	1.2	10cm	650 (20)nm	15mm
C-STAR-25	WETLabs	1.2	25cm	650 (20)nm	15mm
AC-9-10	WETLabs	0.93	10cm	676 (10)nm	8mm
AC-9-25	WETLabs	0.93	25cm	676 (10)nm	8mm
AC-S-25	WETLabs	0.93	25cm	650(15)nm	8mm
LISST-100-B	Sequoia Scientific	0.0269°	5cm	670 (0.1)nm	6mm
LISST-100X-B	Sequoia Scientific	0.0269°	5cm	670 (0.1)nm	6mm
LISST-100X-Floc	Sequoia Scientific	0.006°	5cm	670 (0.1)nm	6mm

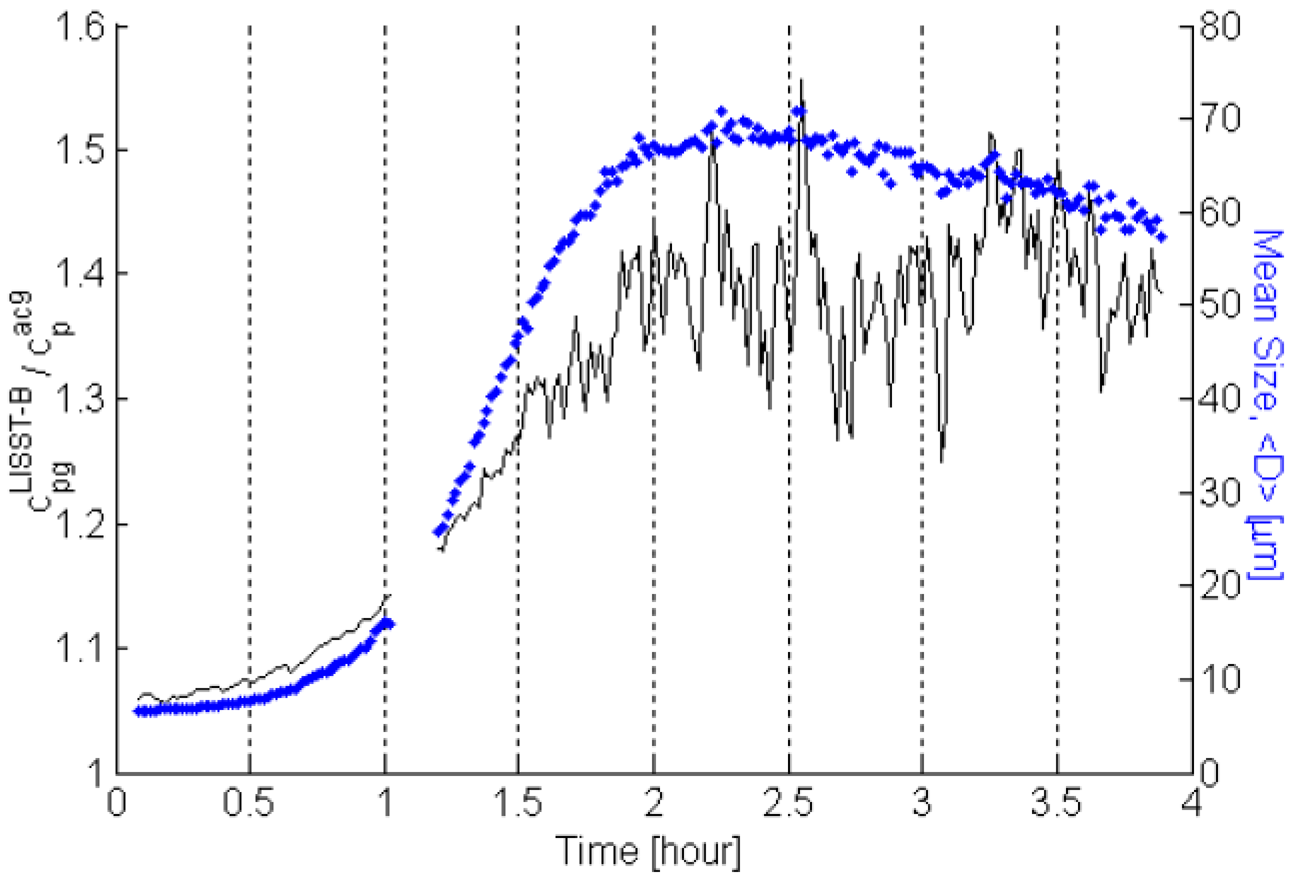
Boss et al., 2009, OE

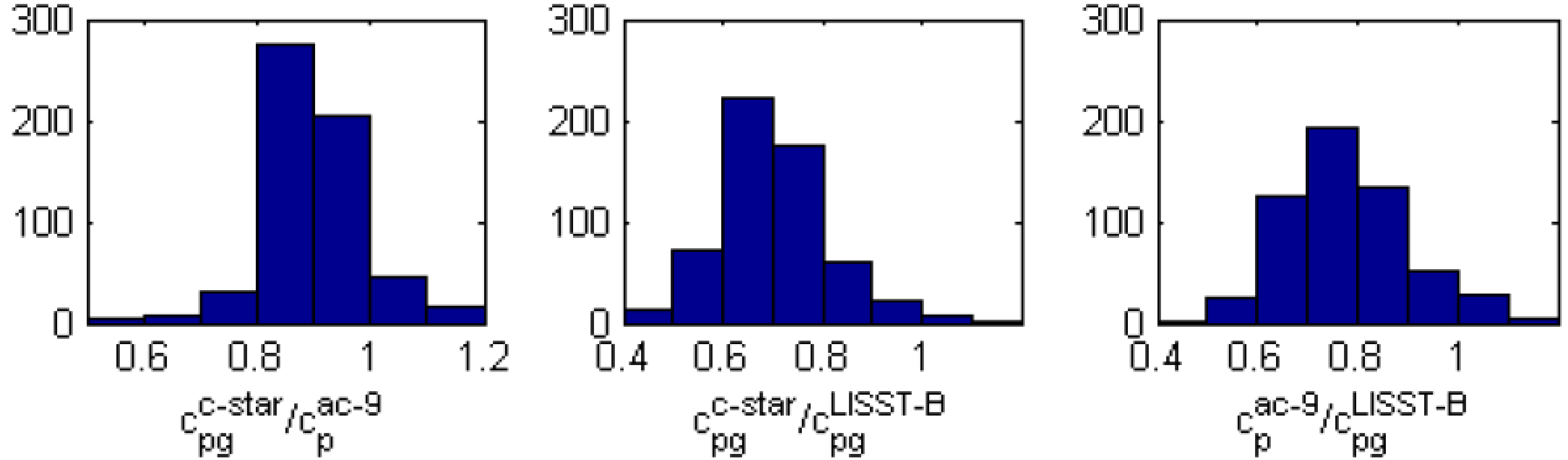
Table 1. Collimated commercial beam transmissometers whose measurements we compare meters we only display information for the wavelength used here. For reference the transmissometer had an acceptance angle of 1.03° [4], a 660nm wavelength and a pa

Instrument	Manufacturer	Acceptance Angle (degrees, in-water)	Pathlength	Wav (ban
C-STAR-10	WETLabs	1.2	10cm	650
C-STAR-25	WETLabs	1.2	25cm	650
AC-9-10	WETLabs	0.93	10cm	676
AC-9-25	WETLabs	0.93	25cm	676
AC-S-25	WETLabs	0.93	25cm	650
LISST-100-B	Sequoia Scientific	0.0269°	5cm	670
LISST-100X-B	Sequoia Scientific	0.0269°	5cm	670
LISST-100X-Floc	Sequoia Scientific	0.006°	5cm	670

- **ac-s**

衰减系数测量中的接收角影响





) and the corresponding ratio of the beam at of the ac-9 at 676nm as function of time periment. Oscillations in the ratio are due clarifies of settling particles ($c_{pg,LISST-B}$

Boss et al., 2009, OE

固有光学性质

吸收和衰减系数的测量

- ac-s

其他

Linear Variable Filter (LVF)

Figure 6. ac-s filter wheel

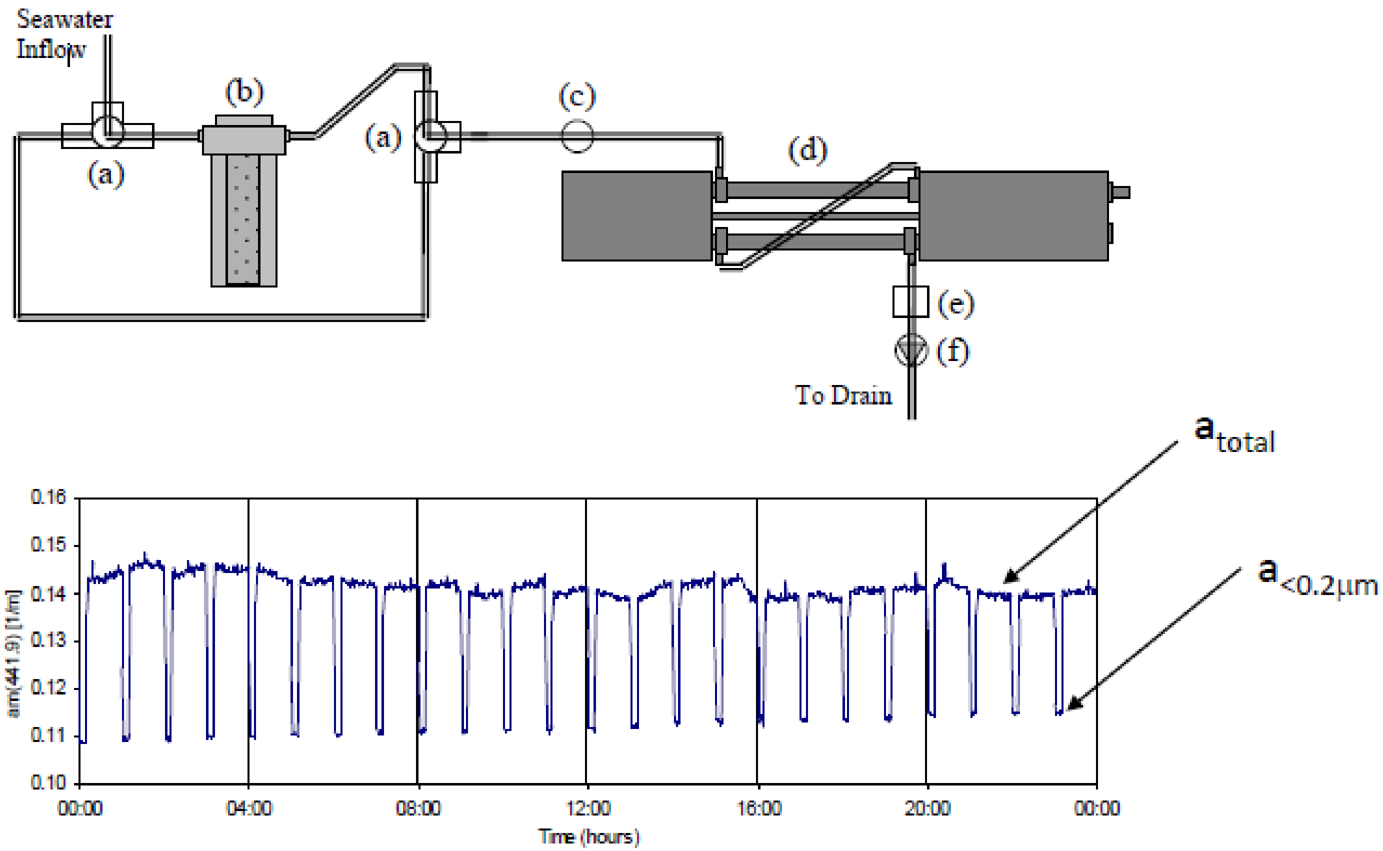
固有光学性质

吸收和衰减系数的测量

- 仪器有自容式和电缆传输式两种。
- 测量水体可以是开放式或带水泵的流体腔式。
- 仪器应具有温度和深度传感器。水温和水深值将用于对测量值进行校正。

吸收和衰减系数的测量

Automated shipboard flow-through method, calibration-independent



Slade et al., 2010

固有光学性质

吸收和衰减系数的测量

操作步骤

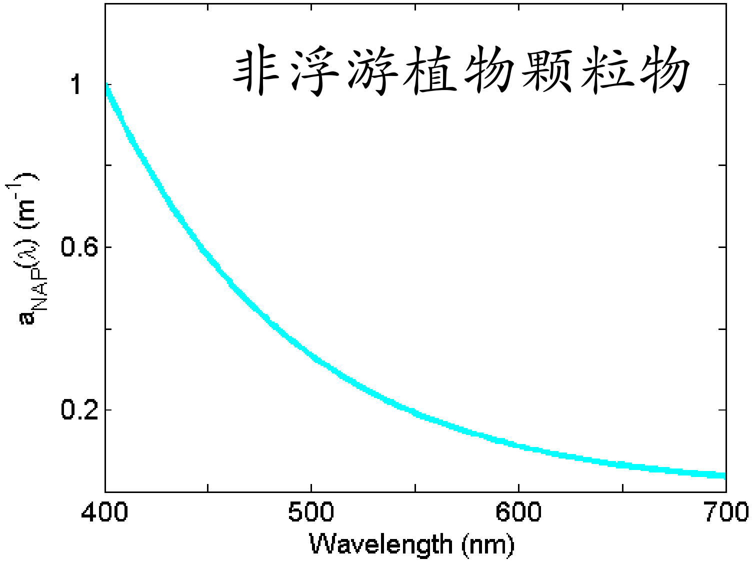
- 仪器清洗和定标
- 安装仪器（支架、负重、真空泵、连线、控制写入）
- 仪器布放、排除气泡
- 采集数据
- 回收仪器、仪器保养

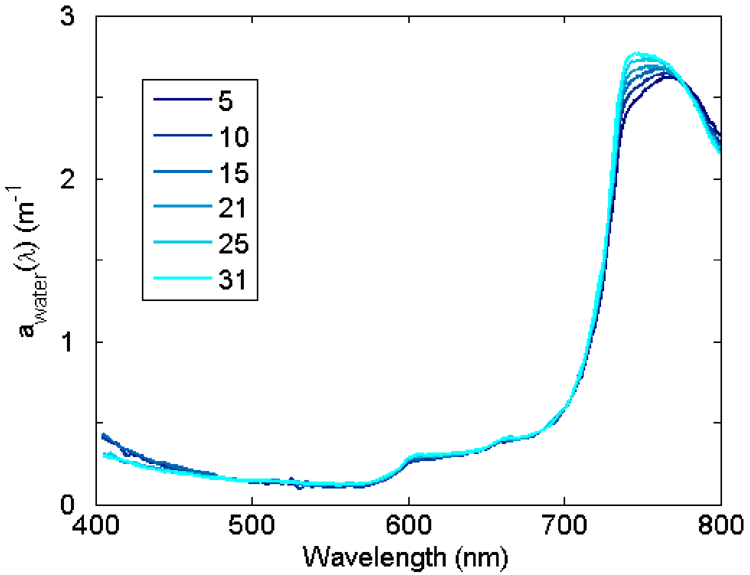
0.006 to 0.013 nm^-1 (Roesler et al. 1989; Babin et al. 2003)

$$a_{NAP}(\lambda = a_{NAP}(440) * e^{-S_{NAP} * (\lambda - 440)}$$

固有光学性质

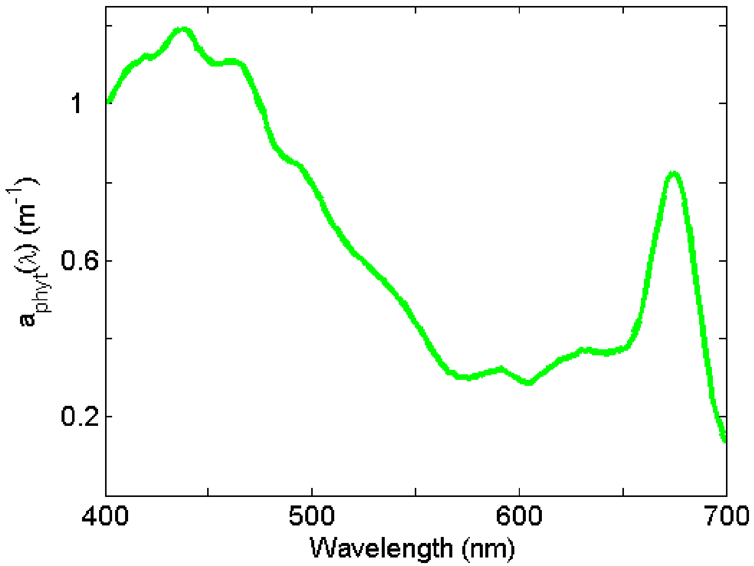
海水组分的吸收



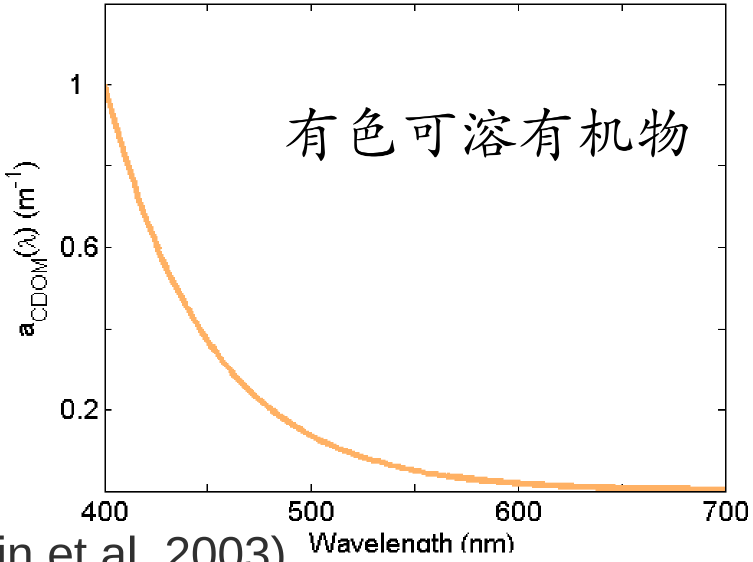


纯水的吸收（随水温变化）

（Pegau and Zaneveld 1993）



浮游植物



吸收作用

0.012 to 0.022 nm-1

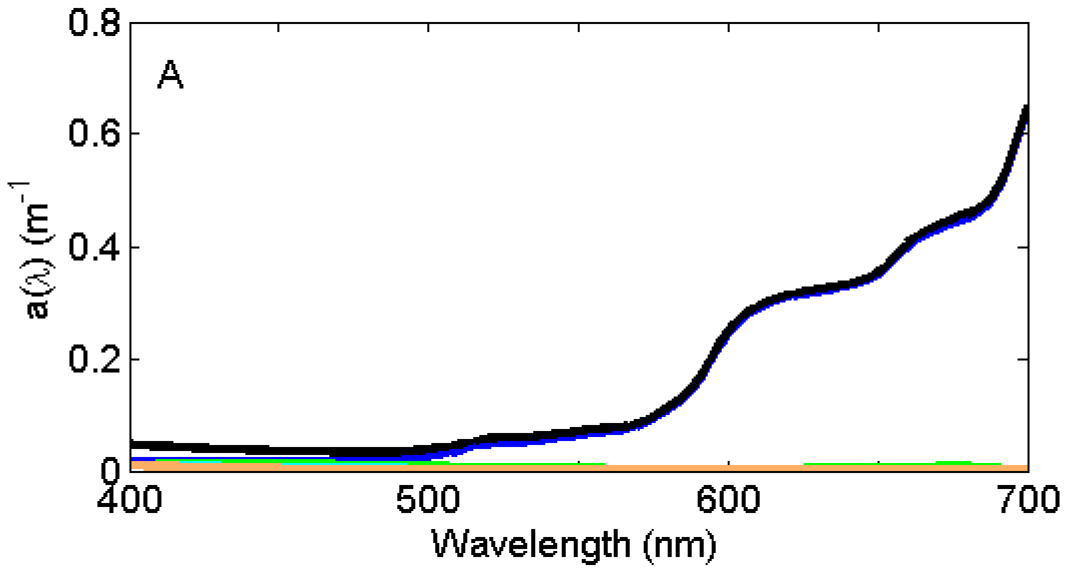
(Roesler et al. 1989; Babin et al. 2003)

$$a_{CDOM}(\lambda = a_{CDOM}(440) * e^{-S_{CDOM} * (\lambda - 440)}$$

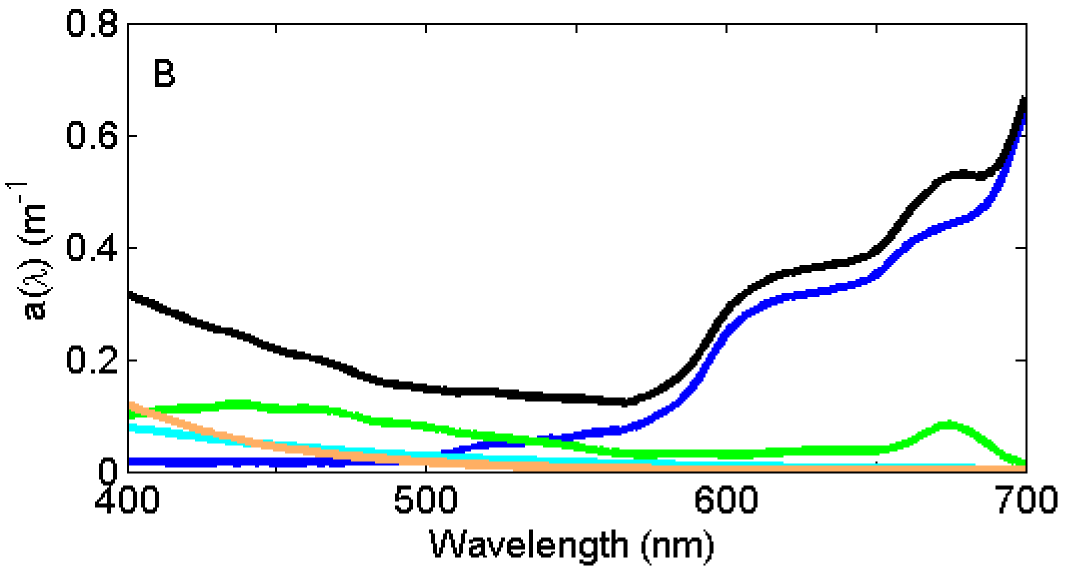
http://www.oceanopticsbook.info/view/absorption/absorption_by_oceanic_constituents

固有光学性质

吸收作用



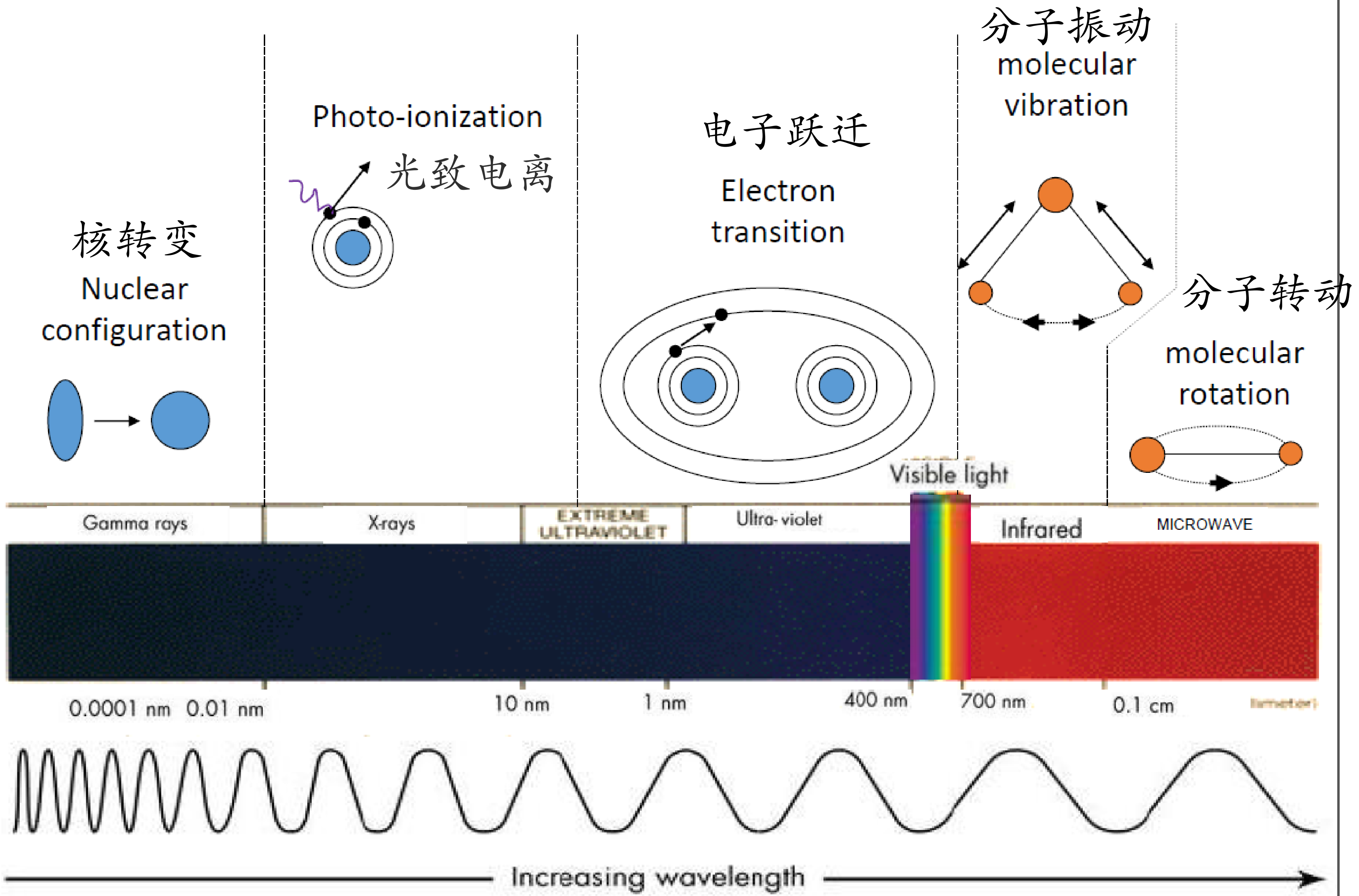
清洁大洋水体



富营养的近岸水体

Interactions between energy and matter

吸收

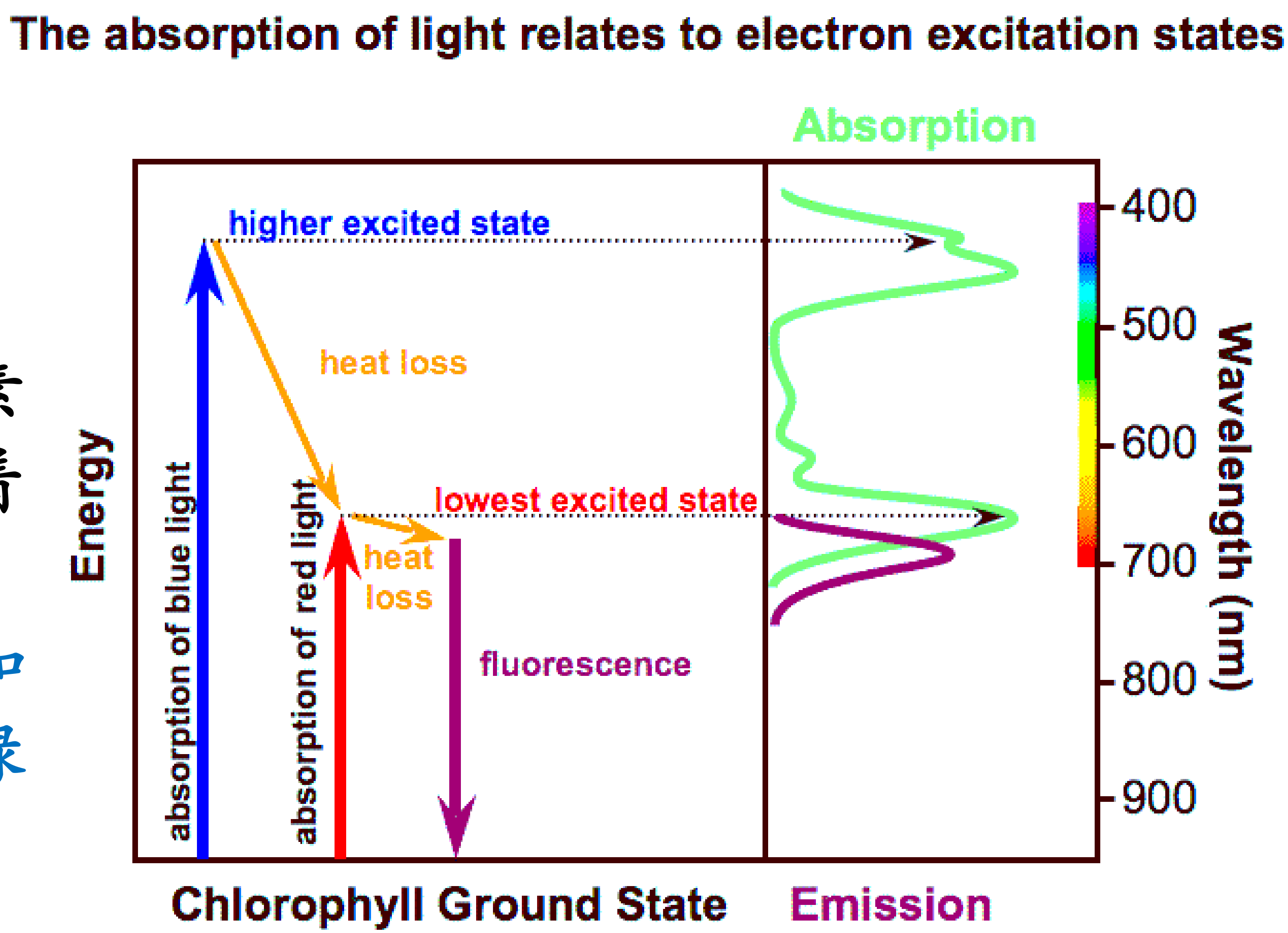


吸收

浮游植物的叶绿素在光合作用中起着重要作用。

叶绿素吸收蓝光和红光，因此呈现绿色。

荧光效应。

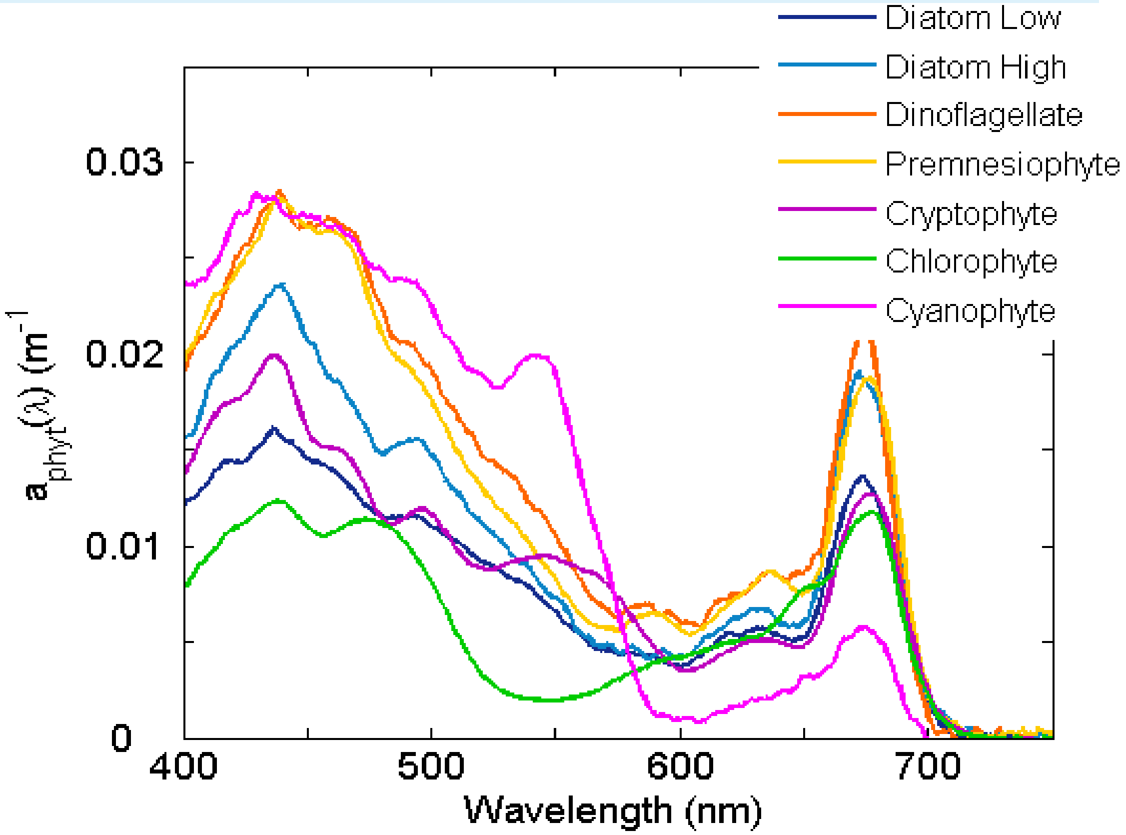


http://plantphys.info/plant_physiology/light.shtml

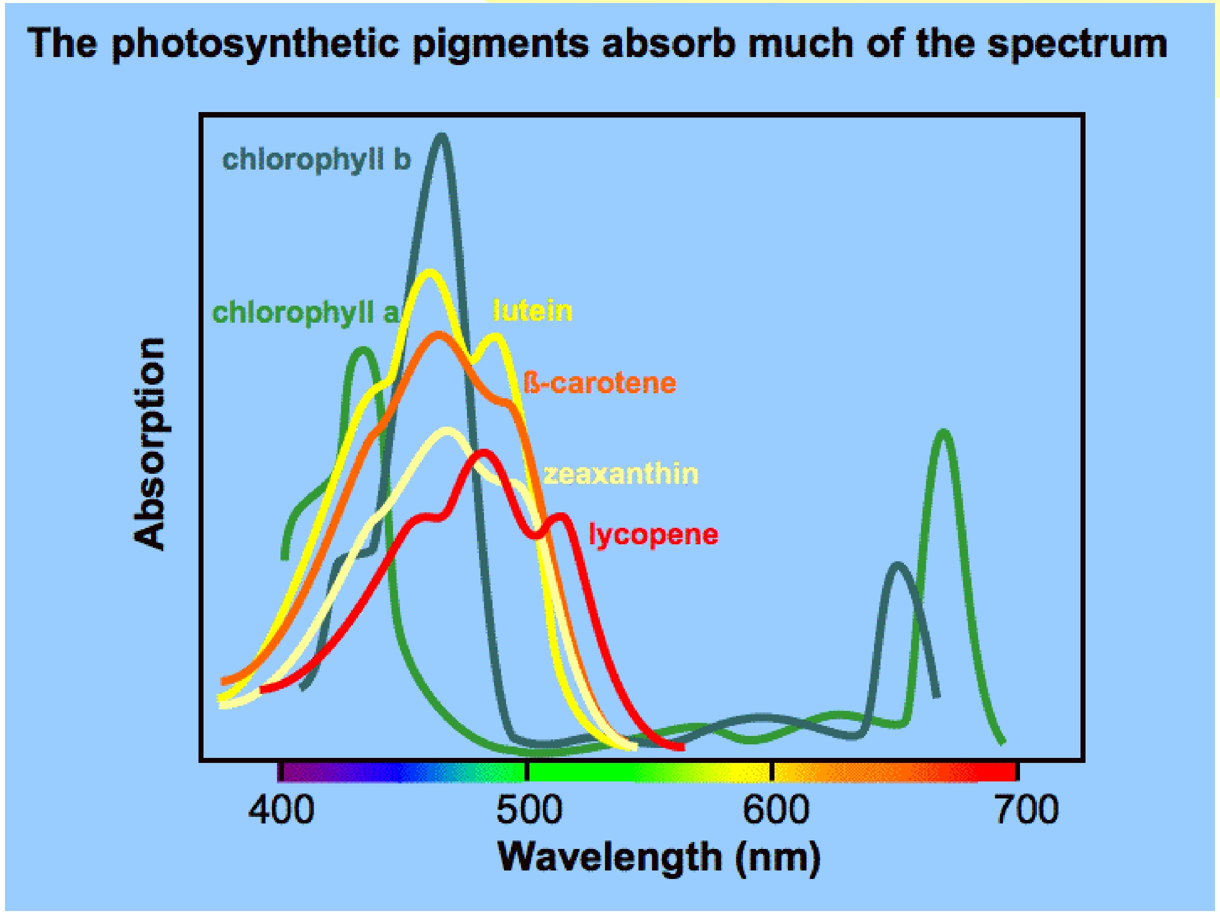
固有光学性质

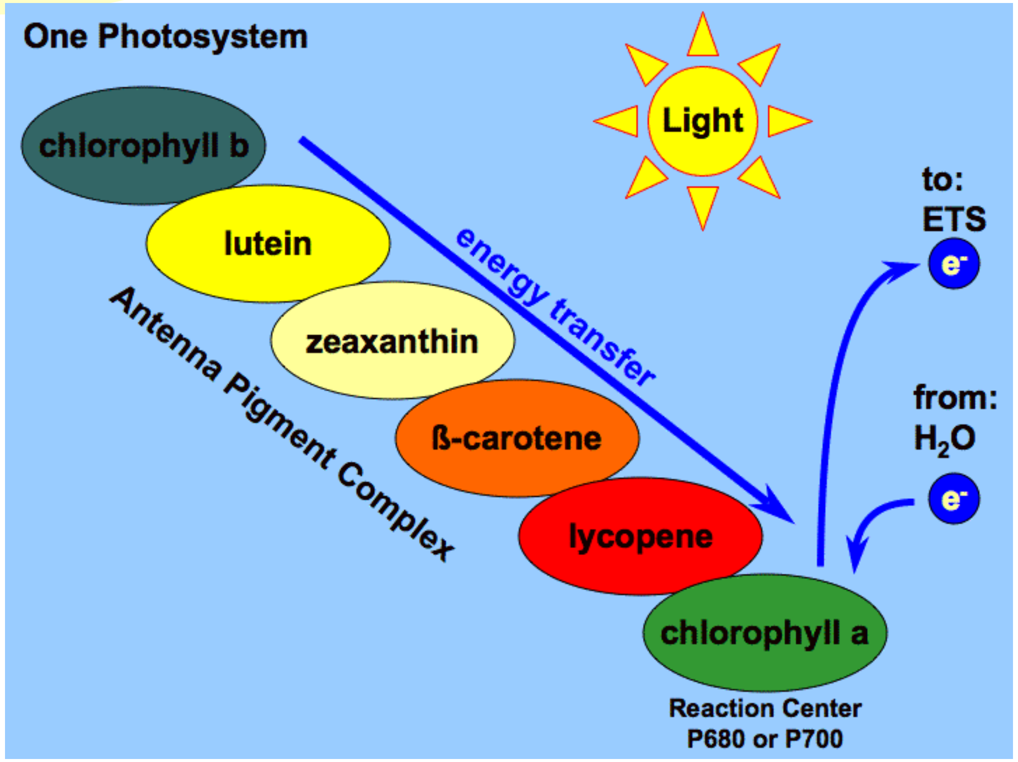
浮游植物的吸收（叶绿素不是唯一的吸收性色素）

硅藻、隐藻、绿藻、蓝藻、鞭毛藻



浮游植物的吸收（叶绿素不是唯一的吸收性色素）



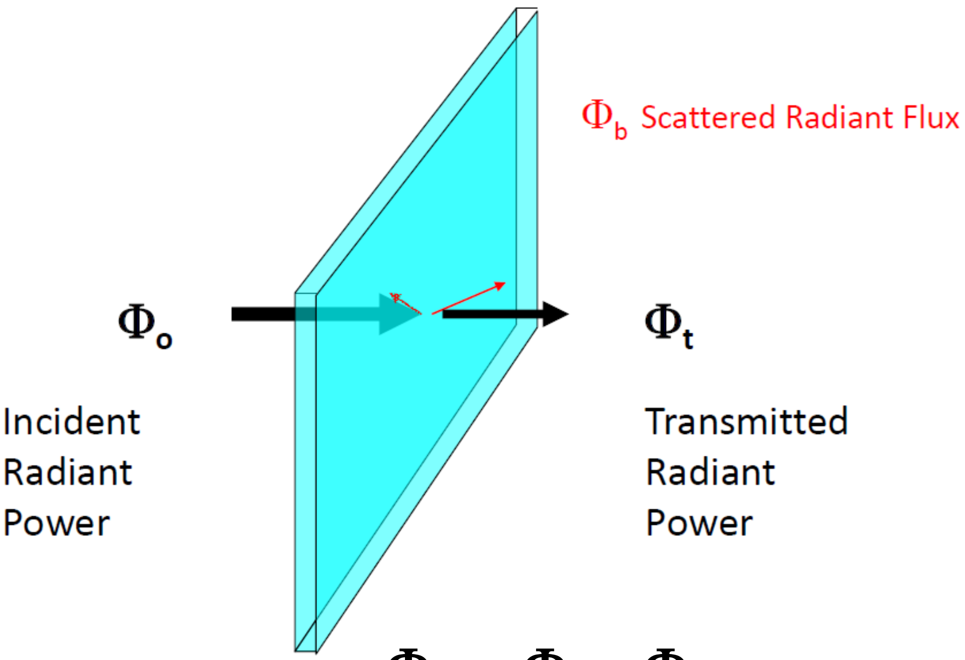


lutein 叶黄素 Zeaxanthin 玉米黄质 carotene 胡萝卜素 lycopene番茄红素

http://plantphys.info/plant_physiology/light.shtml

固有光学性质

散射作用



$$B = \frac{\Phi_b}{\Phi_o} = \frac{\Phi_o - \Phi_t}{\Phi_o}$$

散射率 $B = \Phi_b / \Phi_o$

散射系数 $b = B / \Delta x$

单位距离的散射率

$$b = -\frac{1}{x}\ln\left(\frac{\Phi_t}{\Phi_o}\right)$$

散射测量与吸收、衰减测量有何不同?

Volume Scattering Function (VSF)

散射作用

$\beta(\theta, \phi)$ = power per unit <u>steradian</u> emanating from a volume illuminated by irradiance

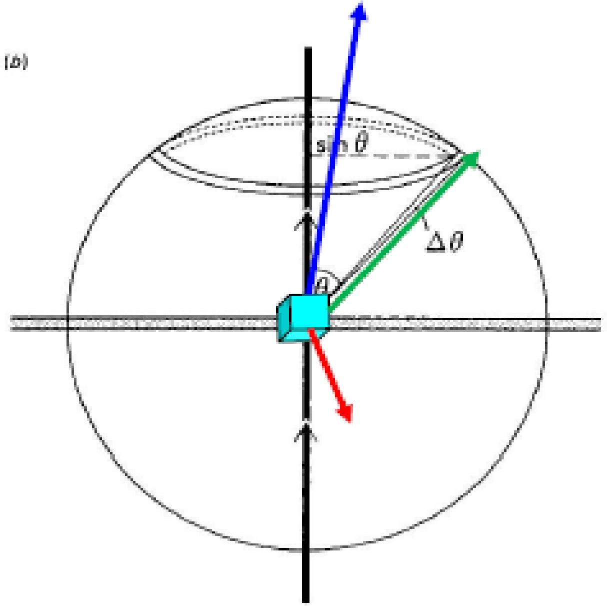
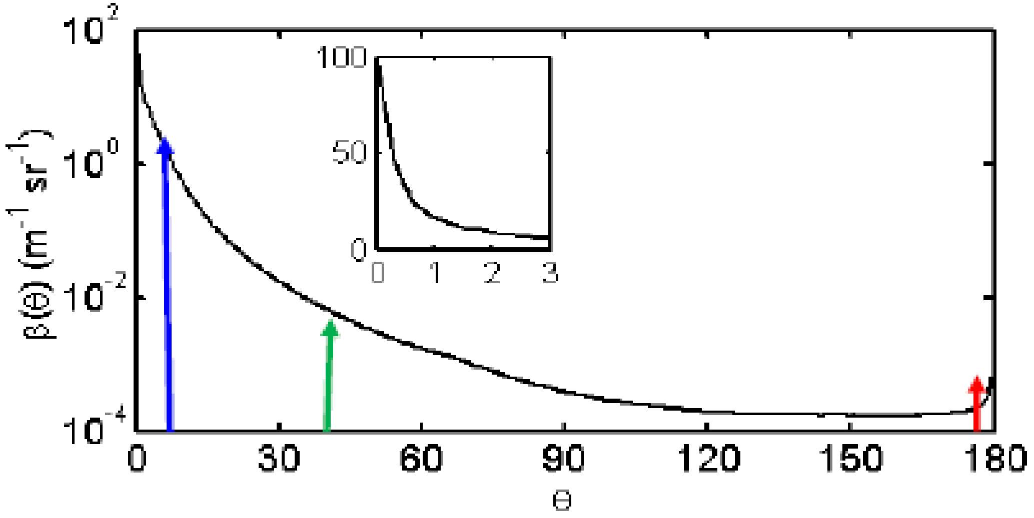


Fig. 1.5. The geometrical relations underlying the volume scattering function. (a) A parallel light beam of irradiance E and cross-sectional area dA passes through a thin layer of medium, thickness dr. The illuminated element of volume is dV. $dI(\theta)$ is the radiant intensity due to light scattered at angle θ. (b) The point at which the light beam passes through the thin layer of medium can be imagined as being at the centre of a sphere of unit radius. The light scattered between θ and $\theta + \Delta\theta$ illuminates a circular strip, radius $\sin\theta$ and width $\Delta\theta$, around the surface of the sphere. The area of the strip is $2\pi \sin\theta\Delta\theta$ which is equivalent to the solid angle (in steradians) corresponding to the angular interval $\Delta\theta$.



$$\beta(\theta,\phi) = \frac{1}{\Phi_o} \frac{\delta\Phi}{\delta r \delta\Omega}$$

$$b = \int_{4\pi} \beta(\theta,\phi)\, \delta\Omega$$

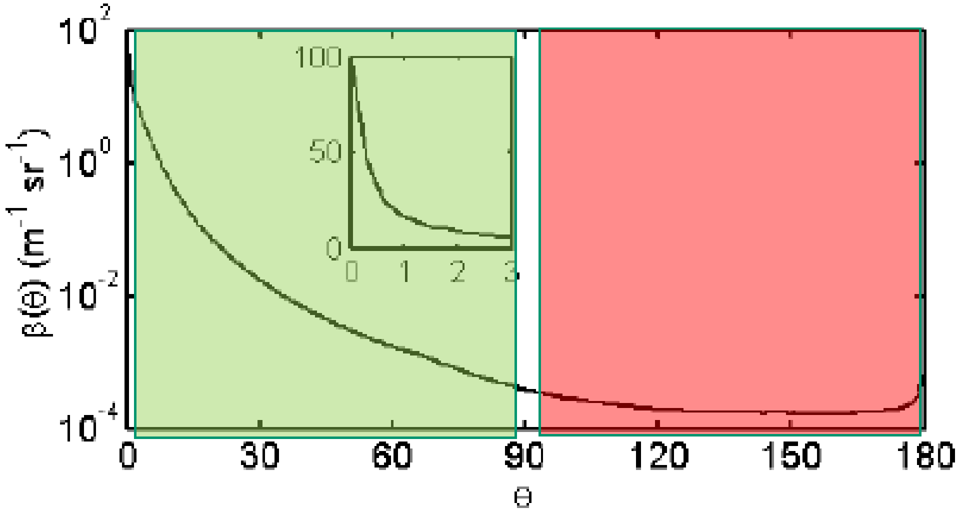
What is $\delta\Omega$?

$$b = \int_0^{2\pi}\int_0^{\pi} \beta(\theta,\phi) \sin\theta\, \delta\theta\, \delta\phi$$

Calculate Scattering, b, from the volume scattering function

If there is azimuthal symmetry

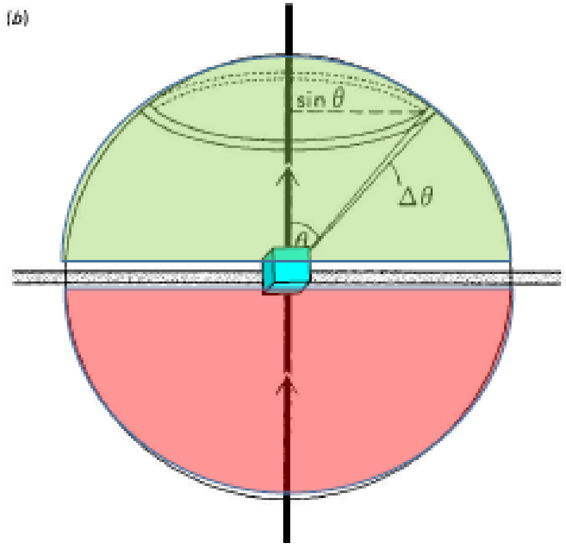
$$b = \int_{4\pi} \beta(\theta,\phi)\, \delta\Omega$$



$$b = 2\pi \int_0^{\pi} \beta(\theta,\phi) \sin\theta\, \delta\theta$$

$$b_f = 2\pi \int_0^{\pi/2} \beta(\theta,\phi) \sin\theta\, \delta\theta$$

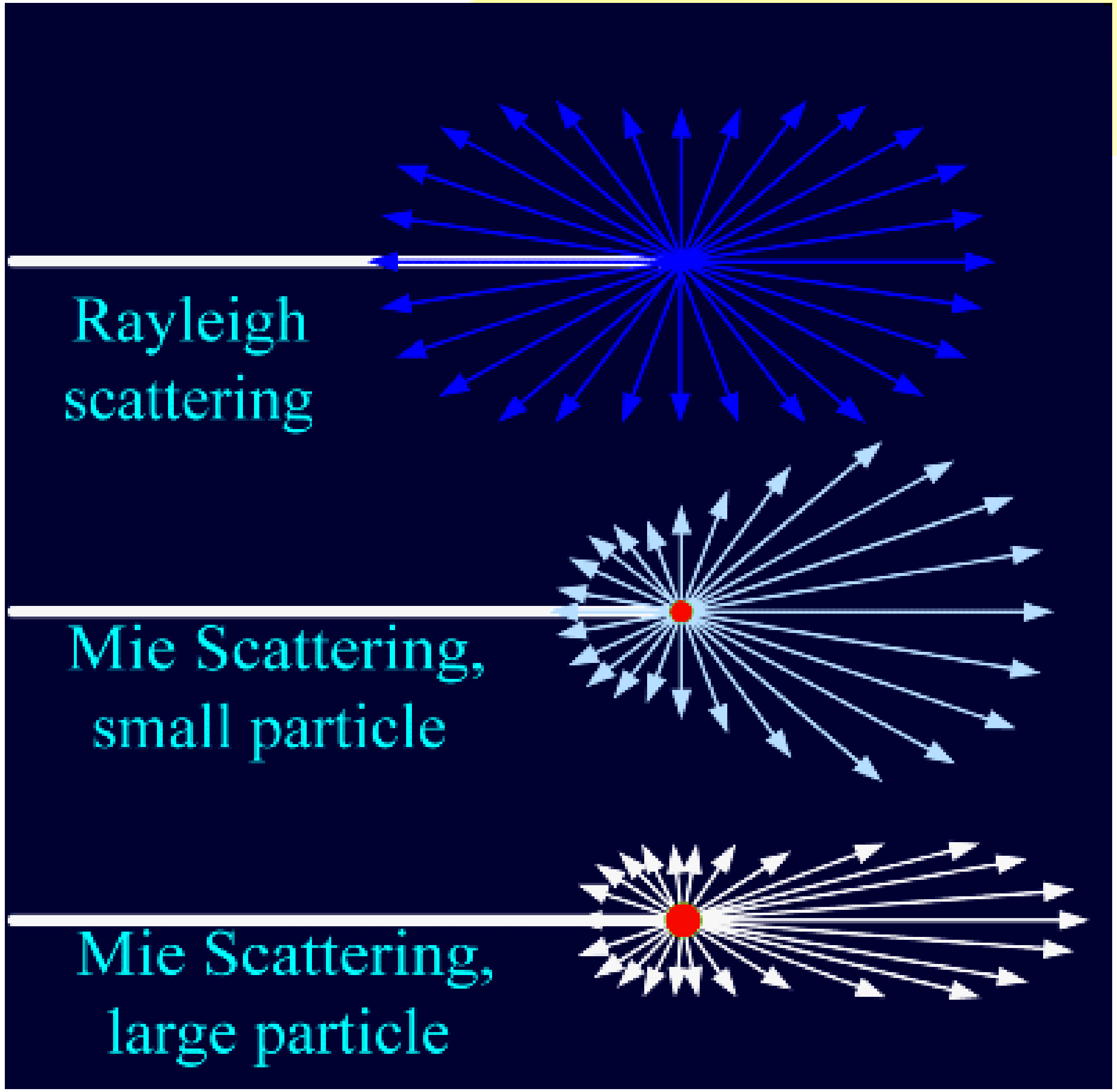
$$b_f = 2\pi \int_{\pi/2}^{\pi} \beta(\theta,\phi) \sin\theta\, \delta\theta$$



Phase function: $\tilde{\beta}(\theta,\phi) = \beta(\theta,\phi)/b$

These are spectral!

固有光学性质



散射作用

$$\alpha = \frac{2\pi a}{\lambda}$$

光束通过不均匀介质所产生的偏离原传播方向向四周传播的现象，称为光的散射。

散射粒子的尺寸远小于入射光波长（约小于(0.2~0.1)λ）时，发生瑞利散射。

散射粒子的尺寸接近或大于入射光波长时，发生Mie散射。

Small Particles: Rayleigh scatterers

- Angular distribution of radiation is called the volume scattering function (VSF or $\beta(\theta)$)
- Equal in forward and backward directions

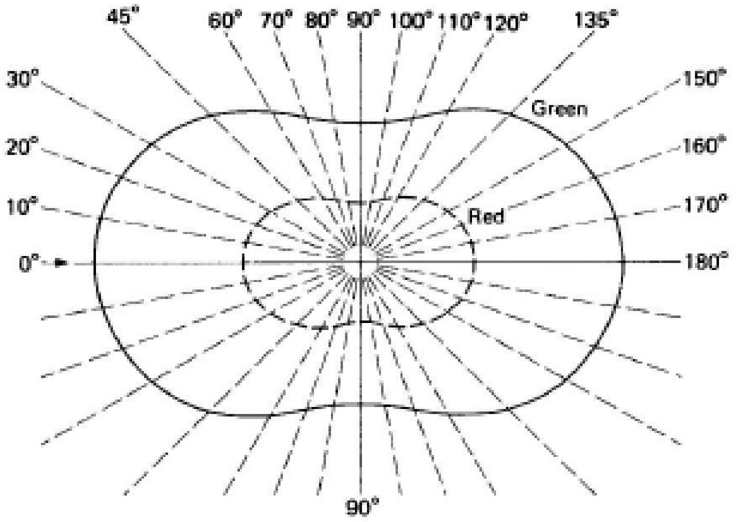


Fig. 2.2. Polar plot of intensity as a function of scattering angle for small particles ($r \doteq 0.025\ \mu m$) for green ($\lambda \doteq 0.5\ \mu m$) and red ($\lambda \doteq 0.7\ \mu m$) light. (By permission, from *Solar radiation*, N. Robinson, Elsevier, Amsterdam, 1966.)

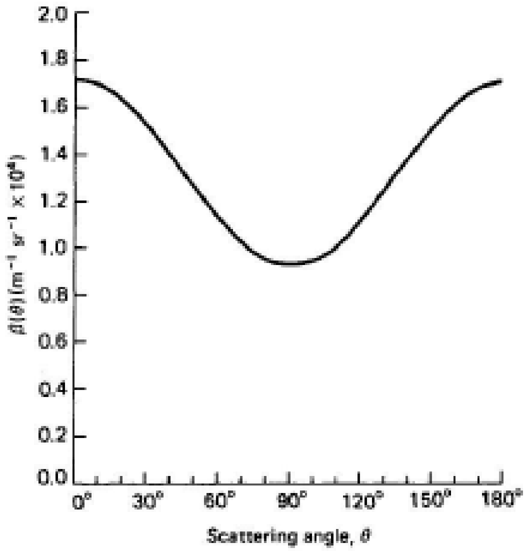
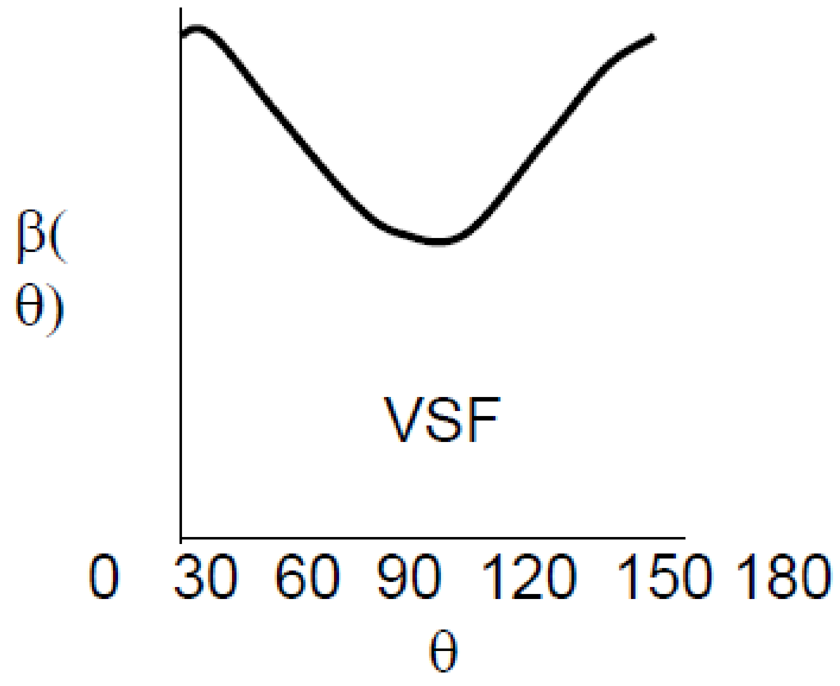
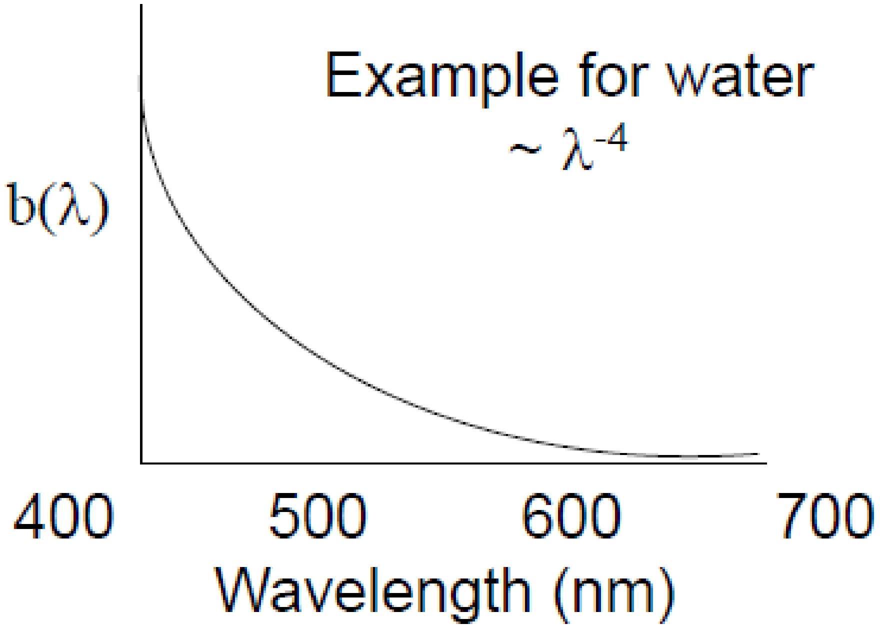


Fig. 4.8. Volume scattering function of pure water for light of wavelength 550 nm. The values are calculated on the basis of density fluctuation scattering, assuming that $\beta(90°) = 0.93 \times 10^{-4}\ m^{-1}\ sr^{-1}$ and that $\beta(\theta) = \beta(90°)(1 + 0.835 \cos^2 \theta)$ (following Morel, 1974).

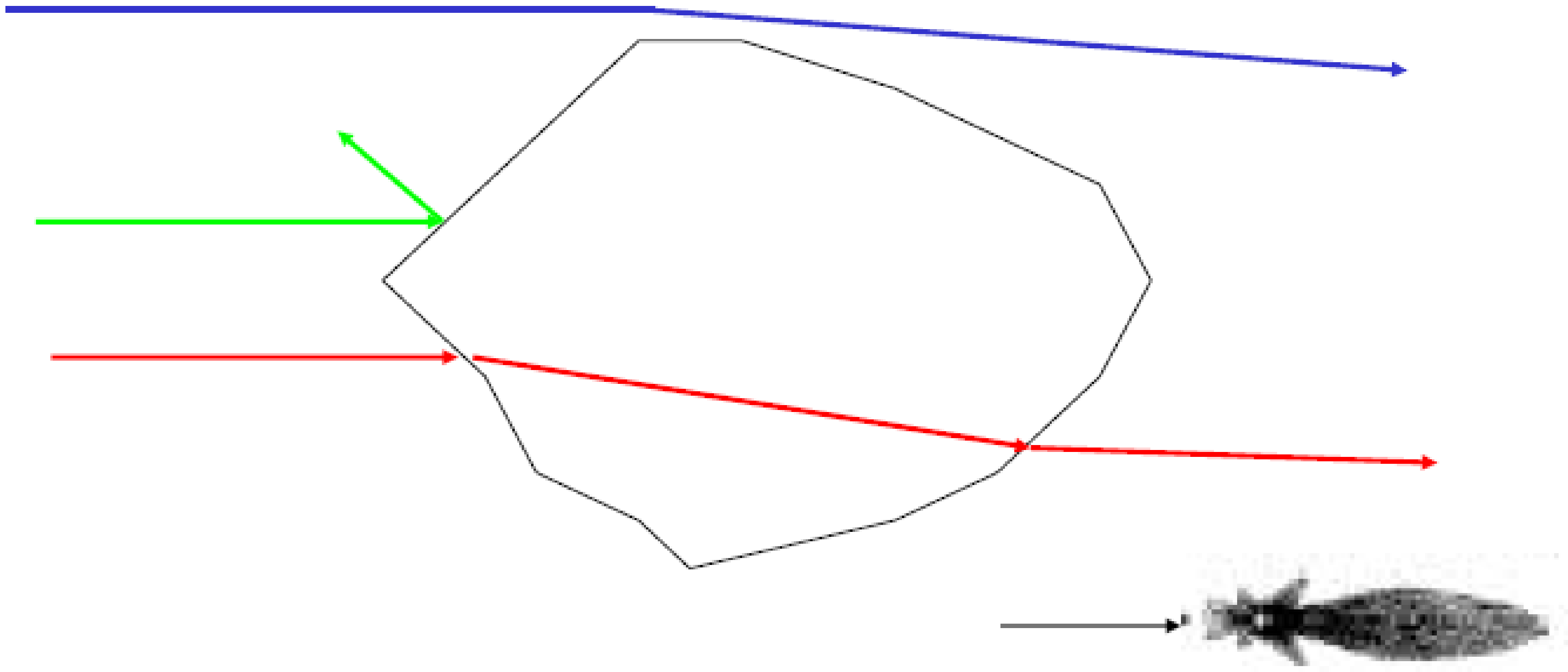
Small Particle Scattering follows Rayleigh Theory



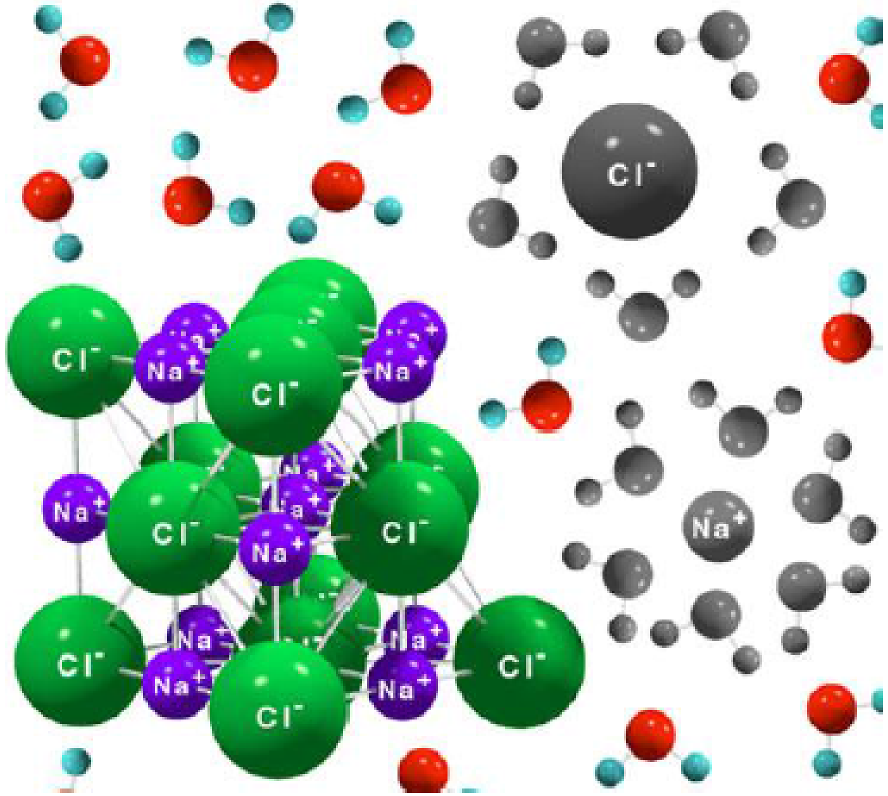


Large Particle Scattering

Three effects: refraction, reflection and diffraction

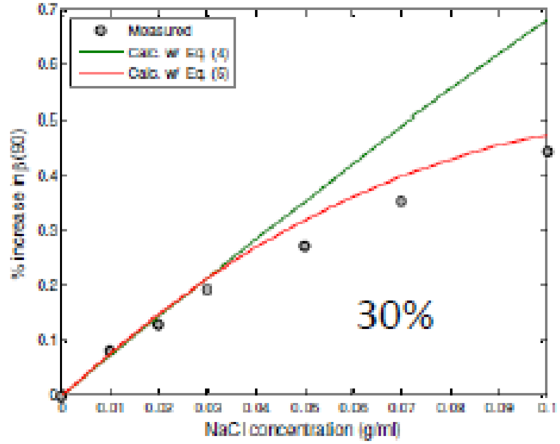


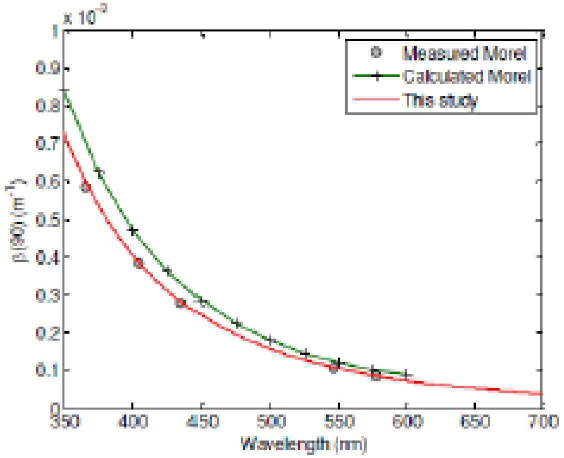
Scattering in the ocean: dissolved salts



Model of salt dissociation

http://www.chemistry.wustl.edu/~edudev/LabTutorials/Water/PublicWaterSupply/PublicWaterSupply.html



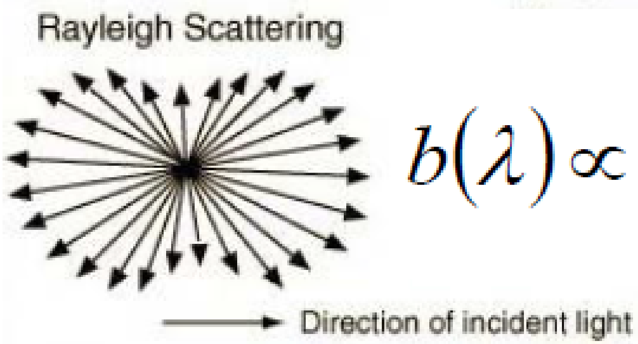


Zhang et al 2009 OptExp

Scattering by CDOM:

From Emmanuel Boss

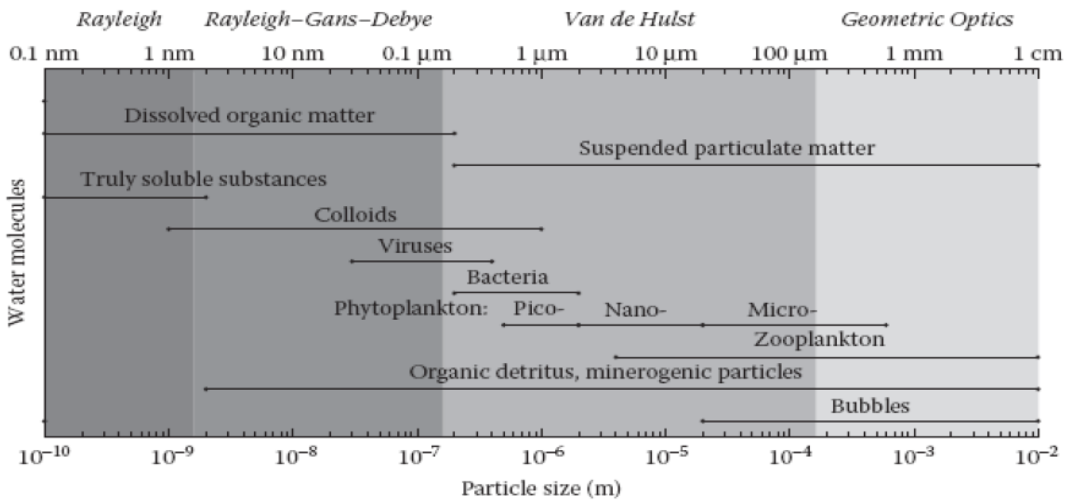
Scattering by molecules whose $D \ll \lambda$. Rayleigh scattering:



$$b(\lambda) \propto \lambda^{-4} \quad \beta(\theta) \propto \left(1+\cos^2(\theta)\right)$$

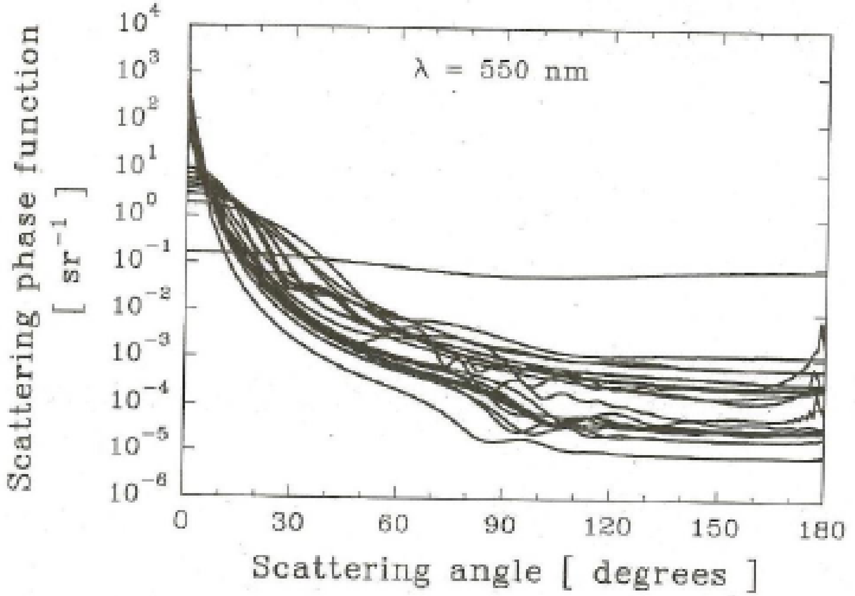
No evidence in the literature that scattering is significant (the only place *I* have ever found significant dissolved scattering ($c_g > a_g$) was in pore water).

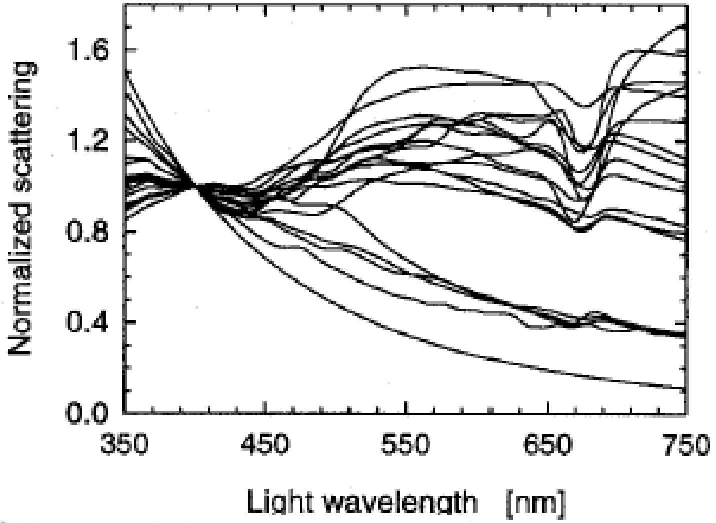
Applicable scattering theory



Particle Size Range

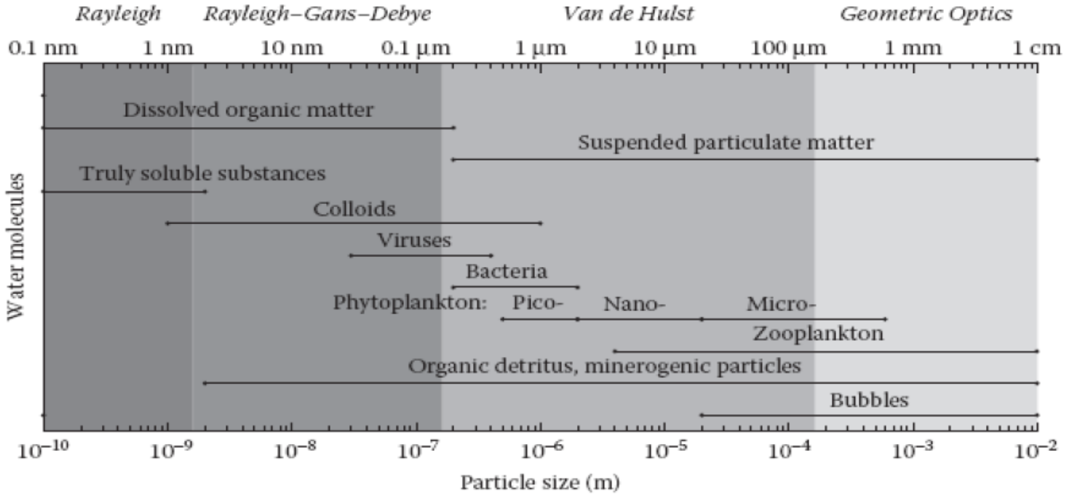
Scattering in the ocean: phytoplankton





Viruses
Heterotrophic bacteria
Prochlorococcus (2 strains)
Synechococcus (Cyanophyceae, 5 s
Anacystis marina (Cyanophyceae)
Pavlova pinguis (Haptophyceae)
Thalassiosira pseudonana (Bacillari
Pavlova lutheri (Haptophyceae)
Isochrysis galbana (Haptophyceae)
Emiliania hyxleyi (Haptophyceae)
Porphyridium cruentum (Rhodophy
Chroomonas fragarioides (Cryptoph
Prymnesium parvum (Haptophycea
Dunaliella bioculata (Chlorophycea
Dunaliella tertiolecta (Chlorophyce
Chaetoceros curvisetum (Bacillario
Hymenomonas elongata (Haptophyc
Prorocentrum micans (Dinophyceae

Applicable scattering theory

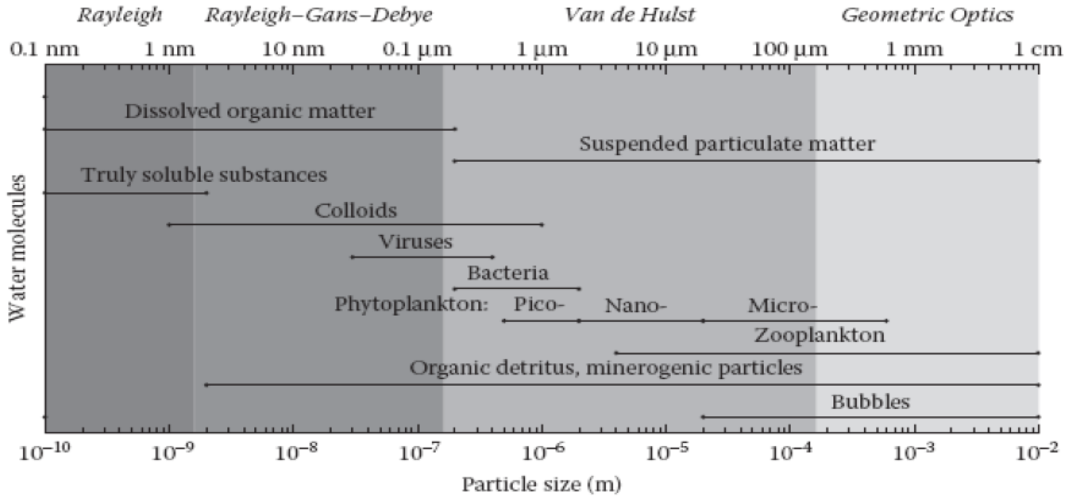


Stramski et al. 2001

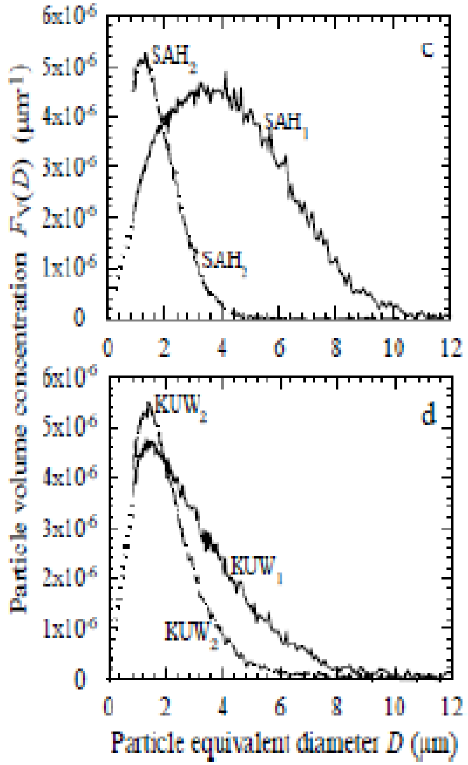
Scattering in the ocean: inorganic minerals

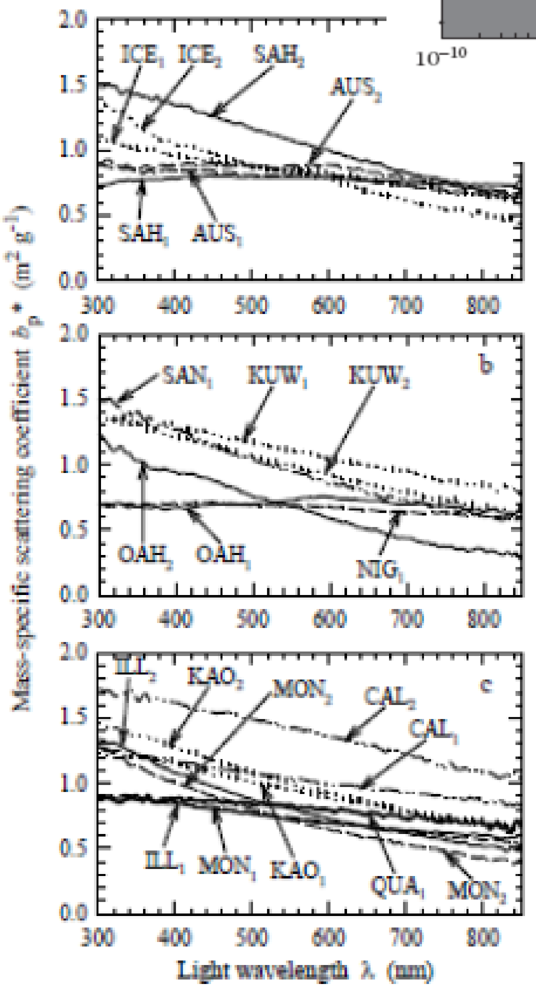
- Terrestrial dust sources

Applicable scattering theory



Particle Size Range

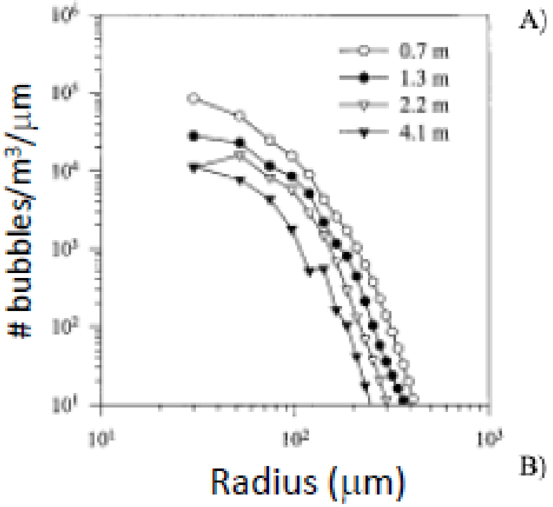


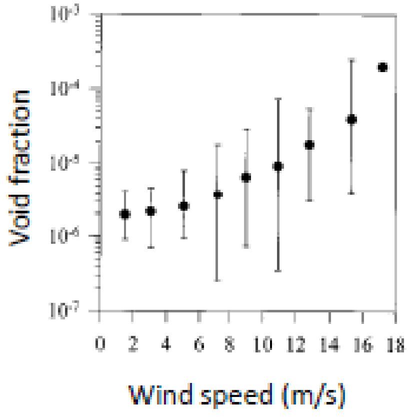


Stramski et al. 2007

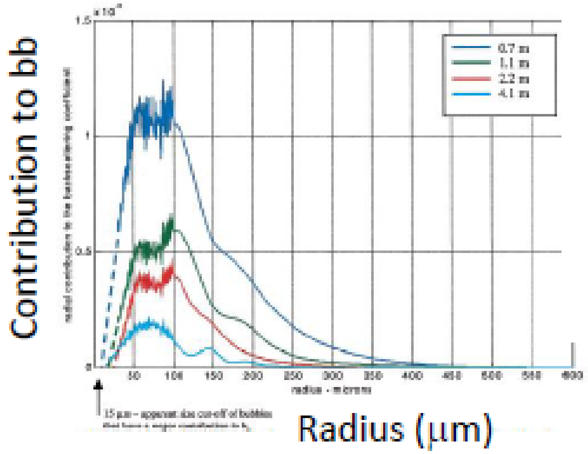
Scattering in the ocean: air bubbles

- Acoustics
  - Size
  - distribution
- Modeled b

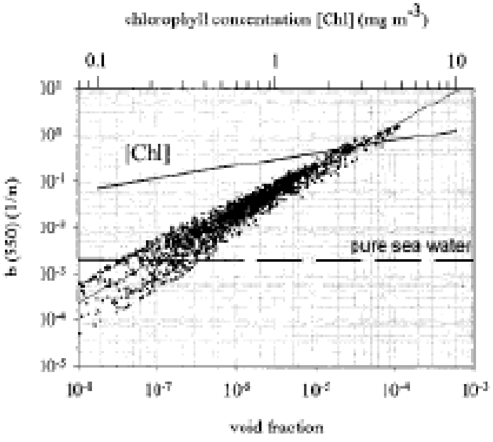


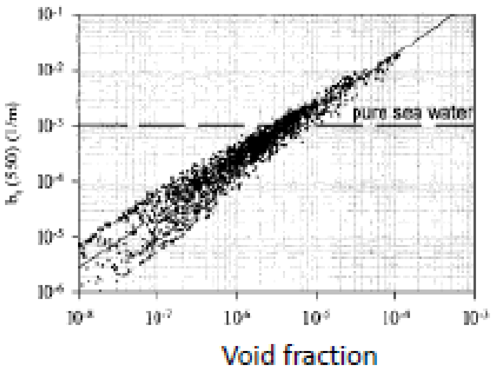


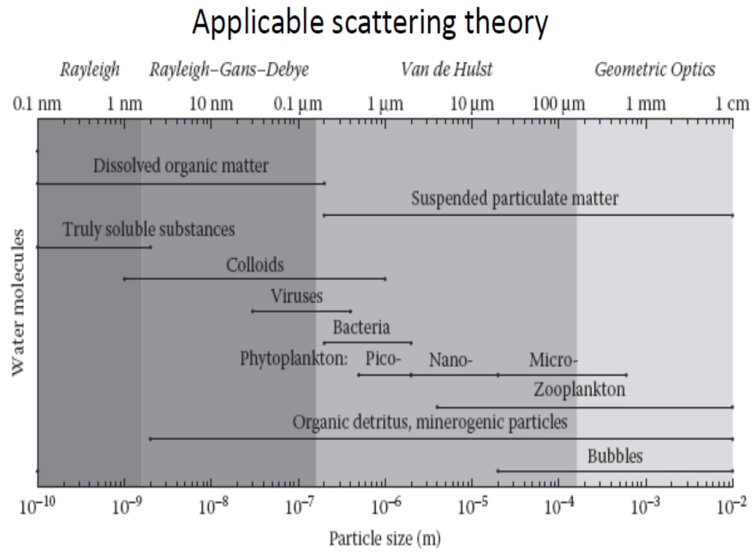
Terrill et al. 1998



Terrill et al. 2001

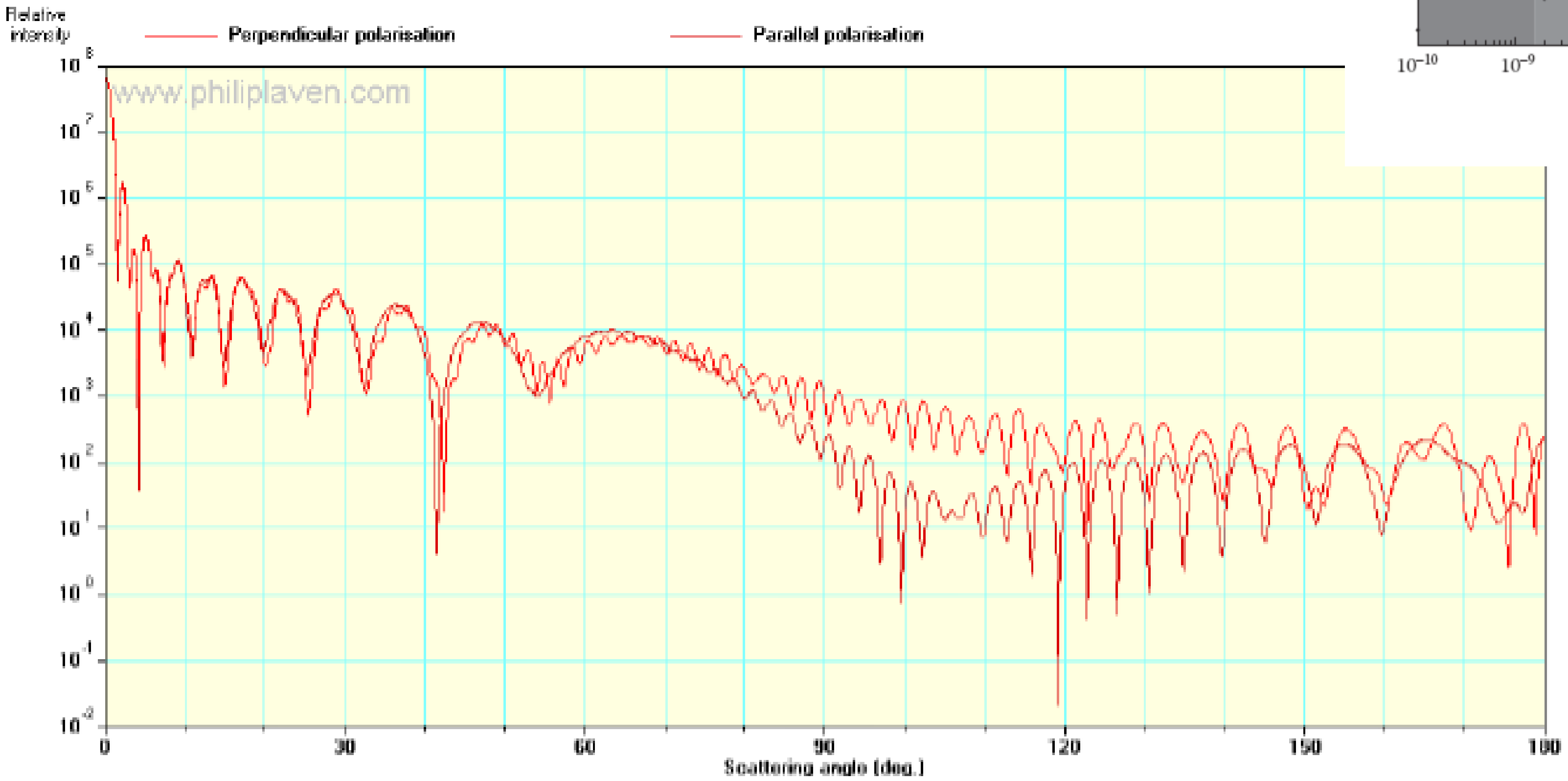


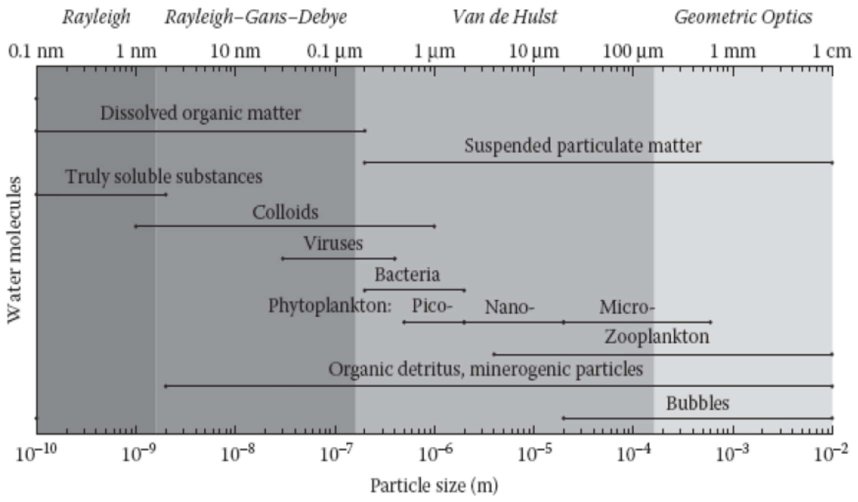




Particle Size Range

Scattering in the ocean: air bubbles





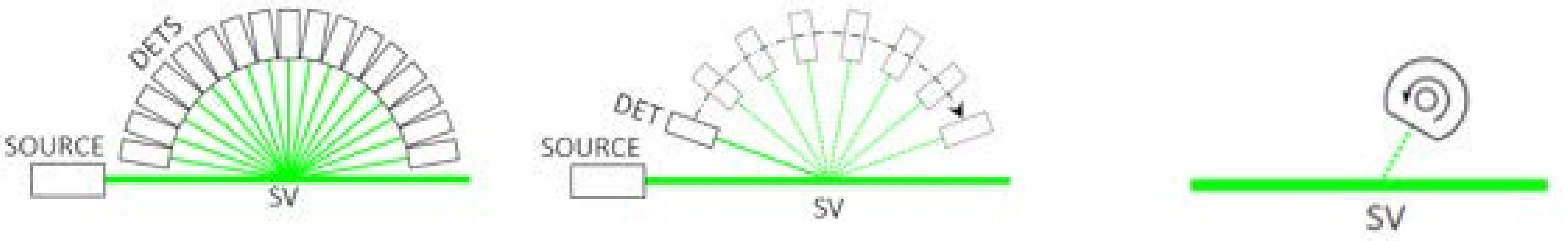
http://www.philiplaven.com/p8h1.html

Particle parameters that influence scattering

- Concentration
- Diameter : wavelength
- refractive index relative to surrounding medium
- absorption of radiation through particle
- Particle shape

固有光学性质

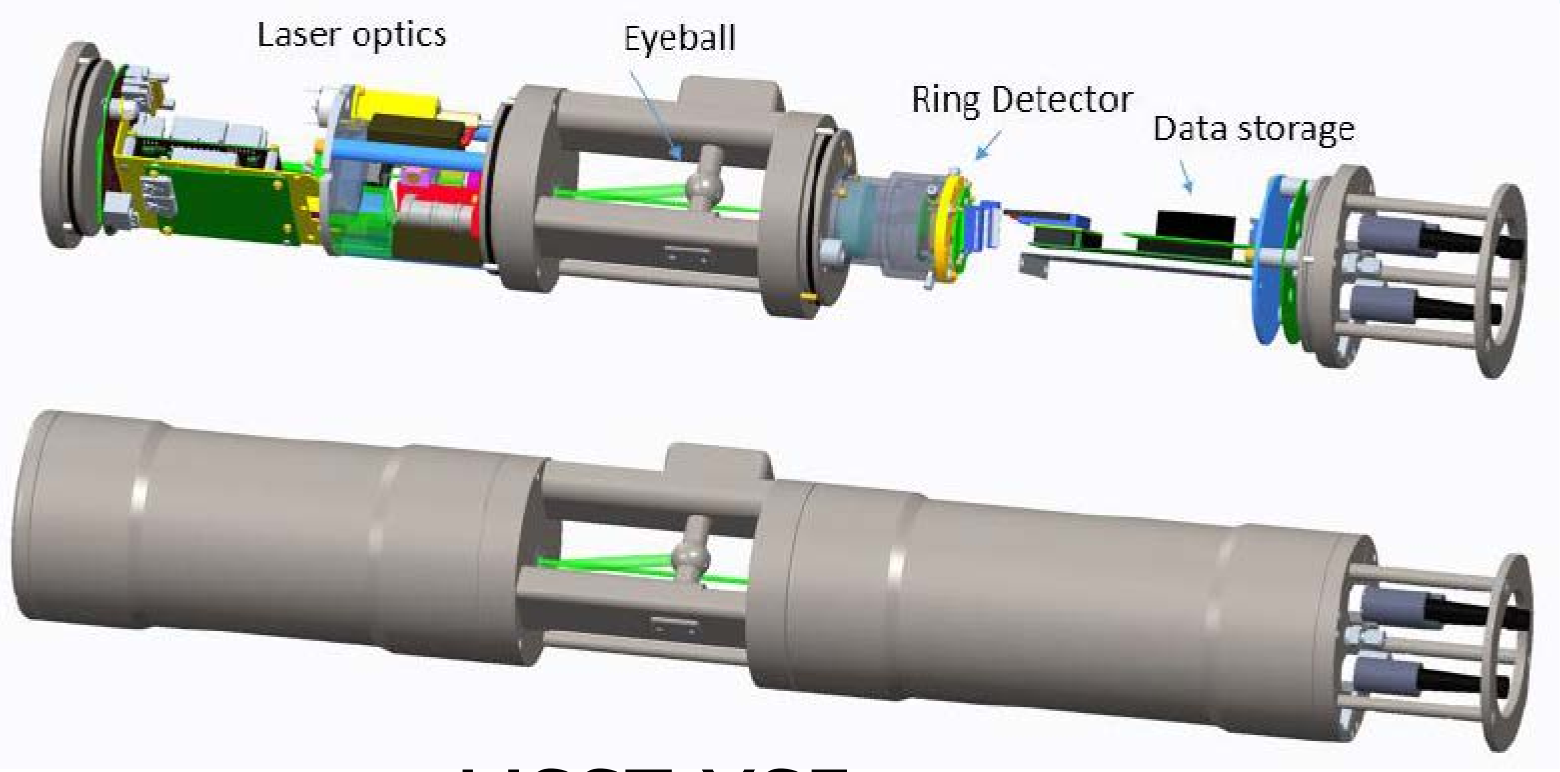
散射作用



散射测量与吸收、衰减测量有何不同?

固有光学性质

散射作用



LISST-VSF

- Small-angle VSF in 32 log-spaced angles, from 0.1 to 15^o
- VSF and P_{12} (DoLP) over 15-150^o in 1o steps

MEASURING VOLUME SCATTERING FUNCTION

Sequoia Scientific, Inc. manufactures the LISST series instruments. The primary measurement in is the Volume Scattering Function. The instruments also measure optical transmission with very low acceptance angles, which yields superior beam attenuation coefficient, *c*.

散射作用

Detail of the LISST-VSF optics path, showing the receive optics and the Roving Eyeball

LISST-200X: Measures Small-angle VSF - from 0.04 – 11.5º, and Beam Attenuation.

This instrument replaces the original LISST-100X. It measures the VSF at 36 log-spaced angles. The beam attenuation measurement has an acceptance angle of just 0.018º. Operating range $c > 0.8\ m^{-1}$. Max. operating depth: 600m.

[Agrawal YC, Mikkelsen OA (2009): Empirical forward scattering phase functions from 0.08 to 16 deg. for randomly shaped terrigenous 1-21 µm sediment grains. Optics Express 17:8805–8814.]

LISST-DEEP: 3000 m Depth Rating

Similar to LISST-200X, it covers angles in water from 0.04 – 6.06º. Beam attenuation has identical acceptance angle as for LISST-200X above, 0.018º. Operating range: $c > 0.4\ m^{-1}$. Suitable for shelf or deep water. Caution: best to use in higher attenuation environments (contact us for details).

LISST-VSF: Covers 0.1 – 150º, and Beam Attenuation

Uses green 514nm laser and optics similar to LISST-200X for small-angle forward VSF. Covers 0.1 to 14.3º in log-spaced angles, and remaining angles in 1º intervals. Also obtains depolarization P_{12}. Beam attenuation acceptance angle: 0.043º. Operating range: $0.1 < c < 8\ m^{-1}$.

[Slade, W. et al., 2013: Comparison of Measured and Theoretical Scattering and Polarization Properties of Narrow Size Range Irregular Sediment Particles; Ocean Optics.]

作 业

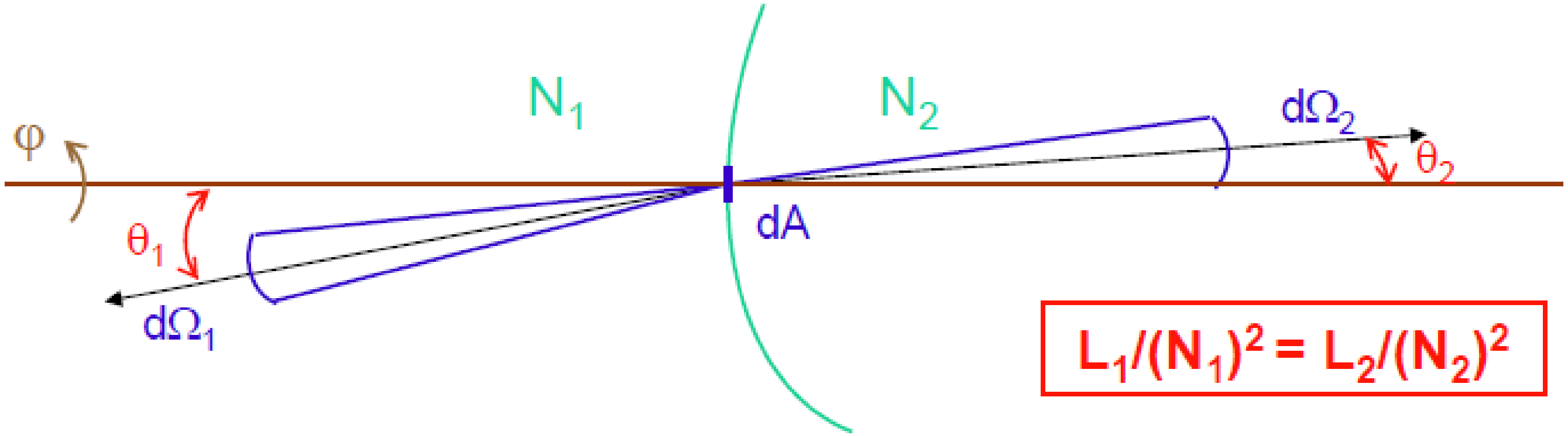
编程读取NOMAD现场观测数据文件nomad_seabass_v2.a_2008200.txt，

- 请问分别有多少个有效的chla、a、R_{rs}数据？请将有效数据分别存为文本文件。
- 请画出有效chla、a、R_{rs}数据点位置分布地图（三种数据用不同颜色或不同标志在同一张地图上标示，或分别在三张地图上标示）。
- 请分别画出a、a-a_w、R_{rs}数据的光谱分布图。
- 分别画出chla、a(443)、a(443)-a_w(443)、R_{rs}(443)数据的统计直方图并给出其均值、标准差和数值范围。

考虑波长[411, 443, 489, 510, 560, 619, 670, 683]nm。

提交作业中应包含结果图和程序（建议所有结果图放在同一个word文本中）。

数据下载网址https://seabass.gsfc.nasa.gov/wiki/NOMAD



Suppose we have a beam of radiance, L, passing through a medium with refractive index N_1, falling onto dA from solid angle $d\Omega_1$ inclined at θ_1 w.r.t. dA, then the power passing through dA is given by:

$$d^2\Phi = L_1 dA \cos\theta_1 \, d\Omega_1$$

We would like to find θ_2 and Ω_2 in terms of find θ_1 and Ω_1. Using polar coordinates, with the axis normal to dA, we have:

$$d\Omega_1 / d\Omega_2 = (\sin\theta_1 \, d\theta_1 d\varphi_1)/(\sin\theta_2 \, d\theta_2 d\varphi_2) \qquad (1)$$

From Snell's law we have: $d\varphi_1 = d\varphi_2$ (pick your plane of propagation)

and $N_1 \sin\theta_1 = N_2 \sin\theta_2$

so that (differentiating):

$$N_1 \cos\theta_1 d\theta_1 = N_2 \cos\theta_2\, d\theta_2$$

Using equation (1) above, we then have:

$$d\Omega_1 / d\Omega_2 = (N_2/N_1)^2 (\cos\theta_2)/(\cos\theta_1)$$

The radiance of the refracted beam is then:

$$\begin{aligned} L_2 &= d^2\Phi/(dA \cos\theta_2\, d\Omega_2) \\ &= L_1\, dA \cos\theta_1\, \Omega_1/(dA \cos\theta_2\, \Omega_2) \\ &= L_1 \cdot (N_2/N_1)^2 \end{aligned}$$

$$\Rightarrow \qquad \boxed{L_1/(N_1)^2 = L_2/(N_2)^2}$$

激光雷达

https://coast.noaa.gov/digitalcoast/training/intro-lidar.html

海洋光学

http://www.oceanopticsbook.info/

数据网站

https://giovanni.gsfc.nasa.gov/giovanni/

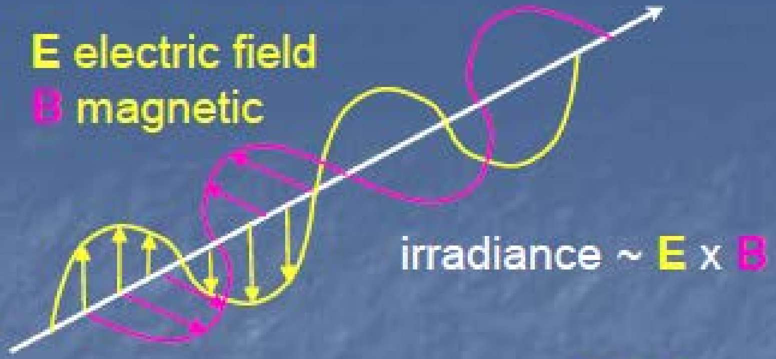
Polarization

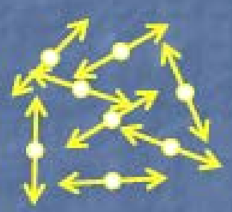
The polarization state of the radiance requires four numbers: the elements of the Stokes vector $S = [I, Q, U, V]^T$

I gives the total radiance, without regard for the state of polarizaiton. Q, U, V describe the linear and circular polarization of the light.

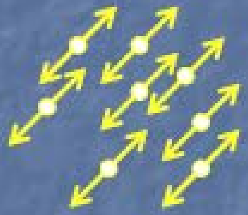
$S = L(z, \theta, \phi, \lambda)\ [1, 0, 0, 0]^T$ represents unpolarized radiance

$S = L(z, \theta, \phi, \lambda)\ [1, 0.3, 0, 0]^T$ shows that the total radiance is partially linearly polarized

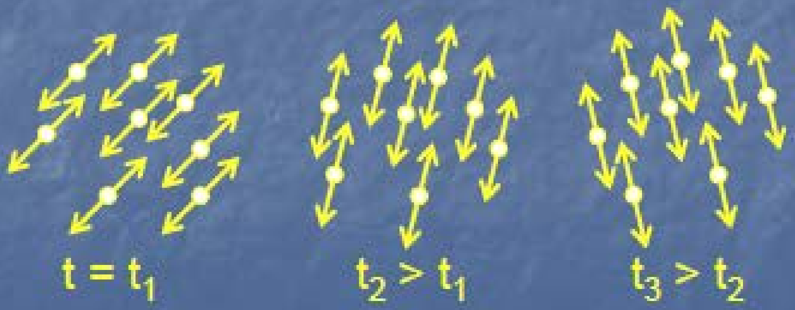




randomly polarized (unpolarized):
E fields are randomly oriented



plane polarized:
E fields are all in the same plane (constant in time)



circularly polarized:
E fields rotate with time

The state of polarization of the radiance contains information about the environment (such as the size distribution, shape, and index of refraction of particles in the water)

However, oceanographers usually measure only the total radiance because

- The 4x1 Stokes vector (and corresponding 4x4 Mueller matrix, which describes scattering of polarized light) is much harder to measure than just total radiance

- The state of polarization is believed to have little effect on processes like phytoplankton photosynthesis or water heating

- The different polarizations of the radiance in different directions tend to average out when the radiance is integrated to get irradiance

- We do not have many models or data for the inputs needed to compute polarization in the ocean

Keep in mind, however, that ignoring polarization (e.g., in HydroLight) causes some error (~10% in radiance, ~1% in irradiance) and that use of polarization will become more important in future years, as instruments and models improve.