GODAE Summer School, Toulon

21st Sep, 2004

Measuring the Ocean from Space, 1

Principles of measurement using altimetry and radiometry

Ian Robinson

Professor of Oceanography from Space, University of Southampton.
Head of the SOC Laboratory for Satellite Oceanography.

Southampton
Oceanography Centre

Purpose of these Lectures

- The Aims:
  - To learn about the basic methods of Space Oceanography so that you can critically appraise global ocean datasets from satellites.
  - To understand how to confront models effectively with satellite data in the context of operational applications.

- Objective of Lecture 1 (Today): To understand what sensors in Space actually measure, and how to derive useful ocean parameters from the primary measurements.

- Objective of Lecture 2 (Tomorrow): To recognise the measurement and sampling limitations of satellite sensors, and learn how best to exploit the benefits of satellite data.

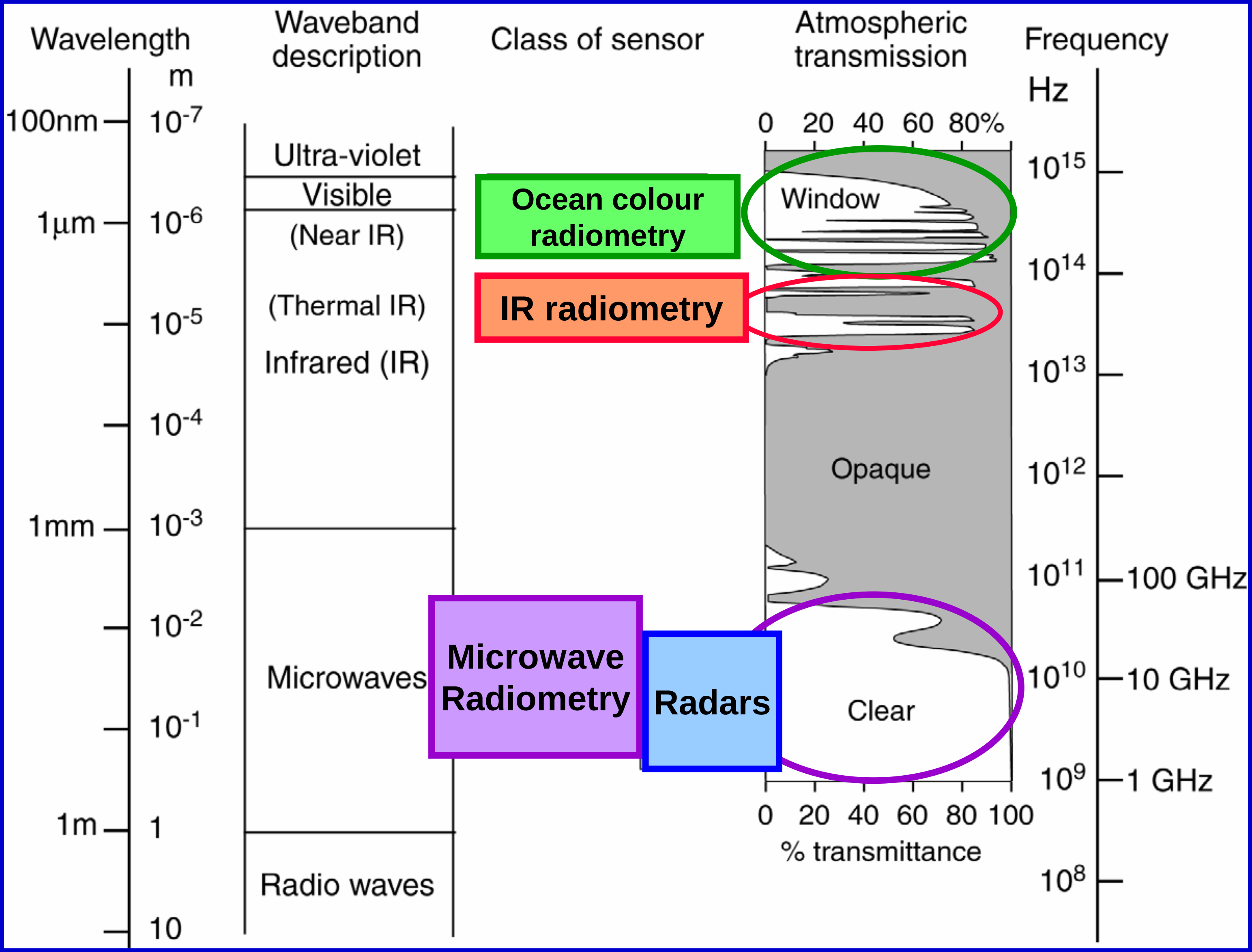
Outline of lecture

- Methods of measuring ocean properties from satellites : A generic outline
- Observing ocean currents using satellite altimetry
- Estimating chlorophyll concentrations from ocean colour
- Measuring sea surface temperature by radiometry

In tomorrow's lecture, where
the GODAE high resolution SST Project
provides a case study

Methods of measuring ocean properties from satellites : A generic outline

Using the Electromagnetic Spectrum

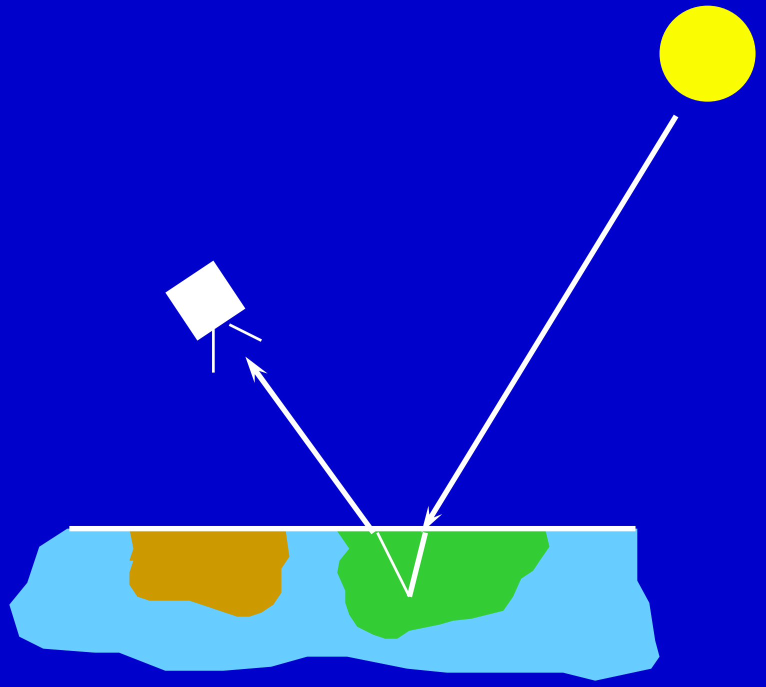


Sensor Types: 1
Passive Sensors - solar radiation

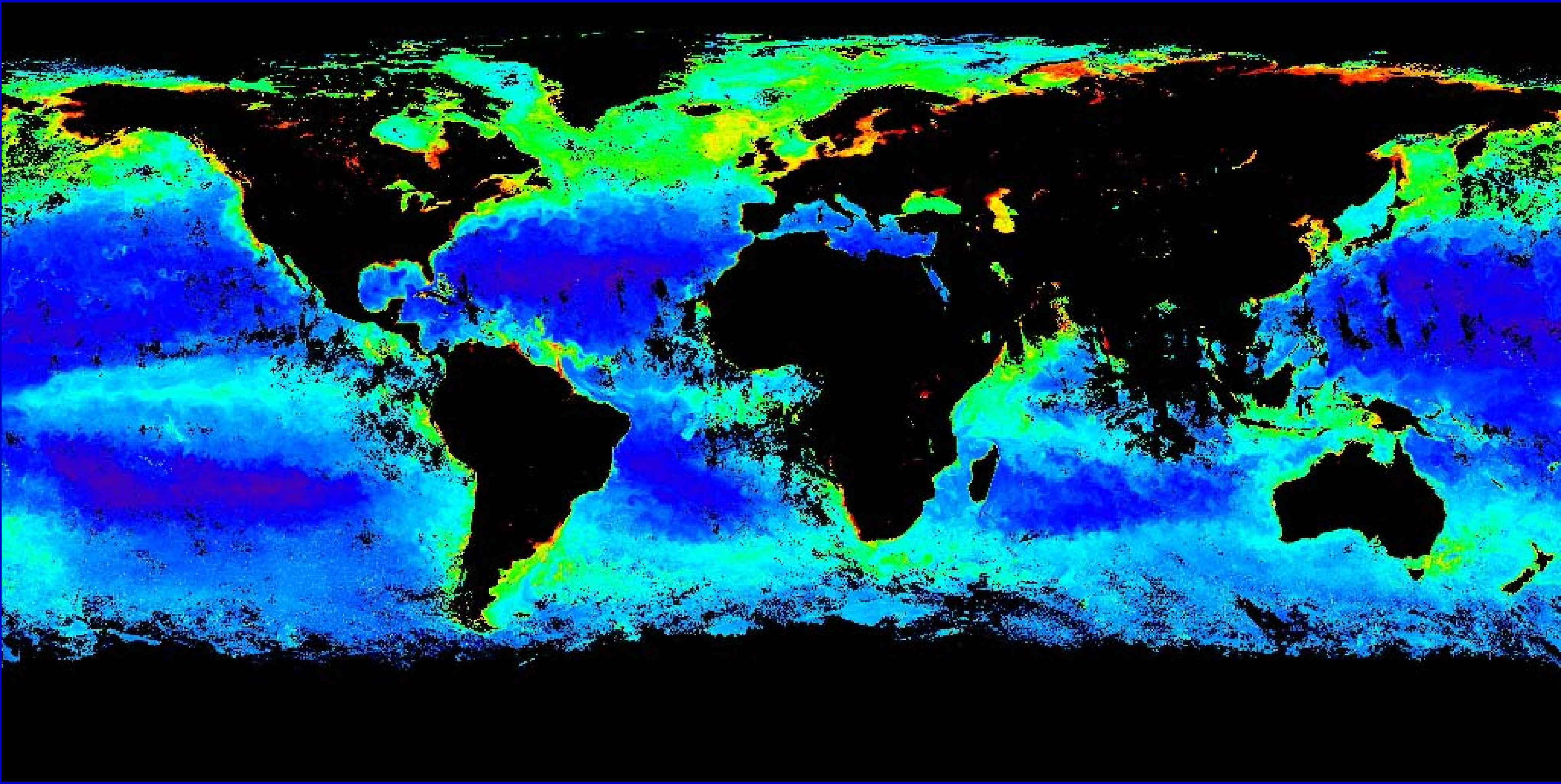
- Use visible and near infra-red wavelengths
- Multispectral (detects colour)
- Scanning (generates images)

- Obstructed by clouds
- Corrupted by the atmosphere

- Measures water properties which colour the sea
- Also measures light reflected at the surface
- Near infra-red light does not penetrate the sea



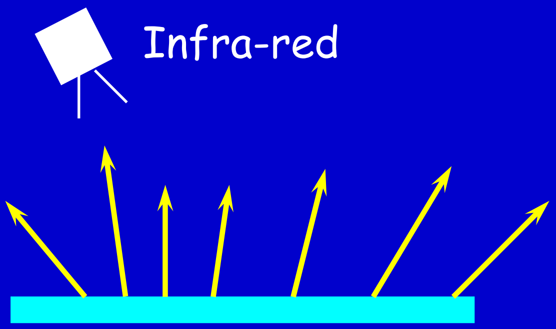
Satellite ocean datasets, 1: from ocean colour



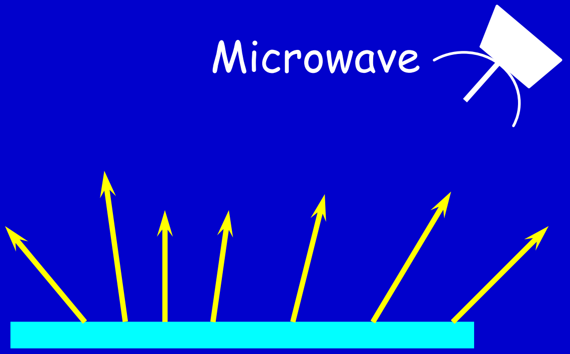
Global distribution of surface chlorophyll concentration derived from the SeaWiFS sensor during 28th August to 4th September 2004

Sensor Types: 2
Passive sensors - emitted radiation

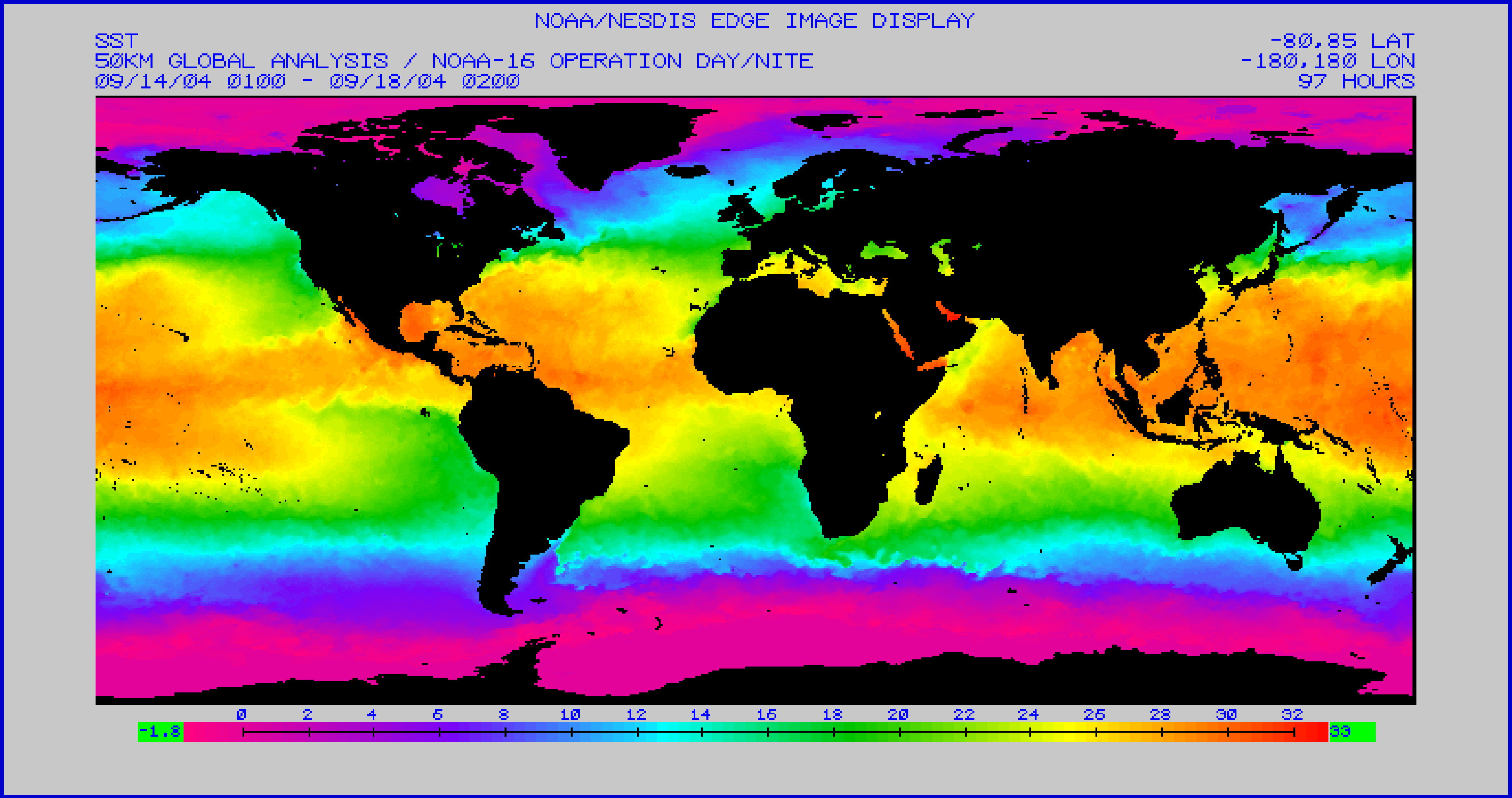
- Thermal Infra-red radiometers
- Multiple wavebands
- Obstructed by clouds
- Requires atmospheric correction
- Measure sea surface temperature



- Microwave radiometers
- Multiple frequency bands
- See through clouds
- Almost independent of atmosphere
- Measure sea surface temperature
- Measure surface roughness
- Measure salinity ?

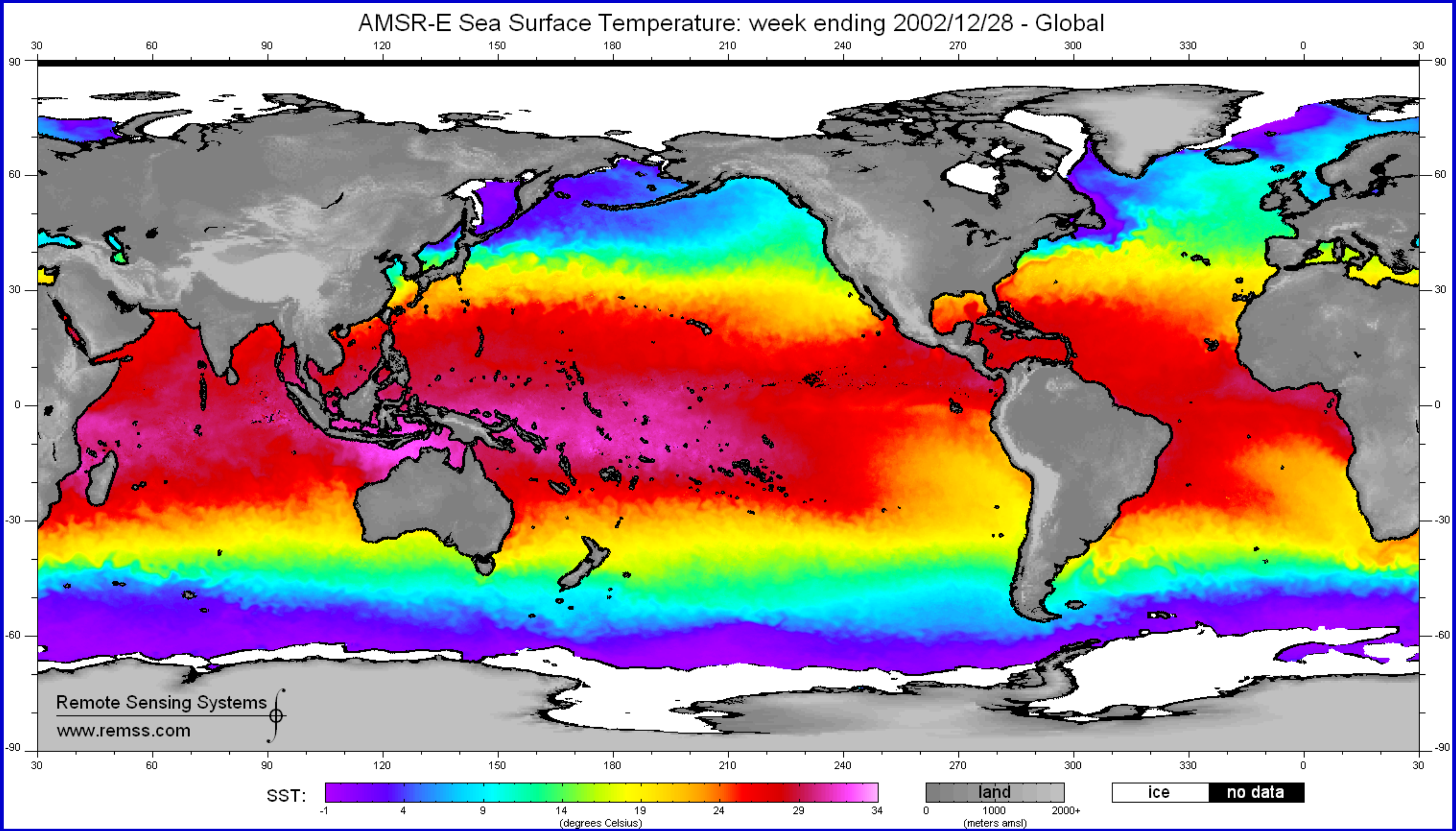


Satellite ocean datasets, 2: from infrared sensors



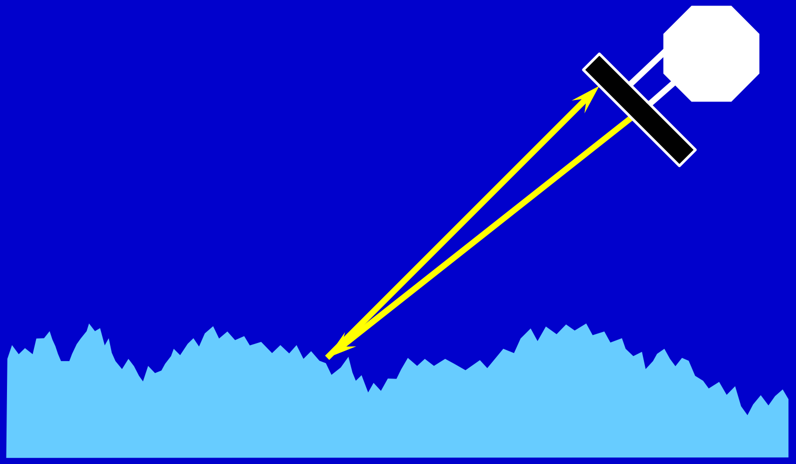
Global Sea Surface Temperature (SST) distribution derived from the NOAA AVHRR sensors during 14th to 18th September 2004

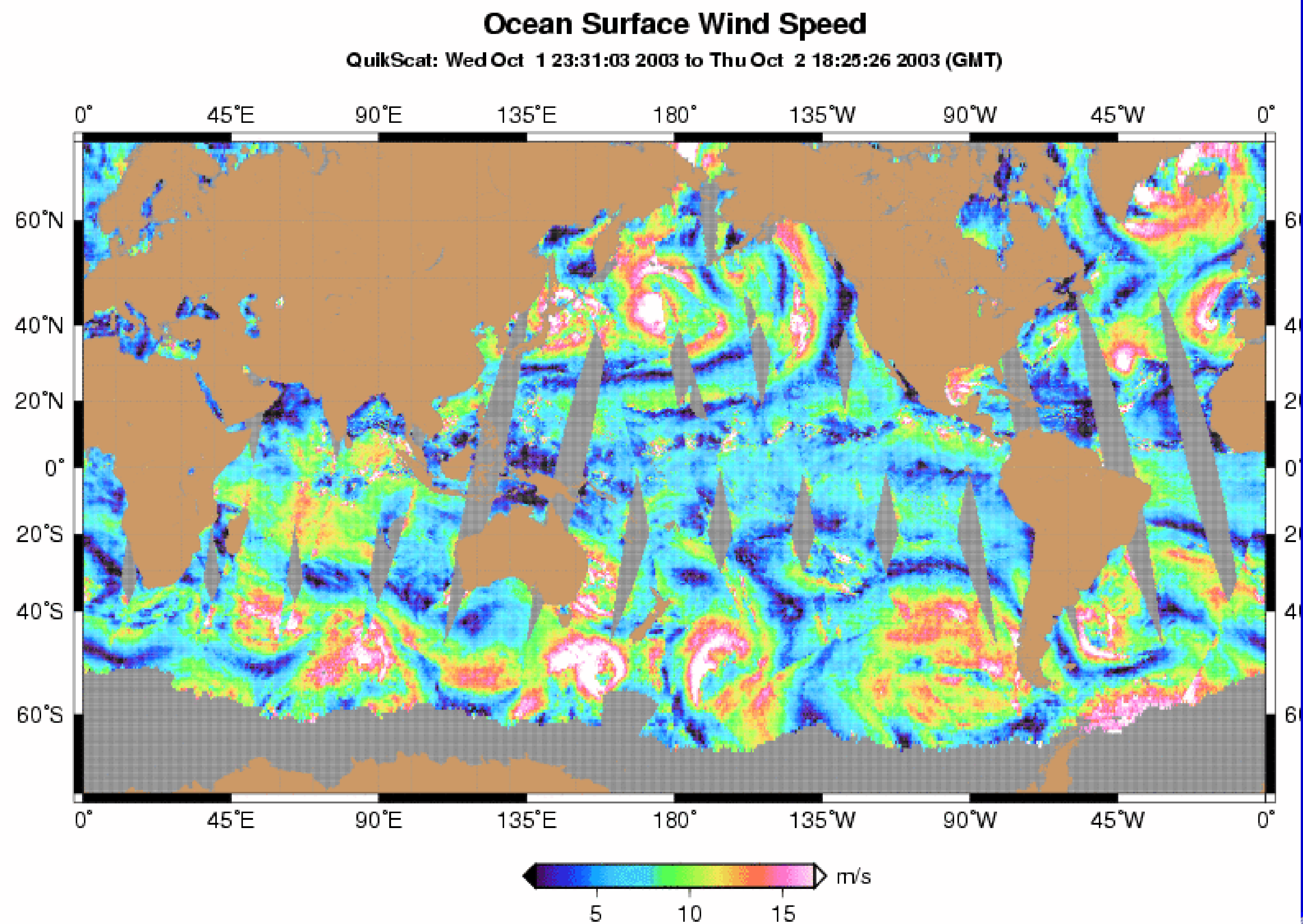
Satellite ocean datasets, 3: from microwave radiometers



Sensor Types: 3. Active Sensors

- Emit radar pulse obliquely
- Scatterometer (course resolution)
- Measure wind speed and direction
- Imaging radar – SAR (fine resolution)
- Detect surface roughness patterns

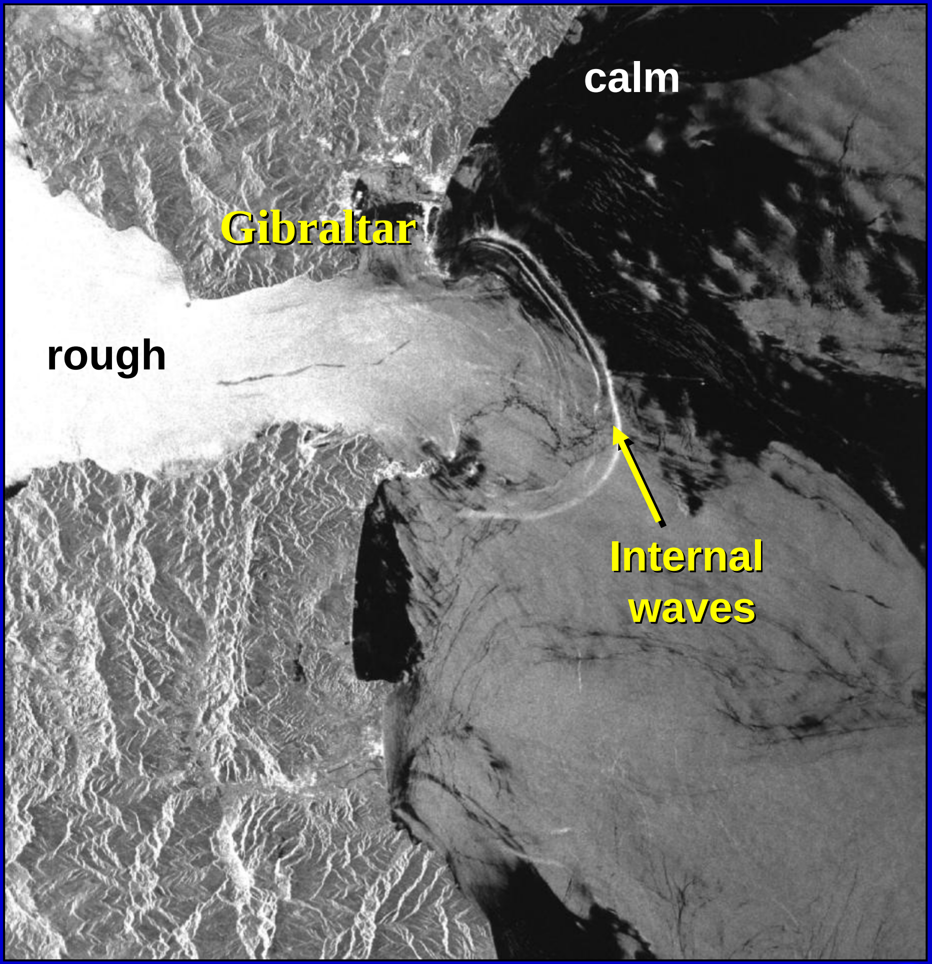




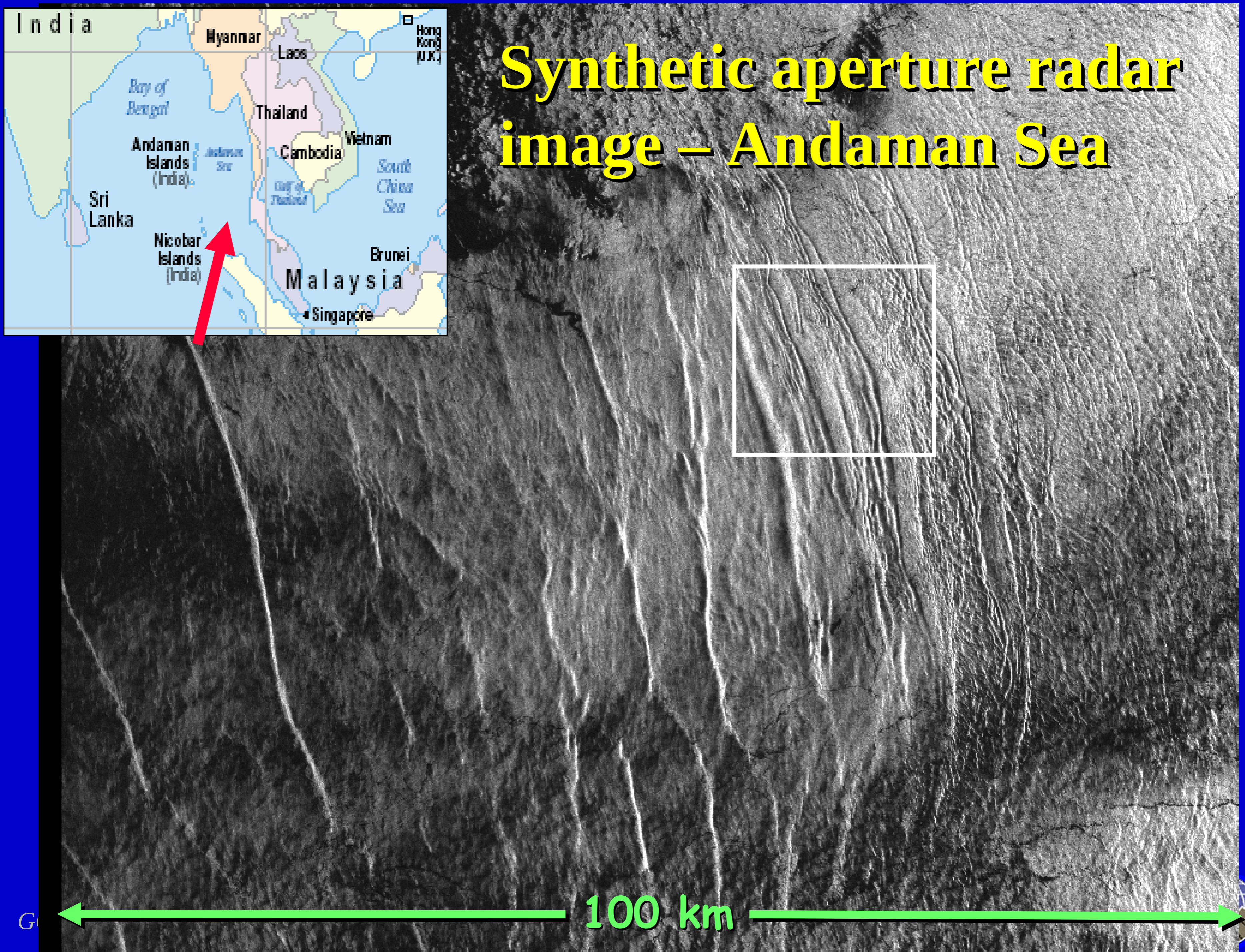
Ocean Surface Wind Speed
QuikScat: Wed Oct 1 23:31:03 2003 to Thu Oct 2 18:25:26 2003 (GMT)
0°
45°E
90°E
135°E
180°
135°W
90°W
45°W
0°
60°N
40°N
20°N
0°
20°S
40°S
60°S
m/s
5
10
15

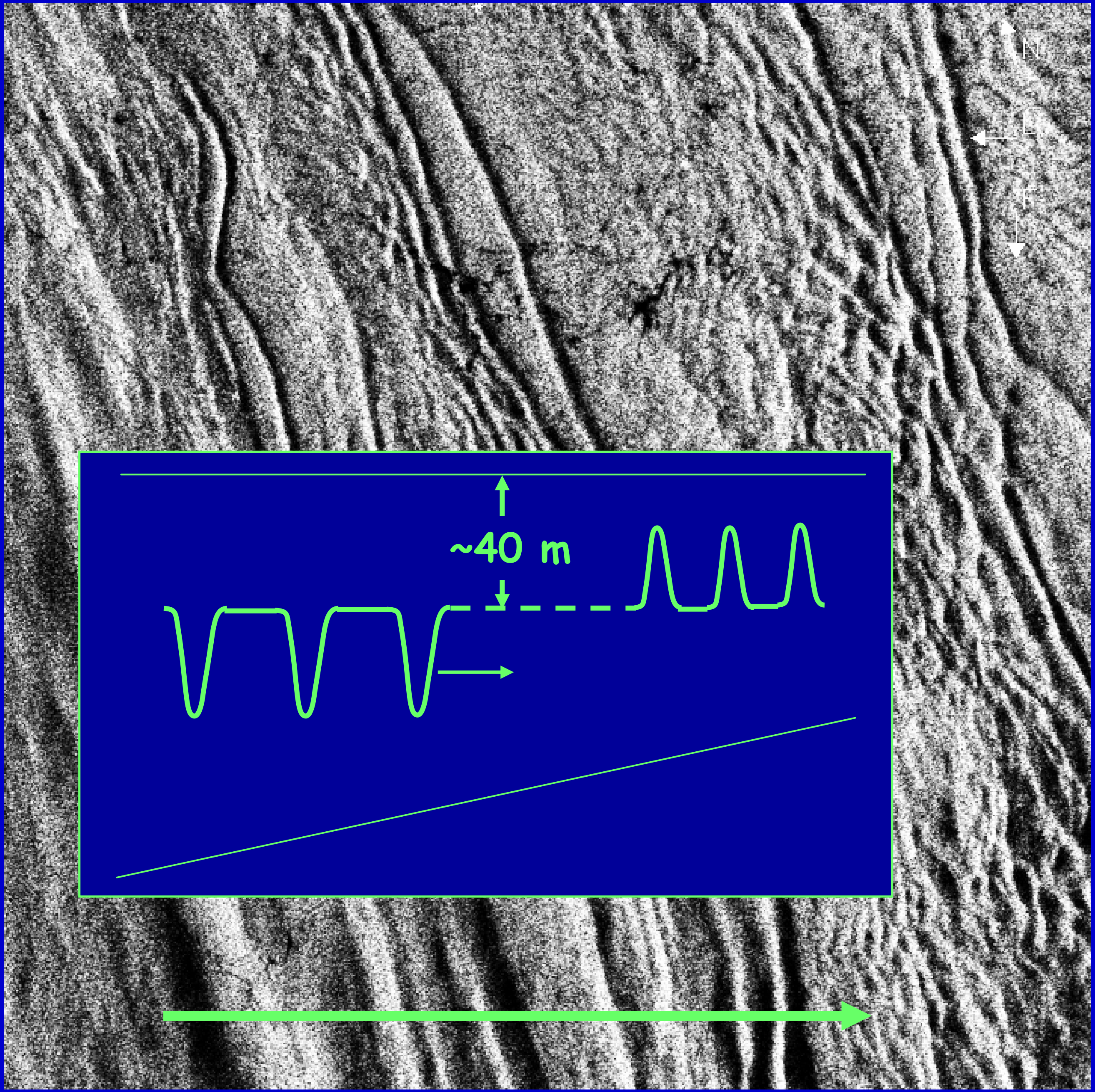
Synthetic Aperture Radar Data

- SAR images: a unique view of the Ocean
  - Measure short scale (5-50 cm) roughness of the sea
  - Bright = rough
  - Dark = smooth
- Capable of observing a variety of ocean phenomena
  - Anything can be imaged that modulates surface roughness
  - Even subsurface phenomena
  - Wind conditions must be right



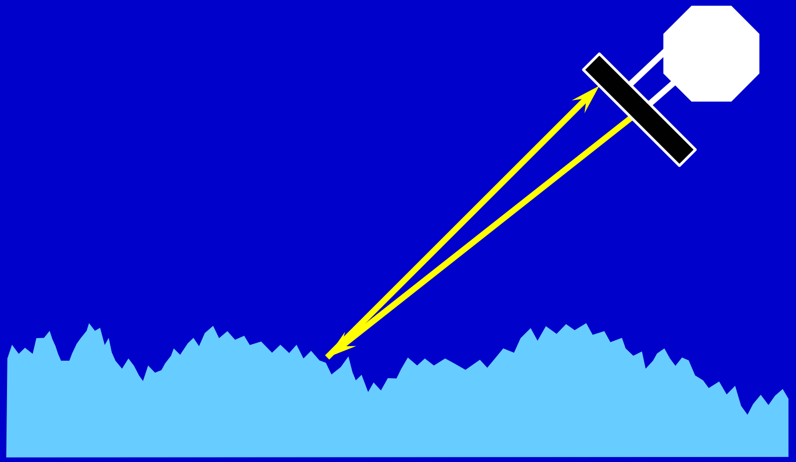
Synthetic aperture radar image – Andaman Sea



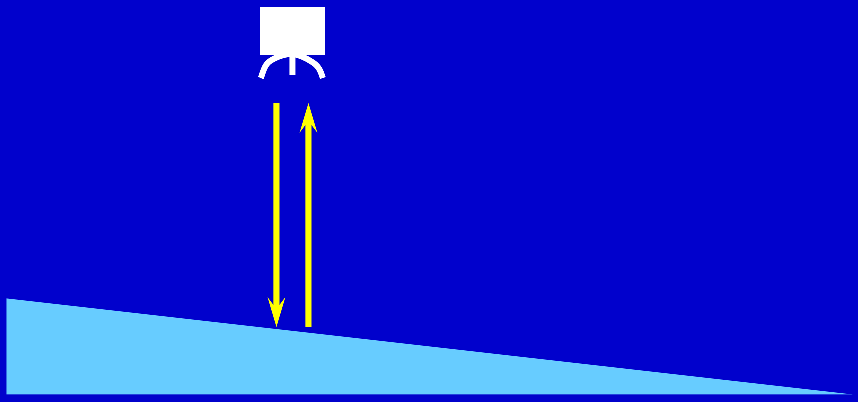

~40 m

Sensor Types: 3. Active Sensors

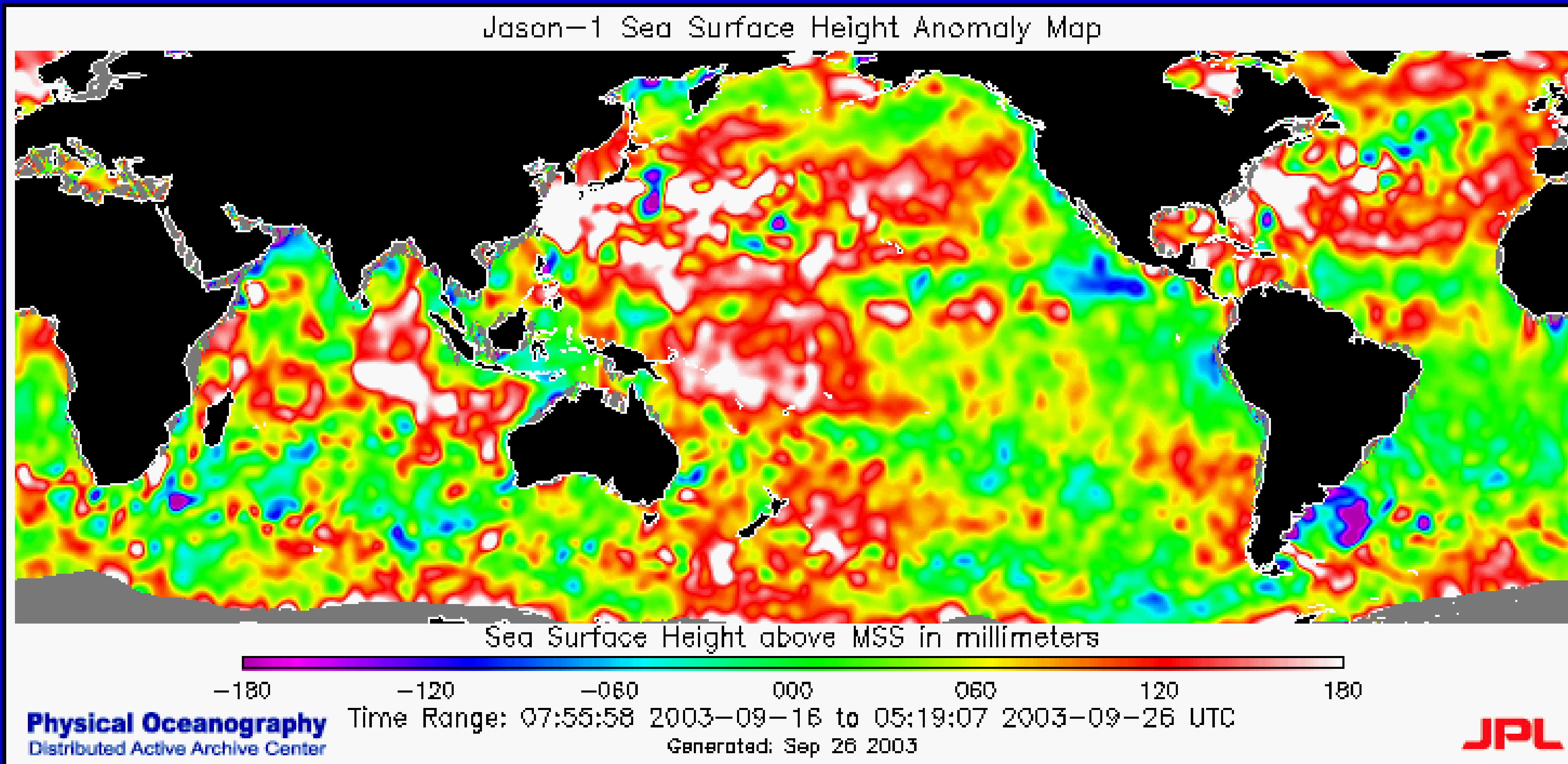
- Emit radar pulse obliquely
- Scatterometer (course resolution)
- Measure wind speed and direction
- Imaging radar – SAR (fine resolution)
- Detect surface roughness patterns



- Emit radar pulse vertically
- Altimeter
- Measure timing of return
- Detect distance to surface
- Measure shape and strength of return pulse
- Detect wave height & wind



Satellite ocean datasets, 4: from altimetry

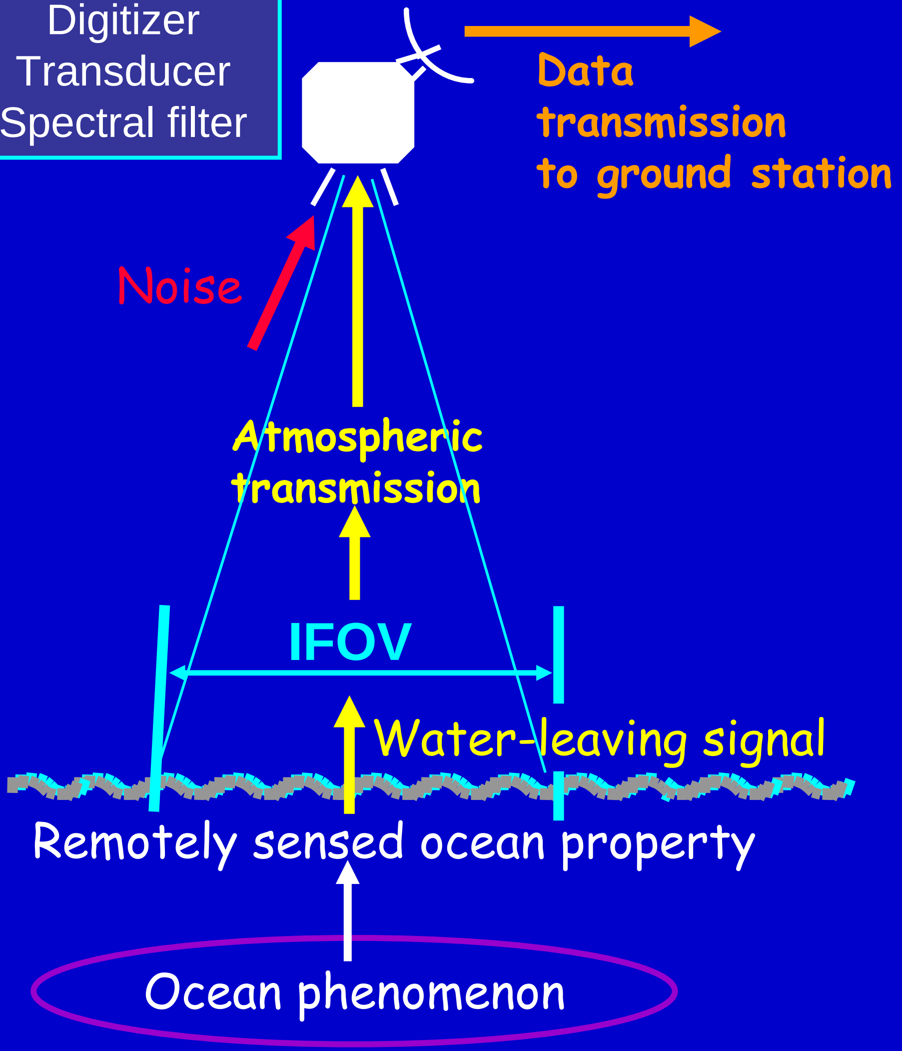


SS Height Anomaly (from Altimeter)

Height 16-26 Sep, 2003 – mean height over several years

Information Flow in a R-S System

Digitizer
Transducer
Spectral filter



Signal processing characteristics

Sensor physics and technology

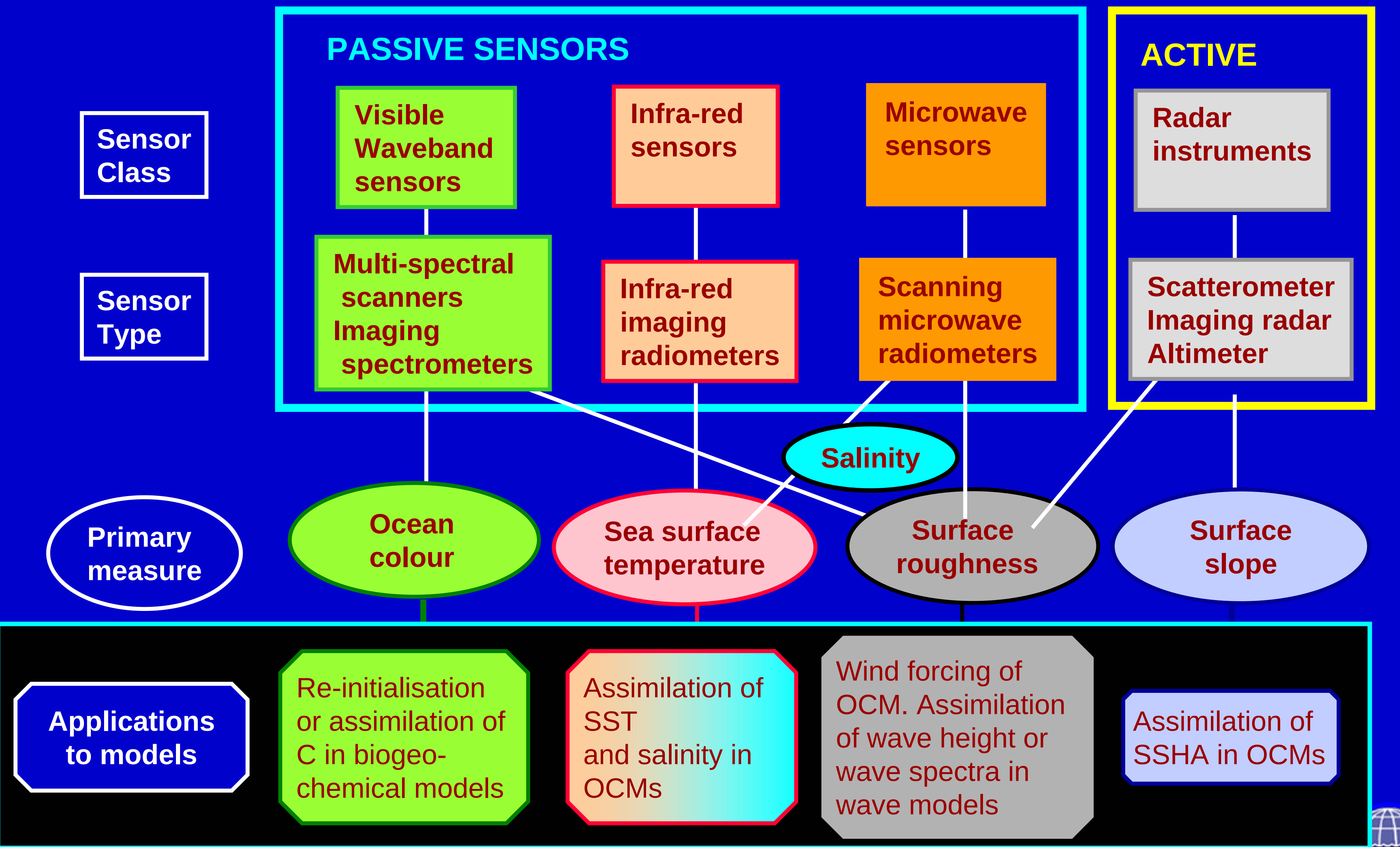
Atmospheric physics

Ocean / e-m interactions

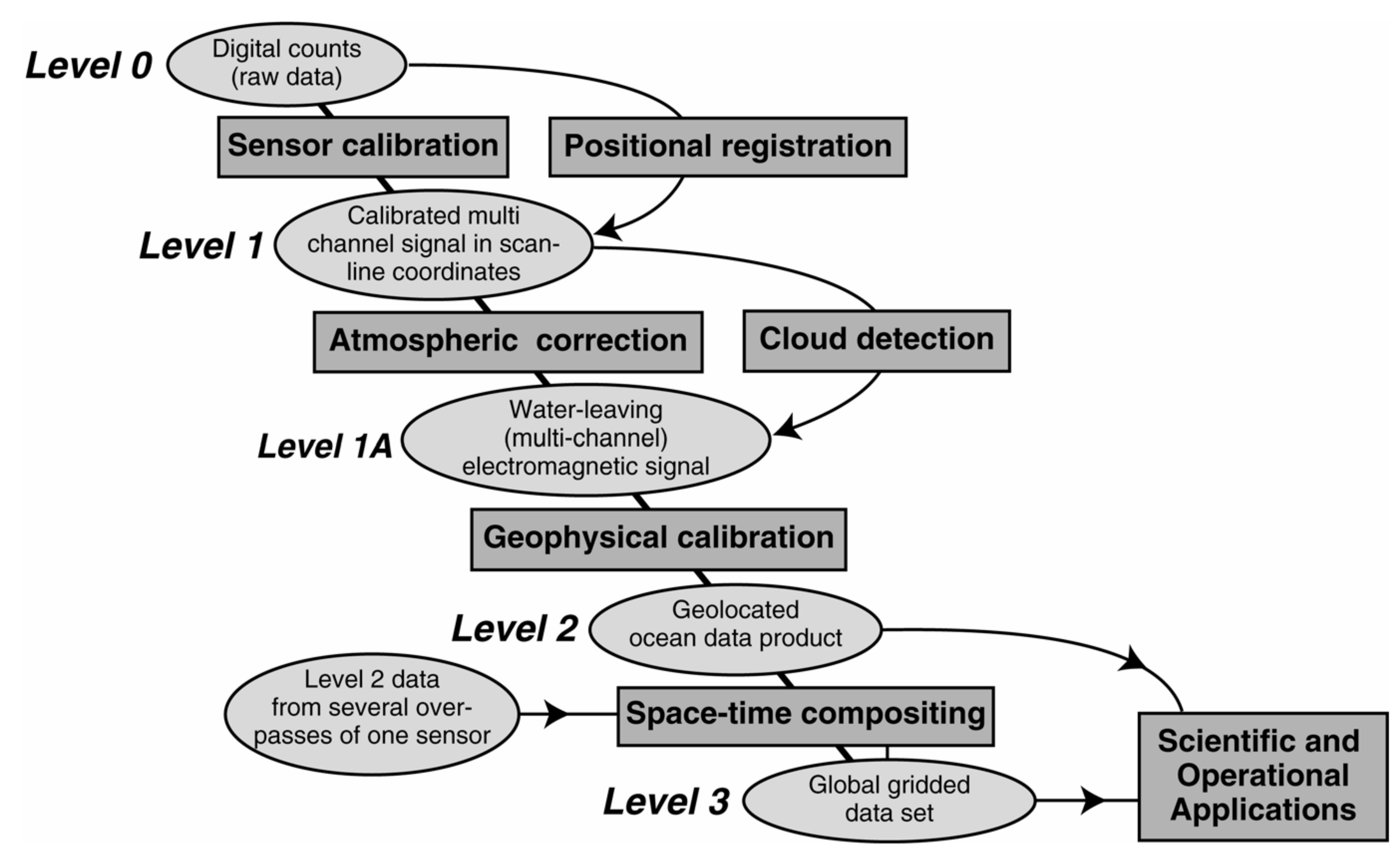
Upper ocean processes

Knowledge needed to understand each stage of the remote sensing process

Sensor types and what they measure



Stages of Processing : Levels of processed data



How important are satellite ocean data ?

- Satellite remote sensing has opened up the study of global ocean phenomena
  - We can now ask questions about large scale processes that previously could not be addressed
  - We can now make observations of ocean scale phenomena which test and stretch theoretical models
- 21st Century Oceanography has become dependent on satellite observations
  - All branches of ocean science now expect to use satellite image data
  - Interest is no longer limited only to specialist "satellite oceanographers"
  - There is a growing use of satellites for operational ocean monitoring and forecasting

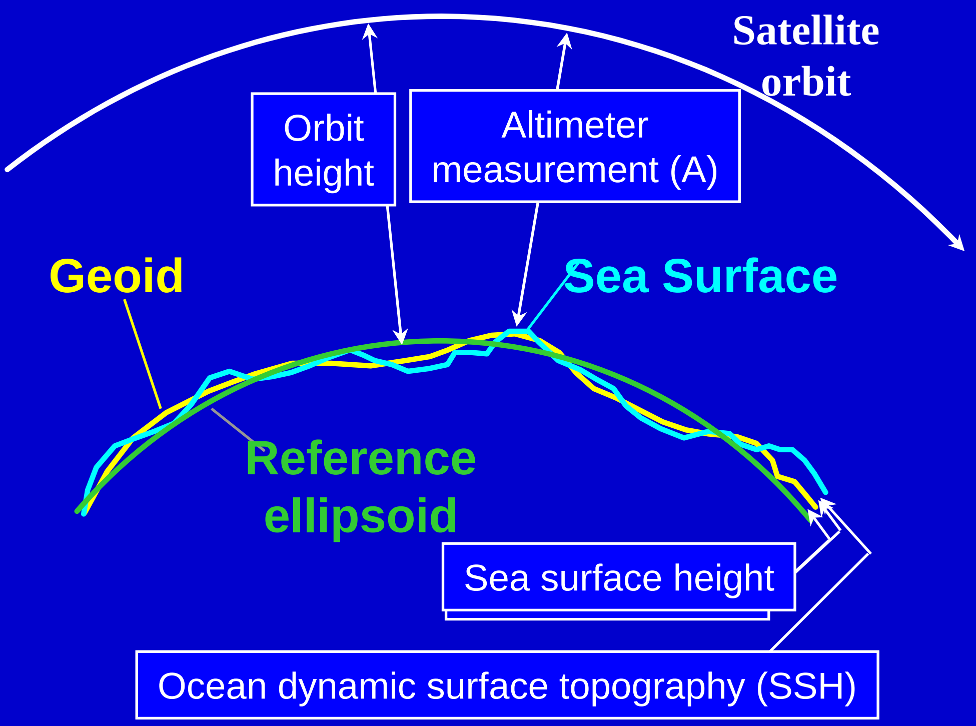
Fundamental limitations of satellite ocean remote sensing

- Can observe only some of the ocean's properties and variables
- Measures the ocean only at or near the surface
  - Although the surface is the most critical place to measure
- Ocean measurements may be corrupted by the atmosphere
- Some methods cannot see through clouds at all
- Measurements can be made only when the satellite is in the right place
- All measurements require calibration and validation using *in situ* data

Observing ocean currents using satellite altimetry

Principles of altimetry

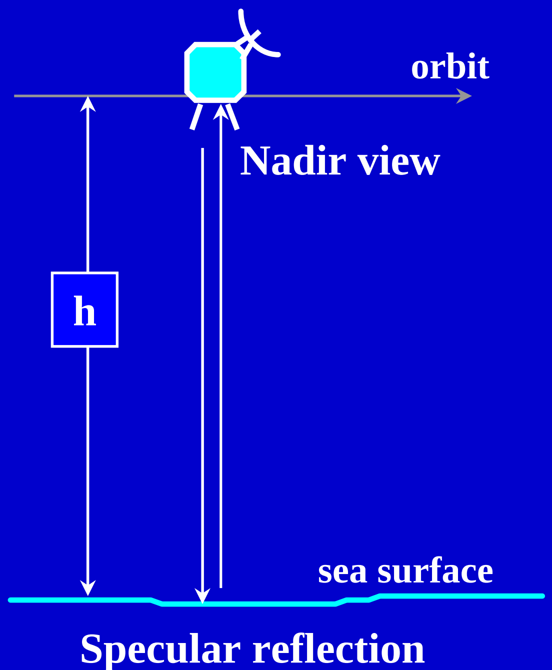
- Measure distance between satellite and sea
- Determine position of satellite
- Hence determine height of sea surface
- Oceanographers require height relative to geoid



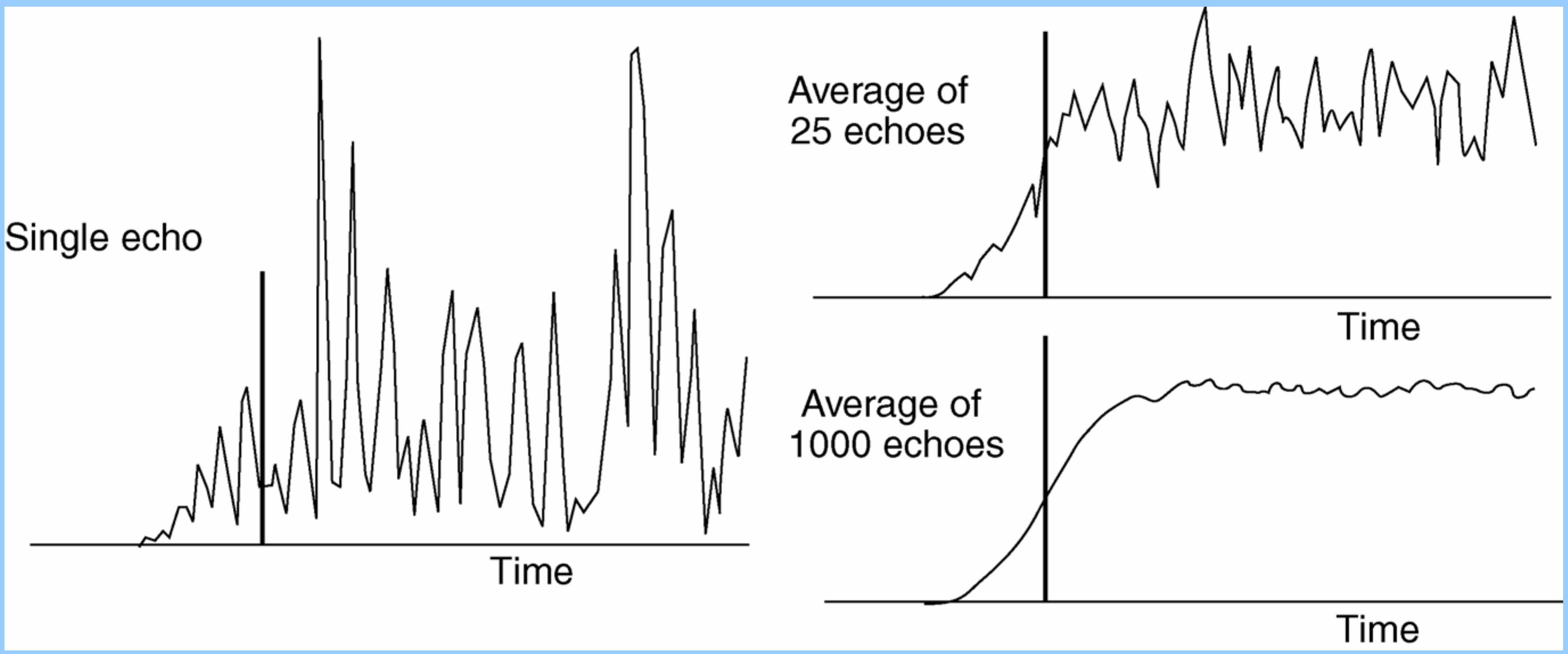
SSH = Orbit - A - Geoid

Measuring distance with radar

- Measure pulse travel time, 2T, from emit to return
- h = T/c (c = 3 x 10^8 m/s)
- Resolution to 1cm needs a timing precision of 3 x 10^{-11}s (30 picoseconds)
- Requires using chirp pulses and compression
- Average ~1000 pulses
- Apply corrections for reduced c in atmosphere / ionosphere, and surface reflection delays



Typical radar altimeter pulse reflections

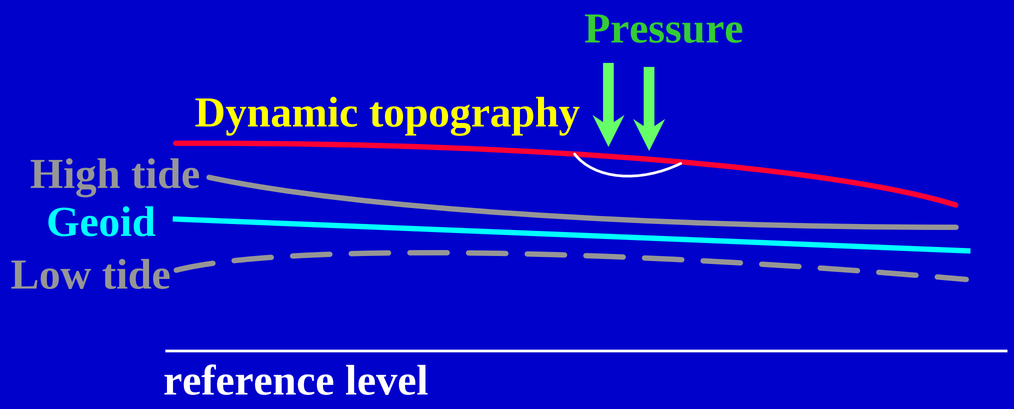


Determining the orbit

- Orbit affected by:
  - Earth's gravitational field
  - Air drag (at 800 km loses 35cm height per orbit)
  - Solar radiation pressure
- Predict the orbit
  - Tracking the satellite
    - Laser ranging from the ground
    - Onboard range and range-rate measurement to ground station (DORIS, PRARE)
    - GPS
  - Model integrates the equations of motion
    - Requires knowledge of gravity field

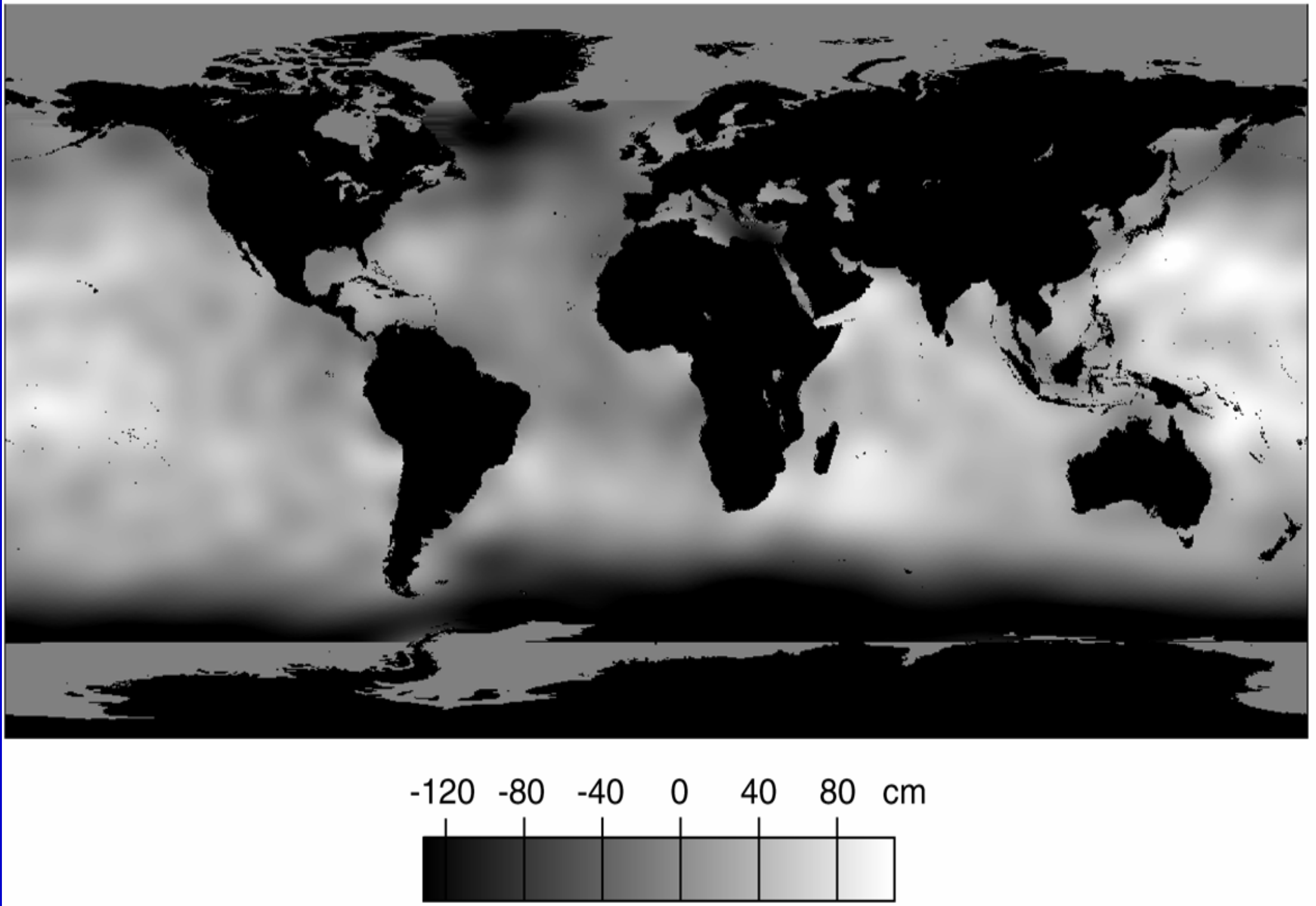
Interpreting the Ocean Surface Topography

- **Geoid (~100 m)**
  - Time invariant
  - Needs to be independently measured (gravity survey)
  - GRACE (~200 km resn.)
  - GOCE (~80 km resolution)
- **Tides (~1-2 m)**
  - Apply a tidal prediction
  - New tidal models derived from altimetry
  - Special orbits needed to avoid tidal aliasing



- **Atmospheric pressure (~0.5 m)**
  - Apply inverse barometer correction (1mbar ~ 1 cm)
- **Dynamic topography (~1 m)**
  - The intended measurement

Ocean dynamic topography



Estimated from Topex/Poseidon altimeter height measurements gridded and averaged over the 10 days of cycle 123, (20th Jan, 1996),

minus the best estimated geoid.

This type of product is of limited value until the Geoid is known more precisely.

Image generated with data produced by JPL on March 8th, 1996 and obtained from the JPL website.

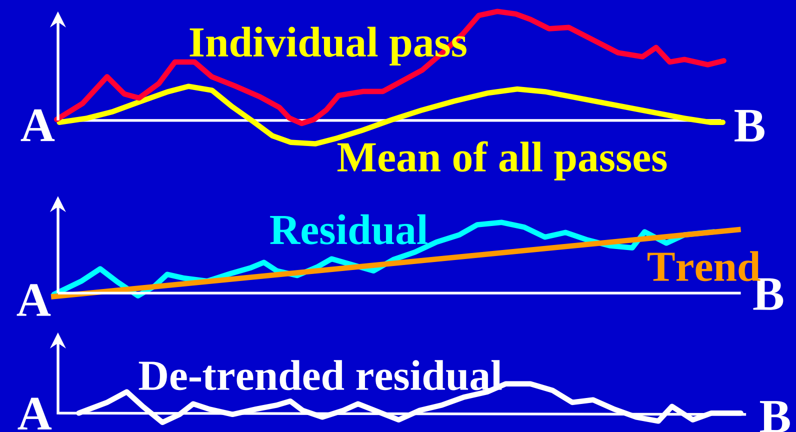
Using altimetry when the Geoid is not known

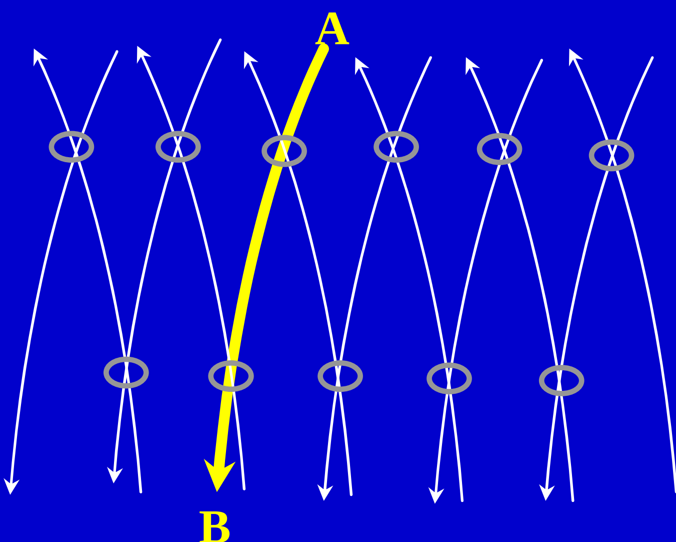
- Repeat-cycle analysis, when orbit errors are small
  - **Step 1: Remove tide and atmospheric pressure contributions.**
  - **Step 2: At each location, average over all overpasses**
  - **Step 3: Subtract time average from individual overpasses to generate the sea-surface height anomalies (SSHA)**
- The result:
  - Contains only the time-varying SSH signal at time scales shorter than the record length used to determine the mean SSH
  - Cannot provide any information about the mean flow

Empirical orbit removal

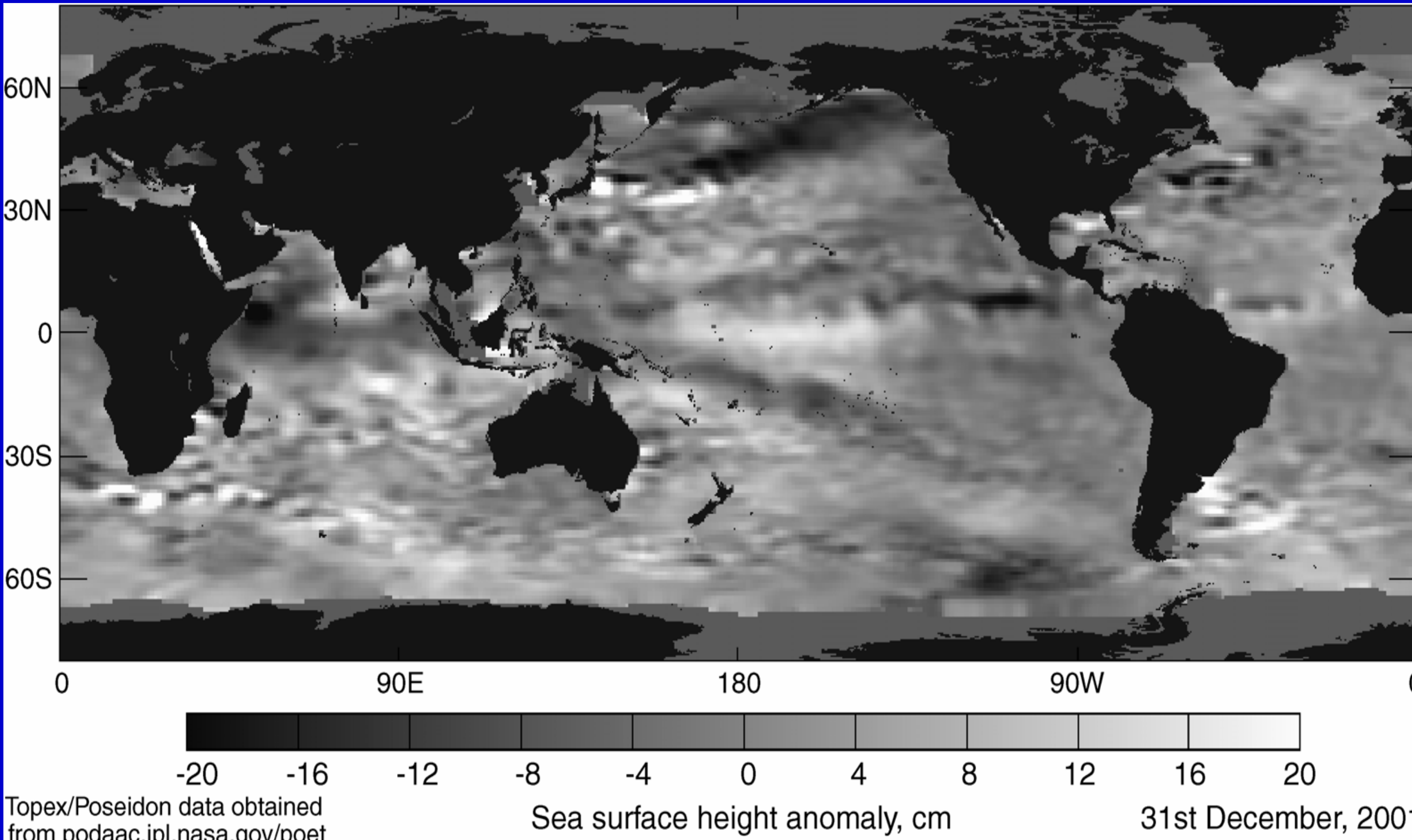
If orbit errors dominate

- **Either:** <u>**Use repeat tracks**</u>
  - ❖ Subtract average of all tracks
  - ❖ Fit linear or quadratic function to each pass to remove trend
  - ❖ Residuals give the time varying signal within the region
- **Or:** <u>**Use cross-over points**</u>
  - ❖ Compute height difference between ascending and descending tracks
  - ❖ Fit smooth function to each pass to minimise cross-over differences
  - ❖ Subtract this function to give SSH residual





SSH residual, or SSH anomaly

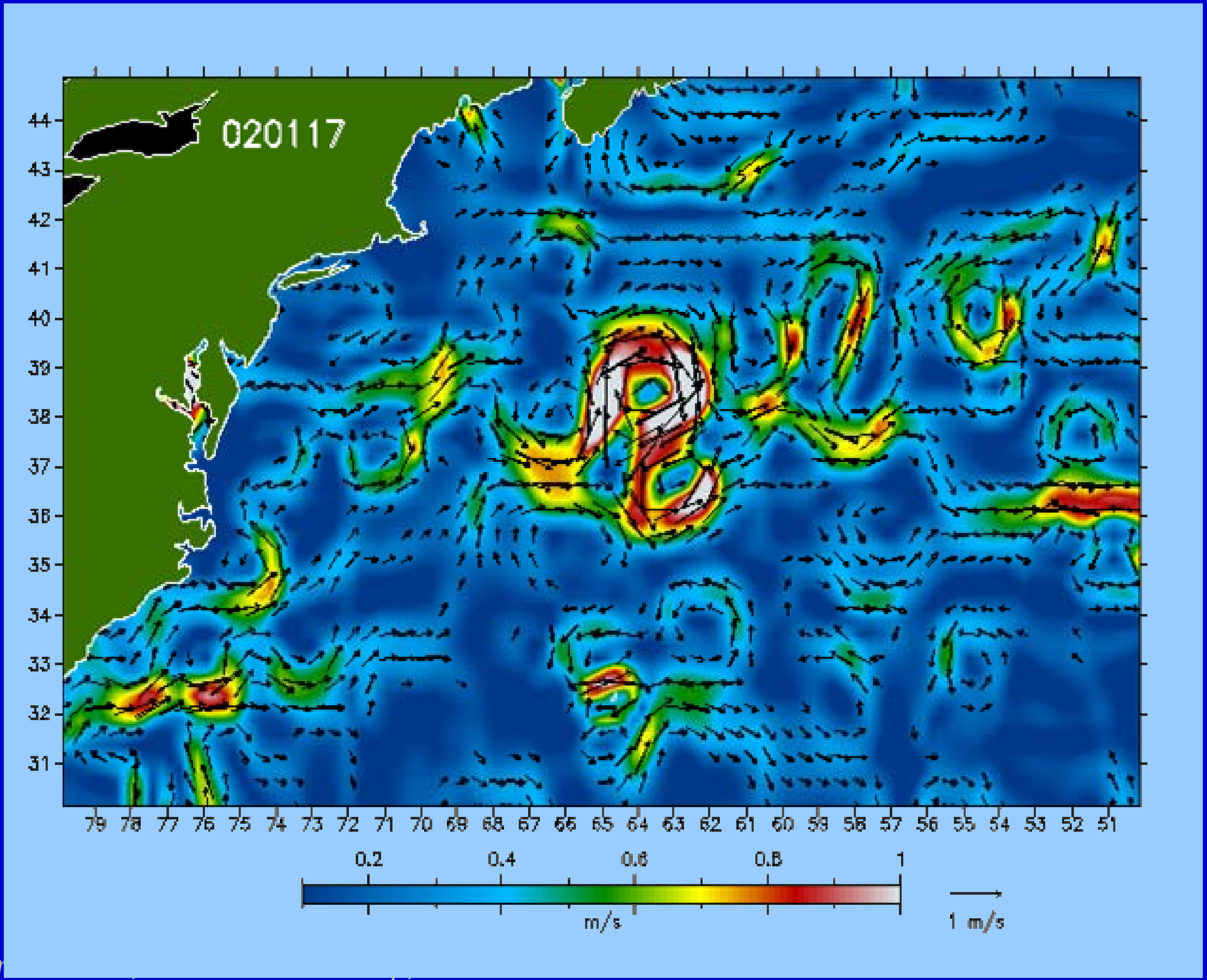


Geostrophic currents from Altimetry

- **Assume geostrophic balance**
  - $$\frac{\partial H}{\partial x} = \frac{fv}{g} \qquad f = 2\Omega \sin(latitude)$$
    $$v = \frac{g}{f}\frac{\partial H}{\partial x}$$
- **Unavoidable limitations**
  - **Measures only cross-track component of current**
  - **Cannot recover currents near the equator**
  - **Only variable (non-steady) currents are detectable**

The Gulf Stream

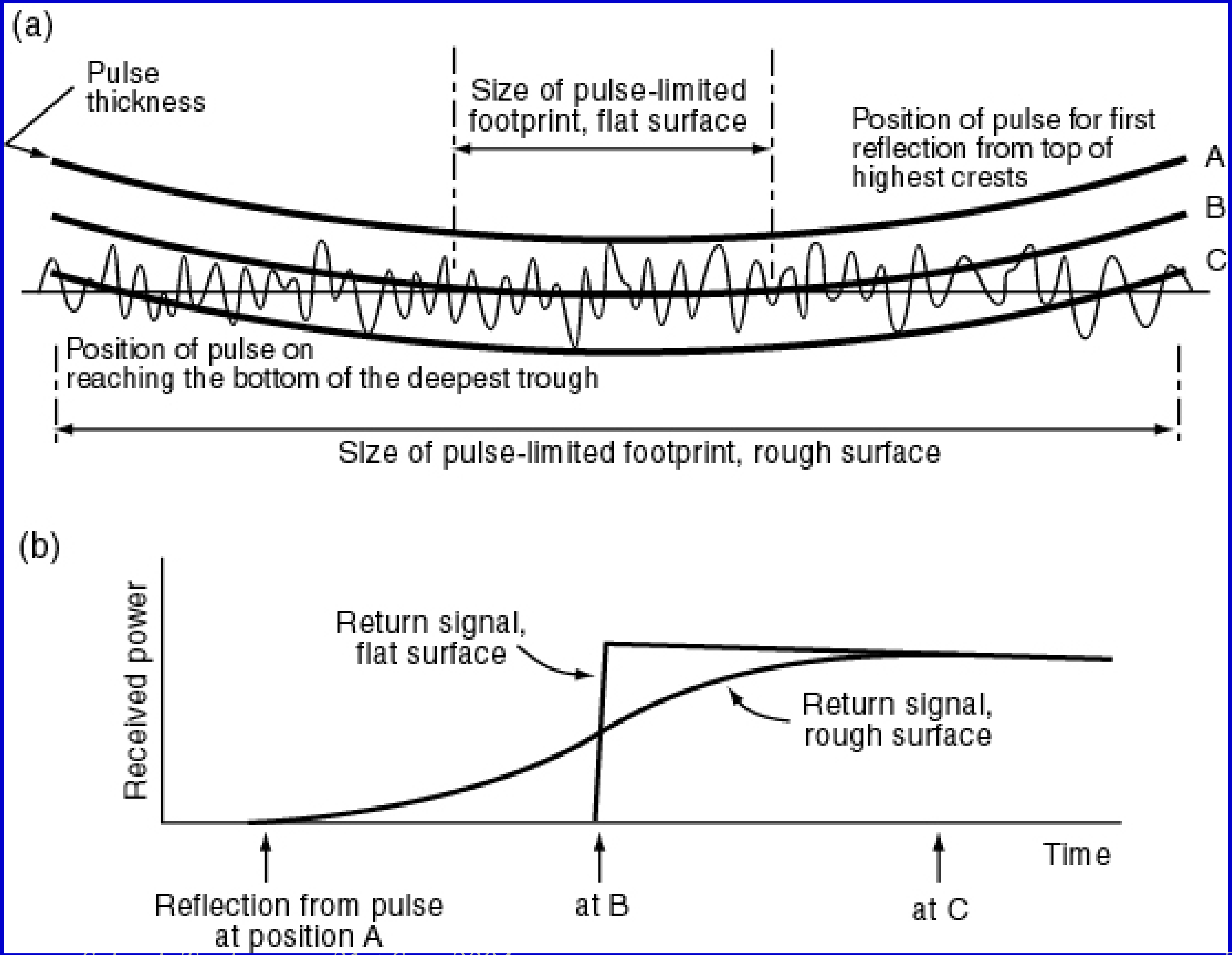
As detected by Altimetry: sees the variable currents only



Limitations of Satellite Altimetry

- Measures SSHA to an accuracy of 2-3 cm
  - ❖Measures only along the precise orbit repeat track
- Detects only the variable signal
  - ❖Long term mean SSH lost in the geoid
  - ❖Mean ocean currents cannot be detected
  - ❖Needs longer time series to measure lower frequencies
  - ❖An independent measure of gravity is needed
- SSH unreliable in shelf seas
  - ❖The tidal signal cannot be accurately predicted
  - ❖Other ageostrophic motions are likely
- Currents cannot be recovered in equatorial waters
  - ❖Geostrophy not valid

Measuring Significant Wave Height from Altimeters



Theoretical waveform equation

$$P(t) = \frac{Kc\tau}{s^2 H^3}\left[1 + \mathrm{erf}\left(\frac{t}{t_p}\right)\right]\exp\left(-\frac{2t}{t_s}\right)$$

Indicates the echo magnitude

The steepness of the waveform

The decay as the reflecting area moves away from nadir

where:

H = height of satellite above mean sea level

τ = half power width of transmitted pulse

s = rms total ocean wave-slope

$$t_p = \frac{2}{c}\left[\frac{c^2\tau^2}{16\ln 2} + 2h^2\right]^{1/2}$$

h = rms ocean wave height

$t_s = 2H\Psi_e^2 / c$

$$\Psi_e^{-2} = \frac{8\ln 2}{\Psi_R^2} + \left[\frac{1 + H/a_e}{s}\right]^2$$

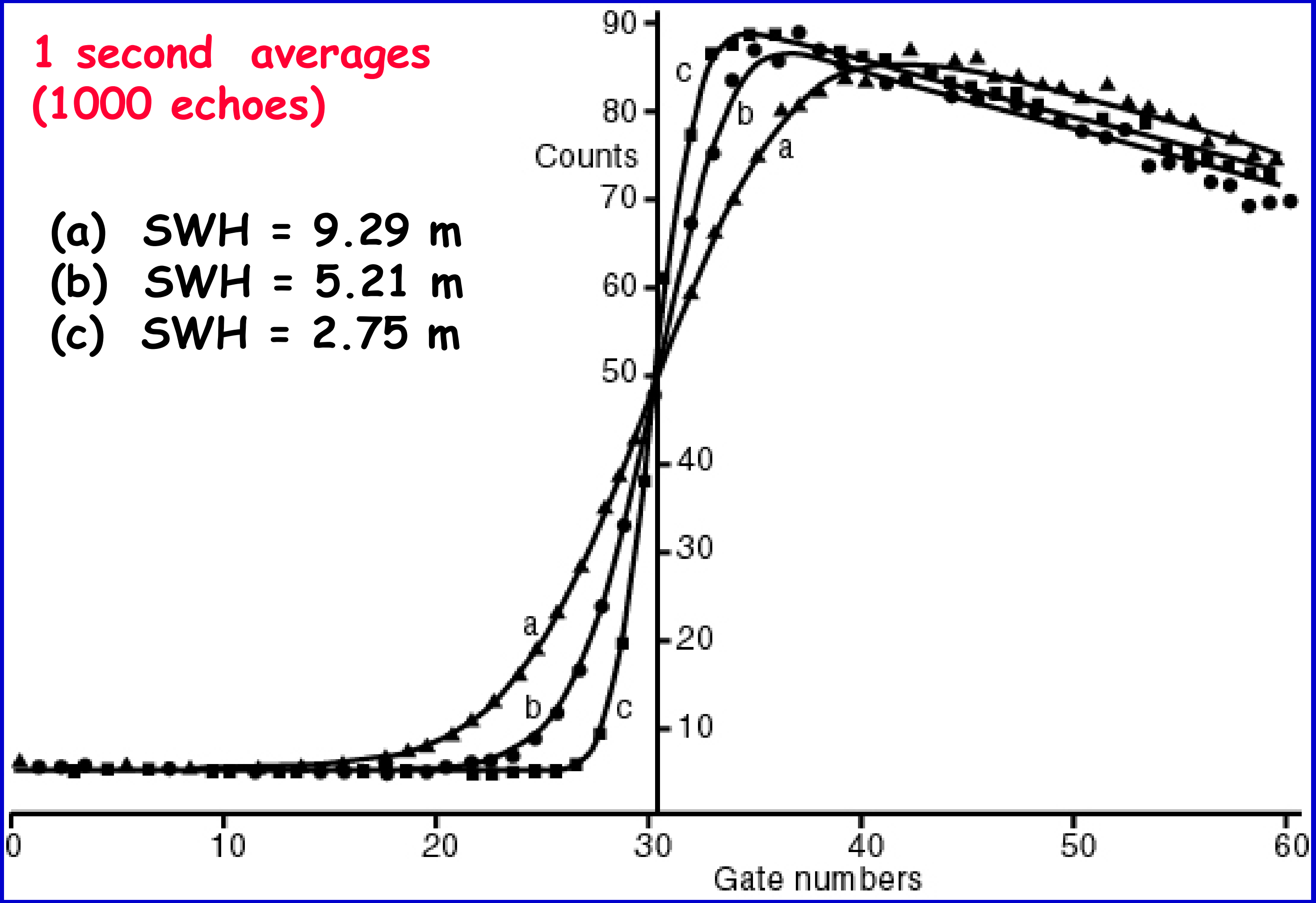
a_e = earth radius

Ψ_R = antenna half-power width

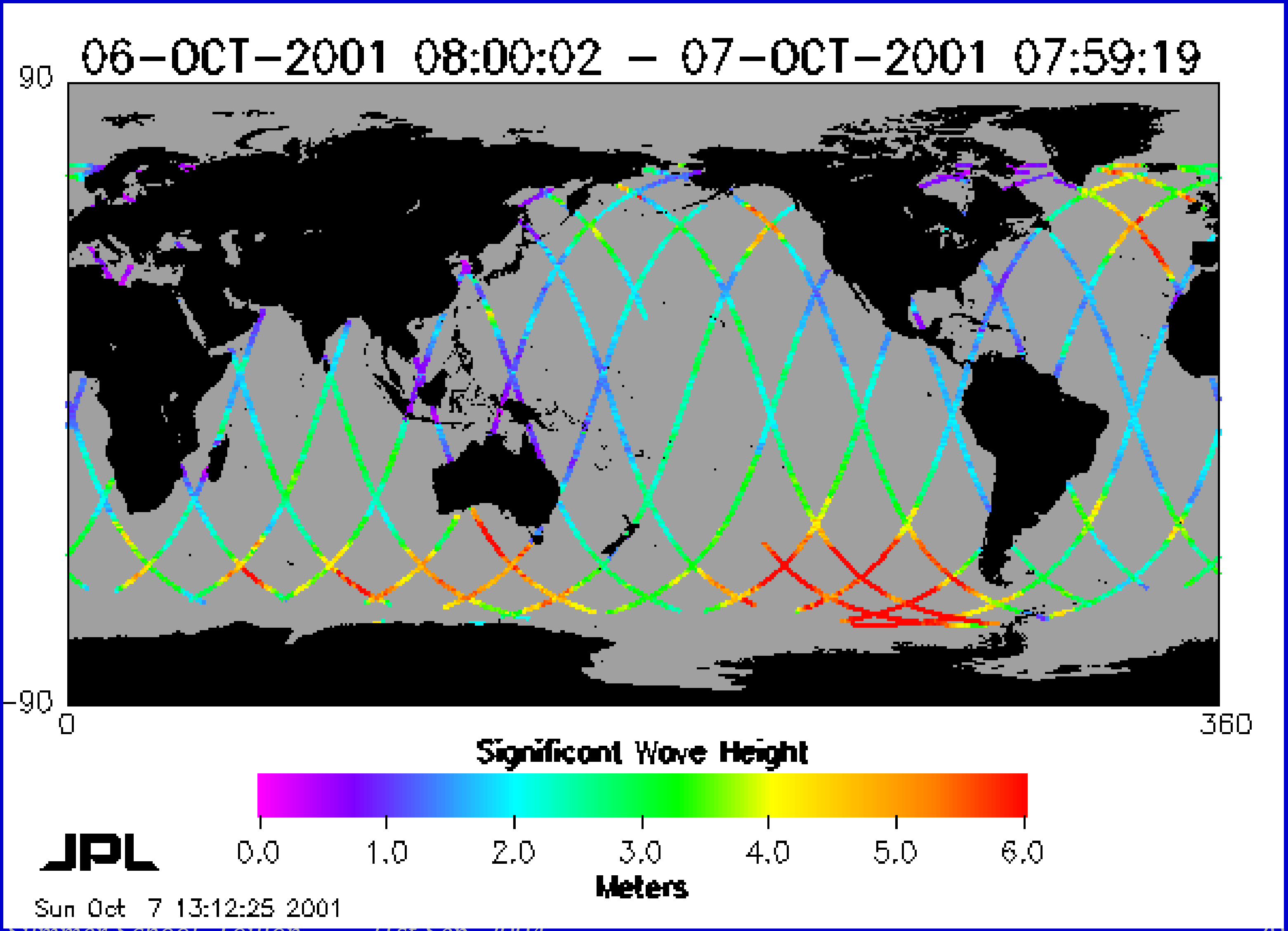
K = constant

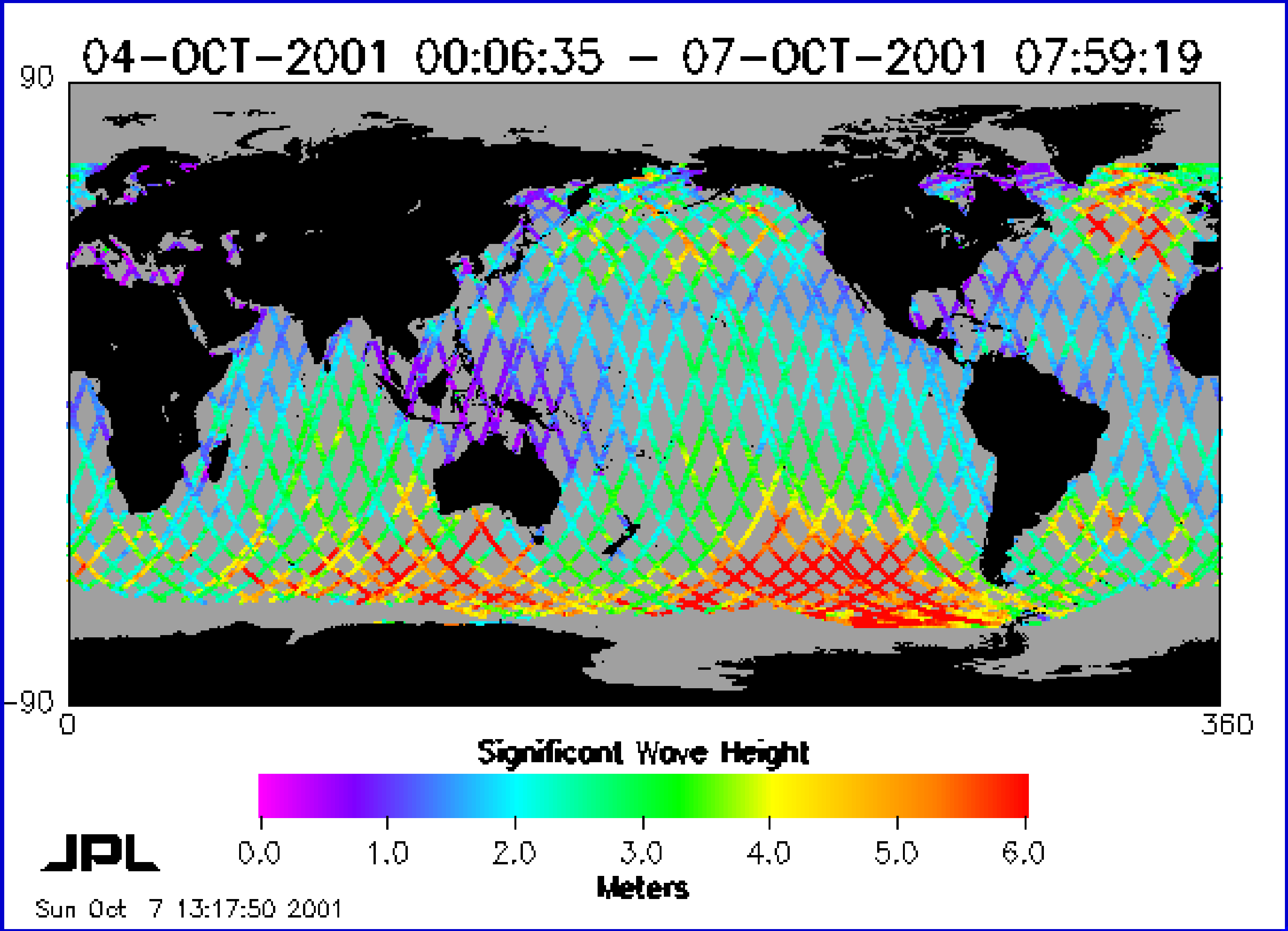
$t = 0$ is defined at the "track point"

Typical altimeter echoes

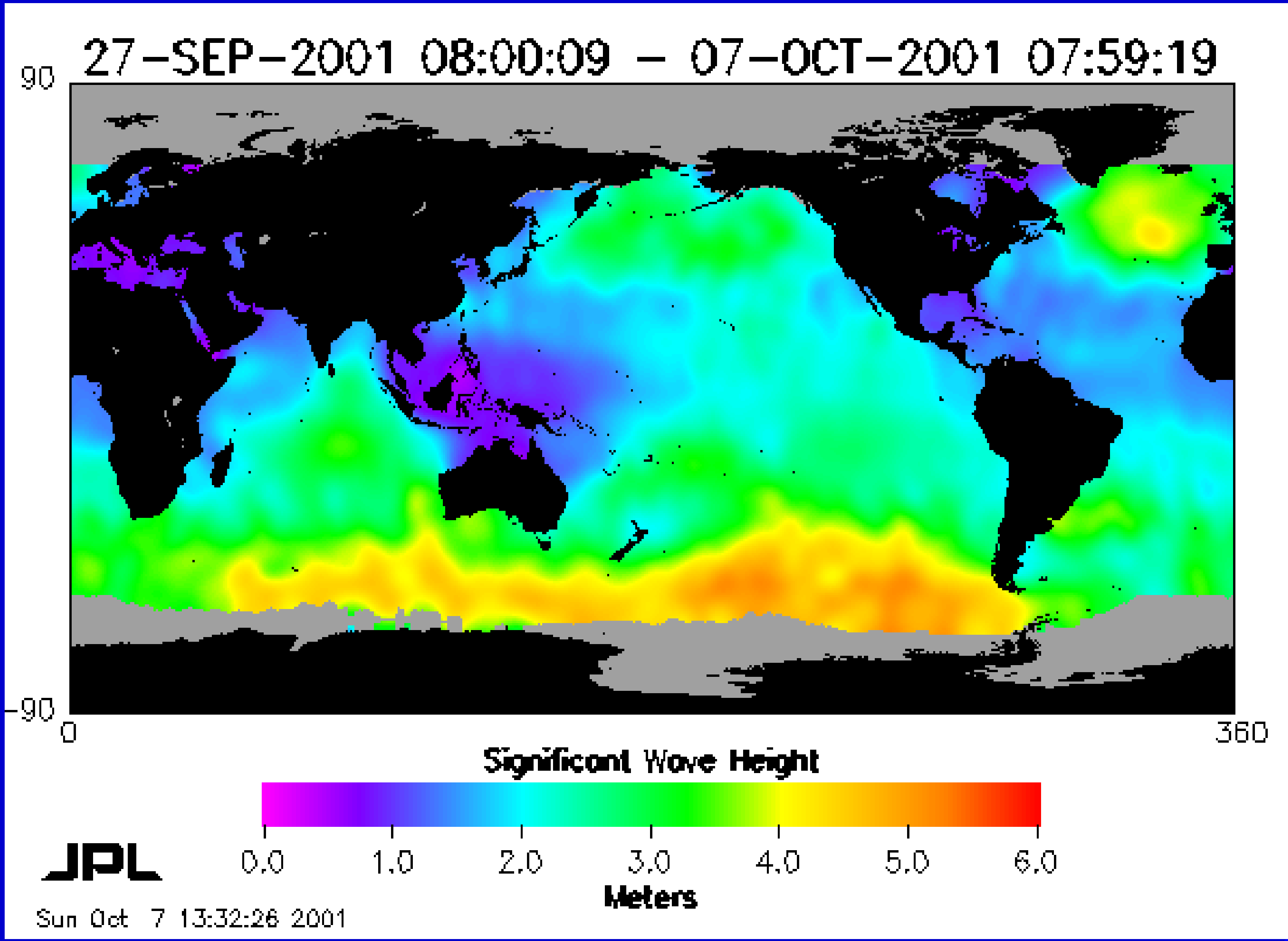


Examples of SWH products from TOPEX



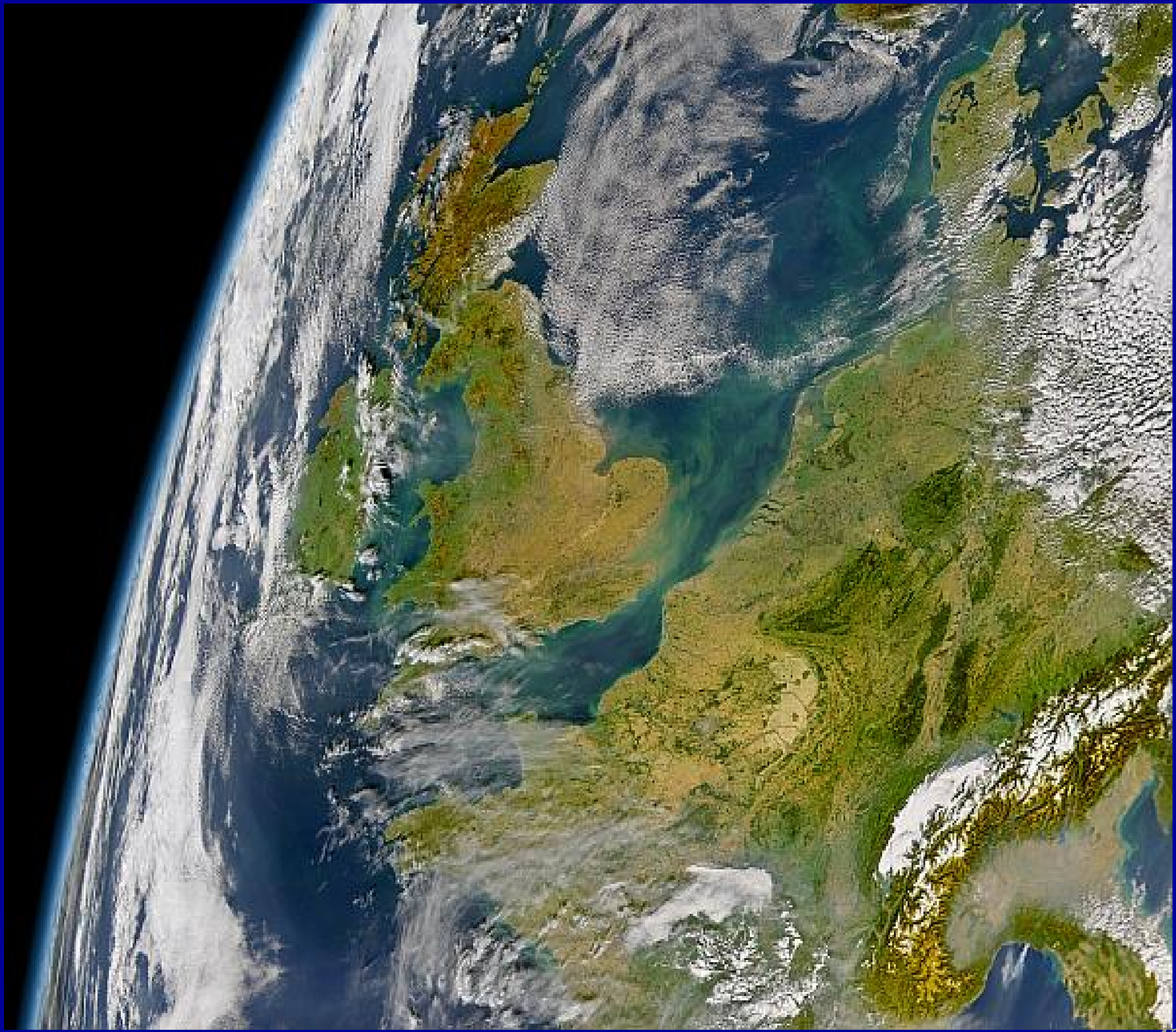


04-OCT-2001 00:06:35 - 07-OCT-2001 07:59:19
90
-90
0
360
Significant Wave Height
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Meters
JPL
Sun Oct 7 13:17:50 2001


27-SEP-2001 08:00:09 - 07-OCT-2001 07:59:19
90
-90
0
360
Significant Wave Height
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Meters
JPL
Sun Oct 7 13:32:26 2001

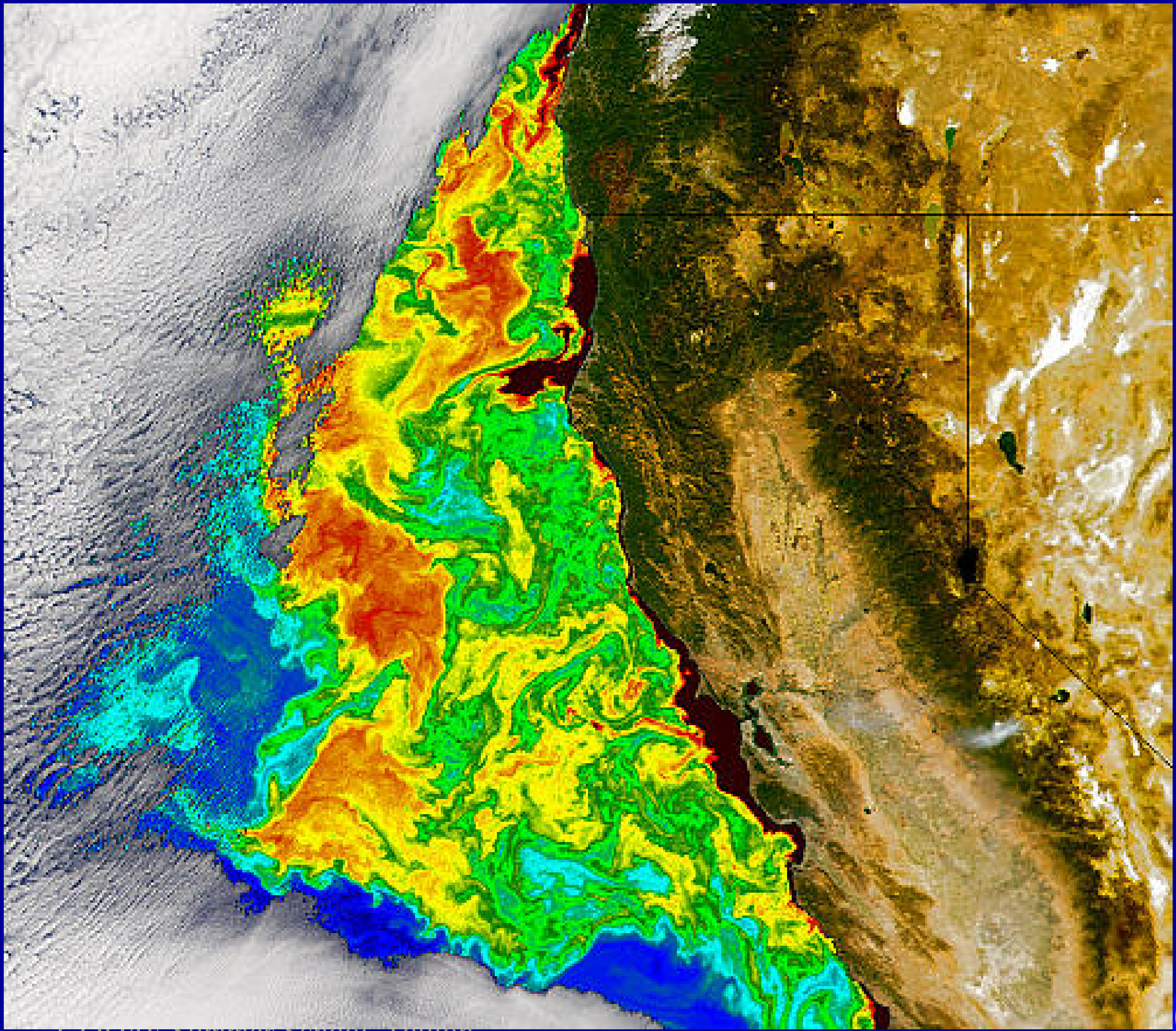
Estimating chlorophyll concentrations from ocean colour

Western Europe on 16th October, 2003 - SeaWiFS

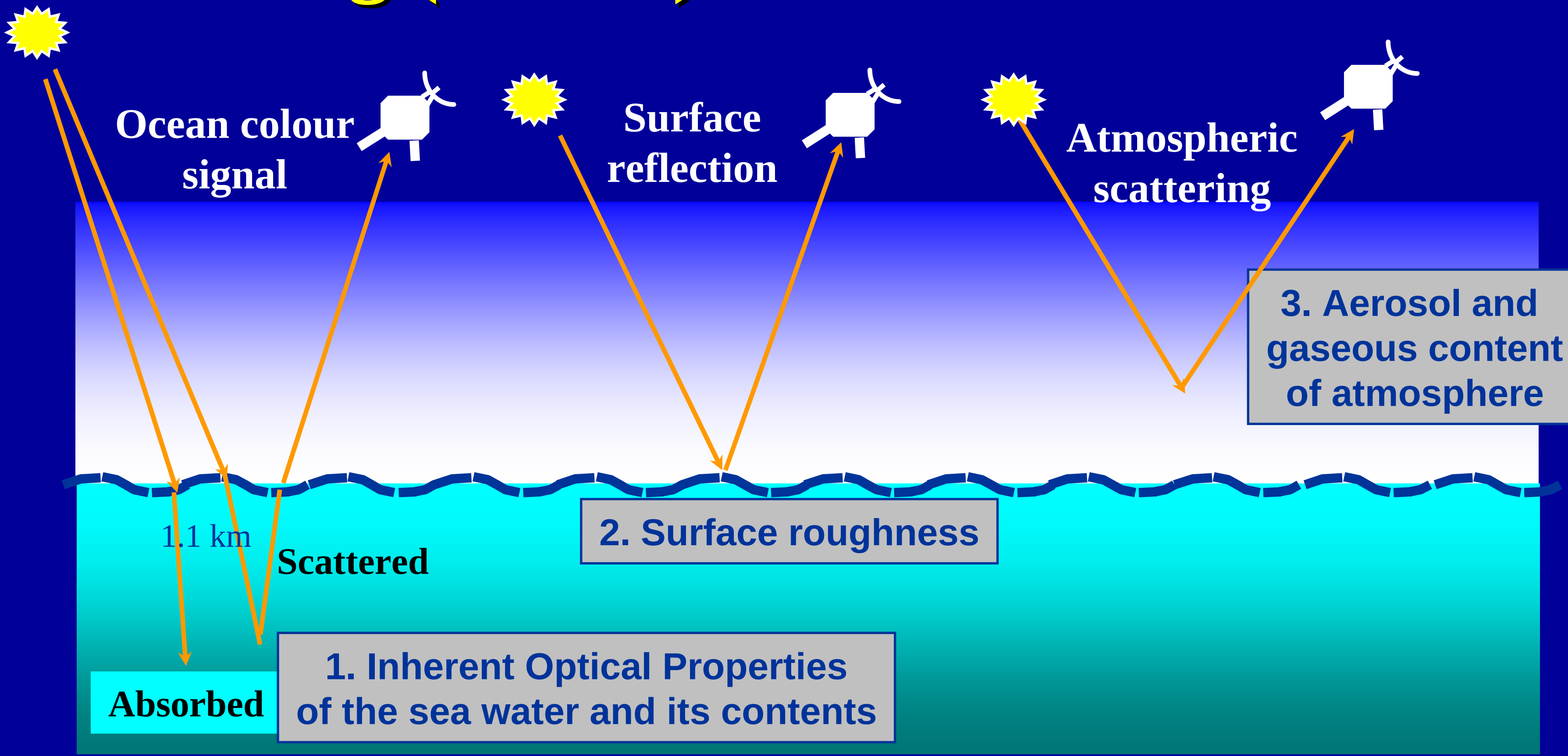


Upwelling off Oregon, 6 Oct 2002

Chlorophyll map derived from SeawiFS



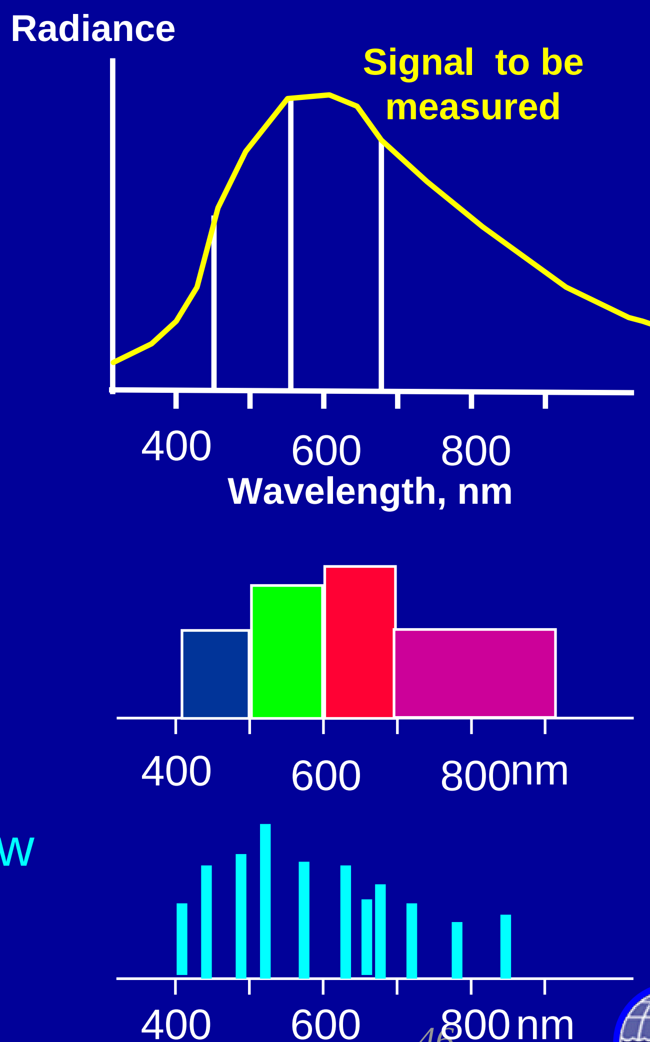
Principles of Ocean Colour Remote Sensing (OCRS): what can be detected?



Note that 1, 2 and 3 are all wavelength dependent. Measure the colour signal in sufficient spectral detail to distinguish the ocean and atmospheric contents. Ideally the roughness should be known.

Using colour to carry information

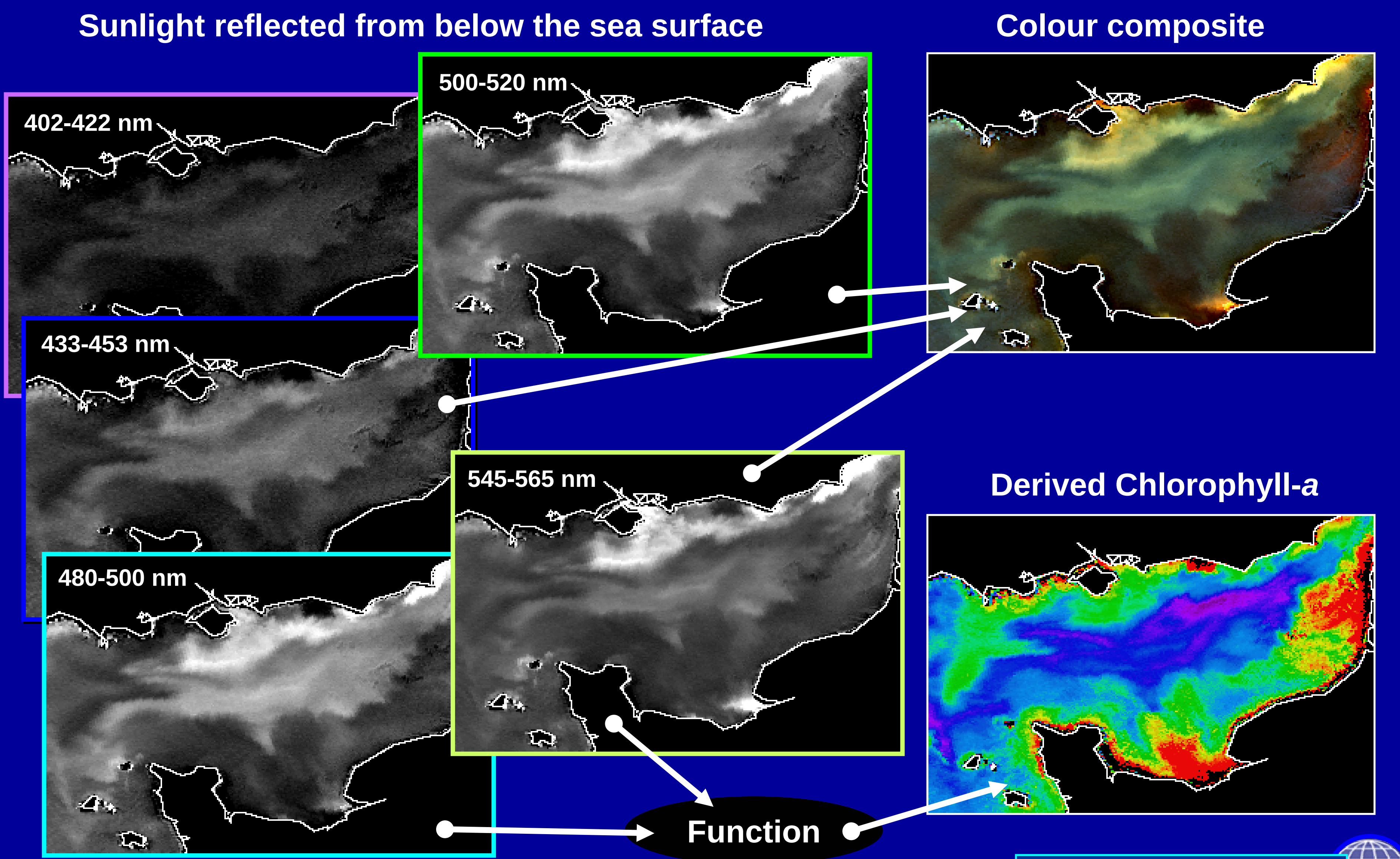
- **What is colour?**
  - ❖The spectral distribution of visible light
  - ❖The spectrum is typically a continuum
- **How is it measured?**
  - ❖A detector samples discrete wavebands
  - ❖The eye detects the response in three bands defined by three spectral functions
  - ❖The “colour” is simply the set of values measured in the different wavebands or “channels” .
  - ❖May be a few broad bands or many narrow bands



Colour capability of different sensors

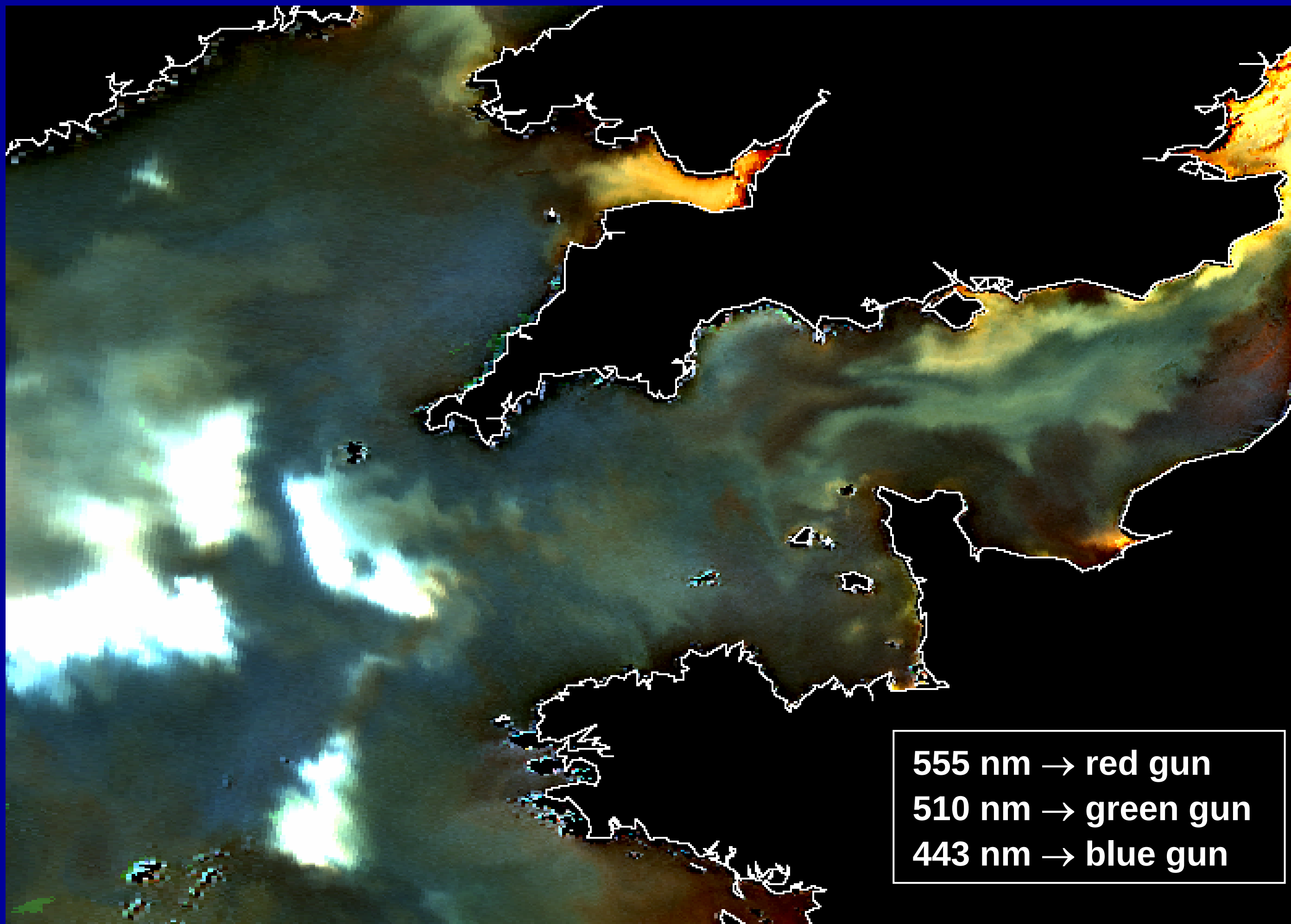
Sensor	Number of channels	Character of channels
Human eye	3	Interleaved
Landsat	4	Wide bands, contiguous
CZCS	4	Narrow, visible
SeaWiFS	8	Narrow, separated Vis and near IR
MERIS	13	Narrow, Vis and near-IR
MODIS	9	Narrow, Vis and near-IR
CASI (airborne)	64	Spectrometer

Information from ocean colour



Data from SeaWiFS

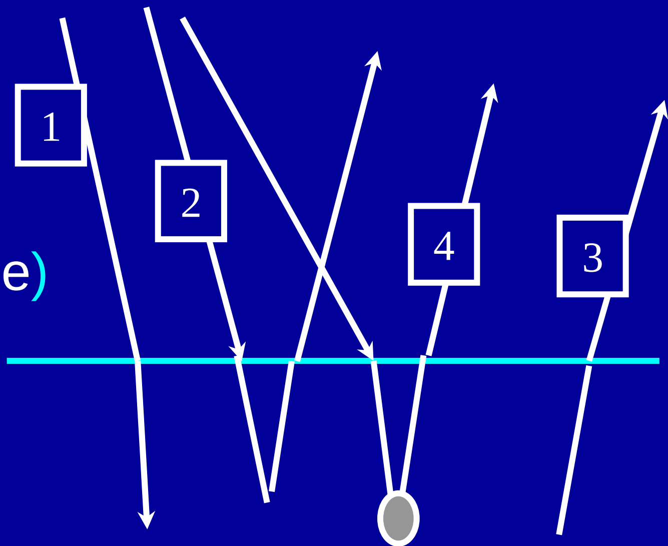
Ocean colour image : English Channel



Enhanced near-real colour composite of English Channel from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS); 19th May, 1998.

What affects light in the sea ?

- **Light entering the sea:**
  - Comes from the sun
  - often scattered by the atmosphere or clouds (75%-95% of TOA radiance)



- **Light in the sea**
  - is absorbed (1)
  - is scattered (2)
  - may be emitted by fluorescence (3)
  - may be frequency shifted (Raman scattering) (4)
- **Light leaving the sea**
  - consists of photons which have been scattered into a direction which brings them back to the surface
  - wavelength distribution (colour) is altered by the sea compared with those that enter the sea.

What affects the colour of the sea?

❖Spectral makeup determined by absorption (a) and scattering (b)

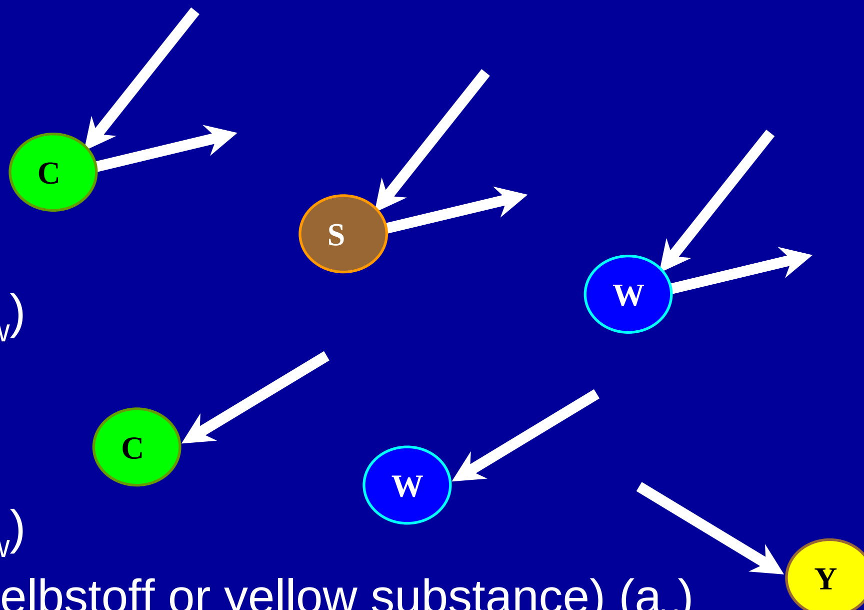
❖Reflectance is roughly 0.33 (b/a).

❖Backscattering (b) is caused by:

- Phytoplankton (b_c)
- Suspended particulate matter (b_s)
- The water molecules themselves (b_w)

❖Absorption (a) is caused by:

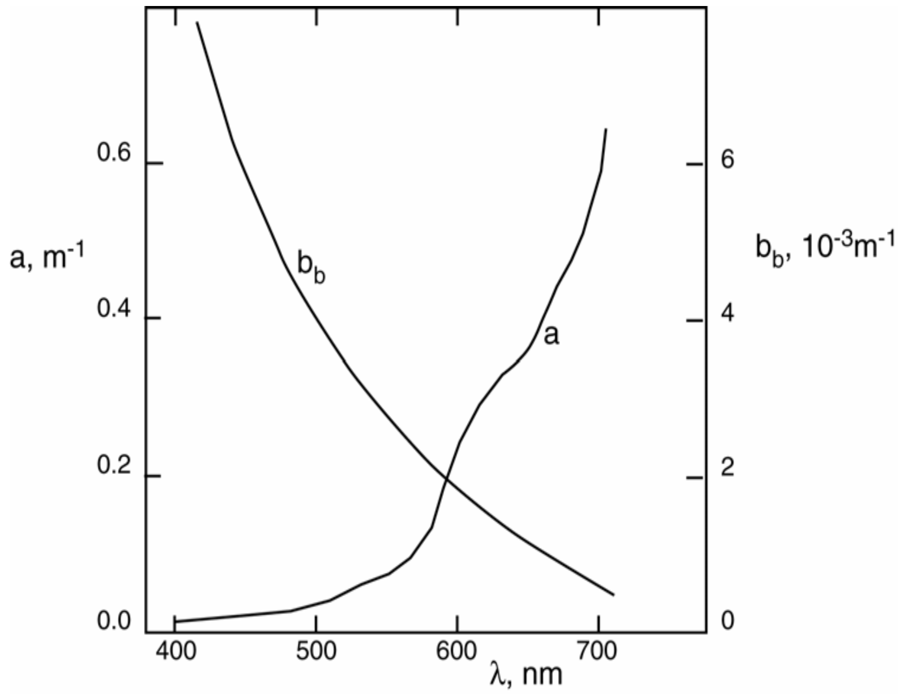
- Phytoplankton (a_c)
- The water molecules themselves (a_w)
- Dissolved organic material (DOM, Gelbstoff or yellow substance) (a_y)



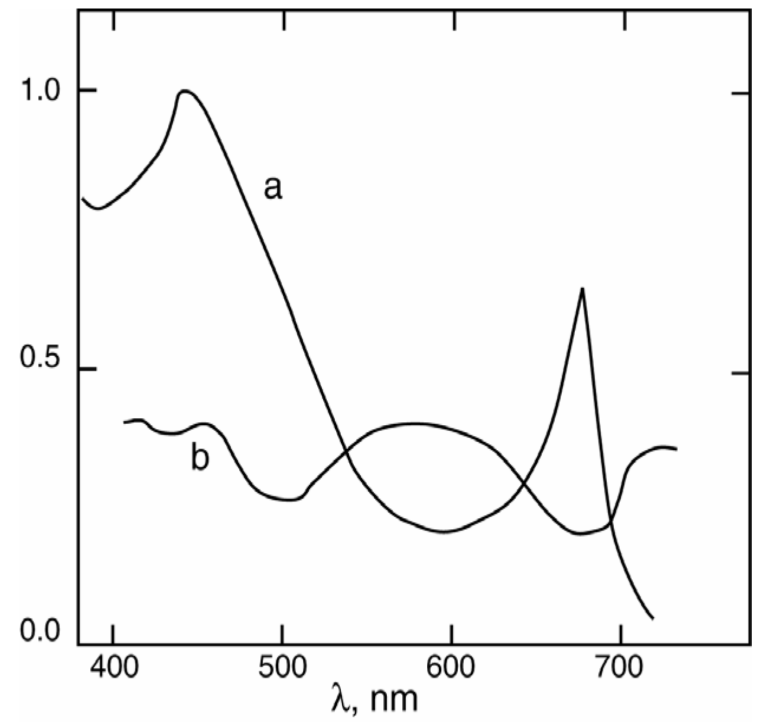
❖Each a_x and b_x has its particular spectral form

❖Therefore the colour depends on the concentrations of those water constituents which interact with the light.

Spectral variation of absorption and scattering of light in the sea



Absolute values for sea water absorption, a
and backscattering, b_b

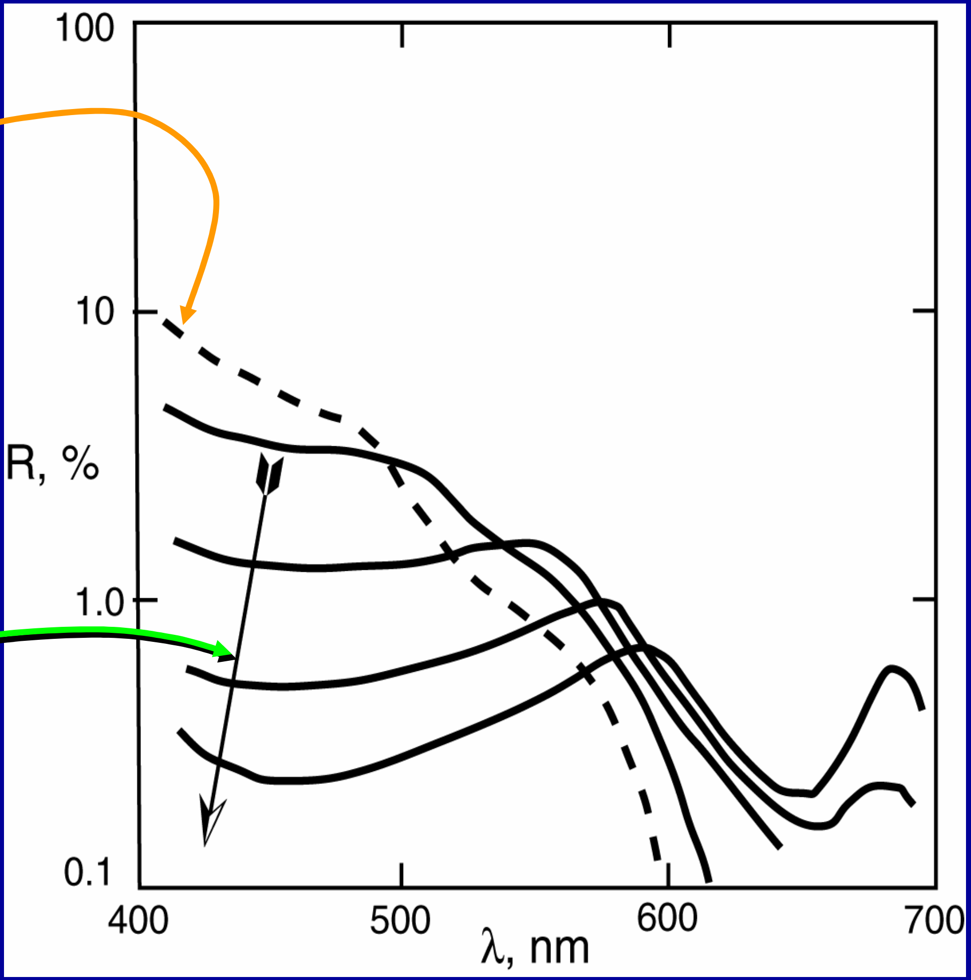


<u>Relative</u> values of absorption, a and backscattering, b for Chlorophyll in Phytoplankton

Reflectance spectra associated with phytoplankton

The dashed line is the reflectance associated with pure sea water

The arrow indicates the direction of increasing chlorophyll concentration for the different lines drawn.



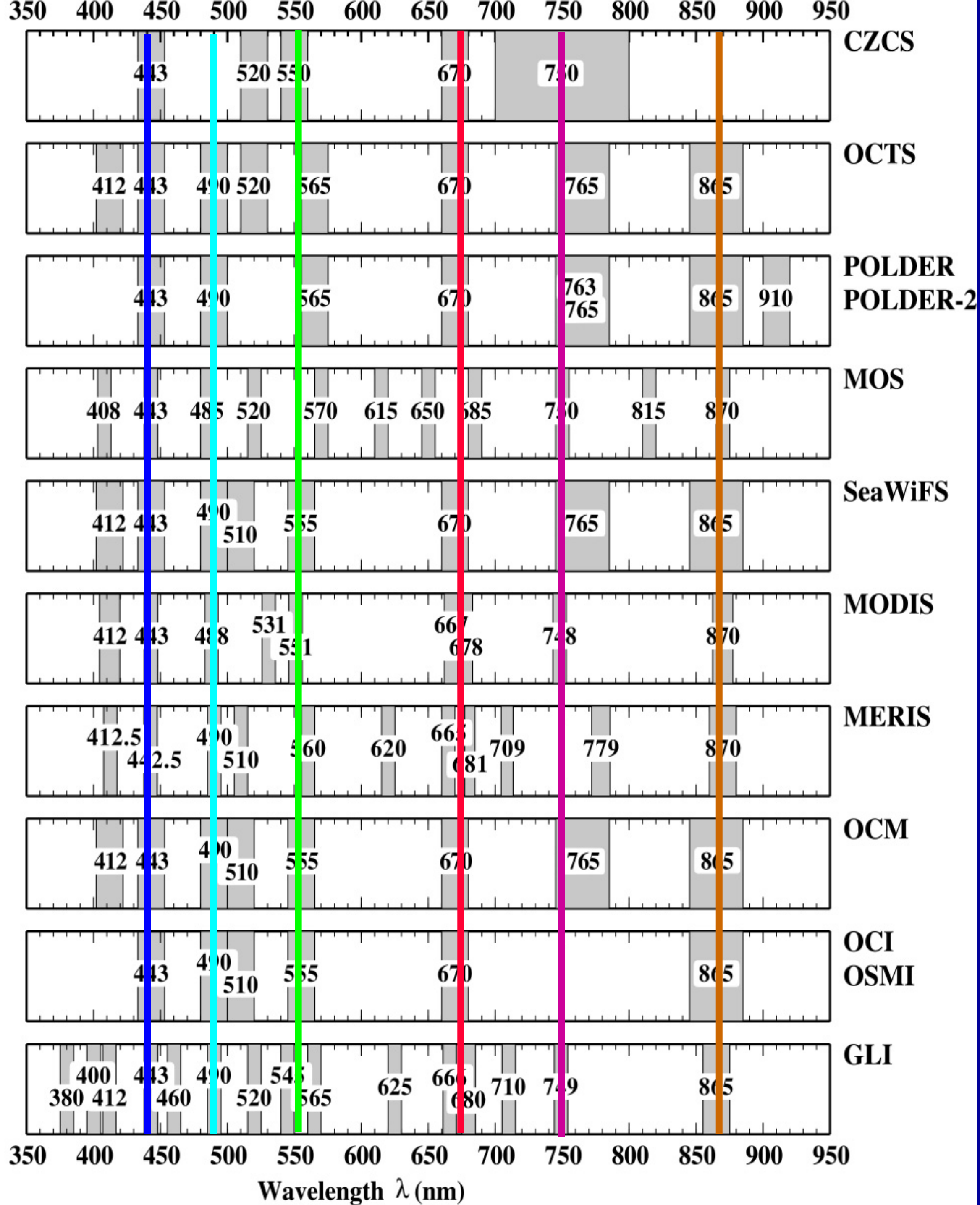
What can be measured from ocean colour?

- **In principle**
  - Colour can tell us about relative and absolute concentrations of those water constituents which interact with the light.
  - Hence we measure chlorophyll, yellow substance and sediment load
- **In practice**
  - Difficult to distinguish independently varying water constituents
  - **CASE 1** waters are where the phytoplankton population dominates the optical properties (typically open sea)
  - **CASE 2** waters are where other factors (terrigenous DOM, suspended or river borne sediments) are also present.
  - Most success with CASE 1 waters so far, using green/blue ratio algorithms for chlorophyll, of the form: $C = A(R_{550}/R_{490})^B$
  - Accuracy for C of ~ ±30% is achievable in open ocean
  - Data from CASE 2 waters are harder to analyse.

Wavebands for important ocean colour sensors

Note the bands common to most sensors:

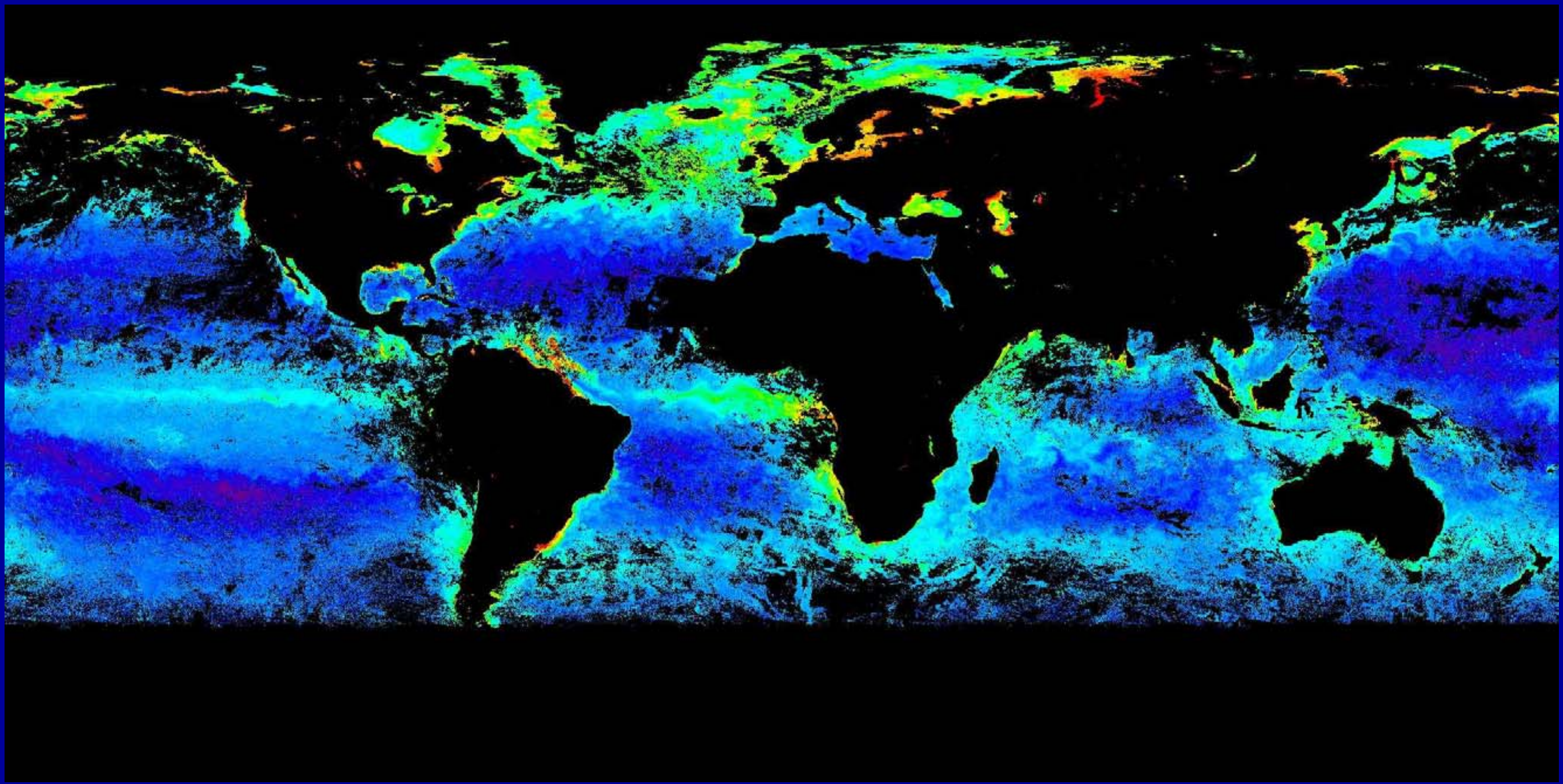
- 440 nm
- 490 nm
- 550-565 nm
- 670 nm
- 750 nm
- 870 nm



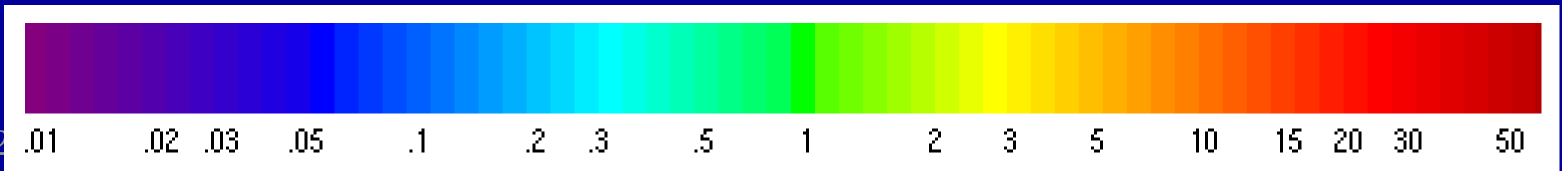
Applications of Ocean Colour

- Measurement of Chlorophyll
  - ❖ Global distribution of chlorophyll
  - ❖ Estimates of primary production
  - ❖ Detection of plankton blooms
- Measure optical diffuse attenuation coefficient
- Measurement of suspended sediment
- Measurement of dissolved organic material
- As a tracer of dynamical processes
- Monitoring pollution
- Water depth

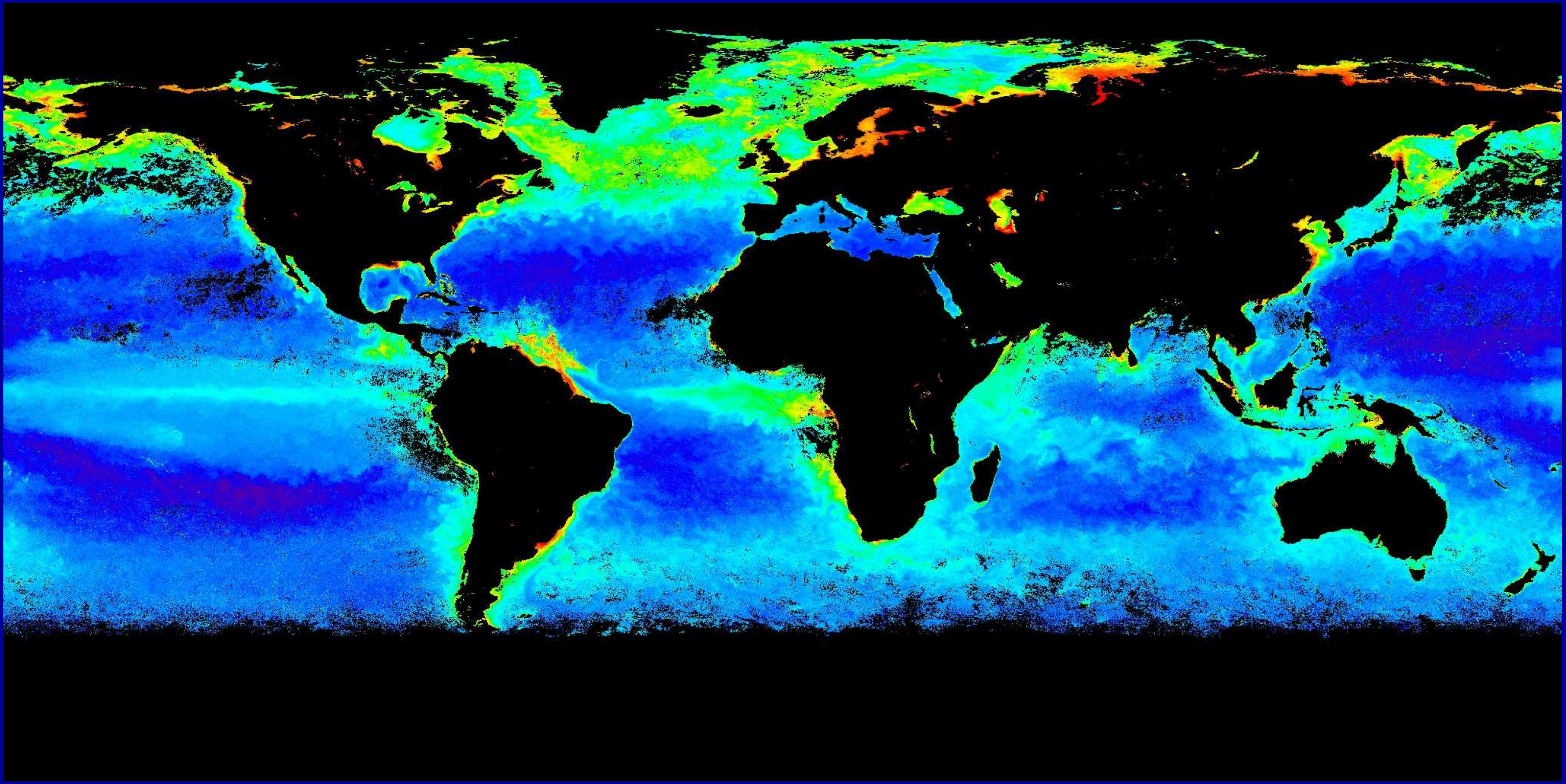
Global 8-day composite of Chlorophyll-*a* distribution from SeaWiFS



12 July - 19 July 2001. Scale below in mg / m^3 Chl-*a*



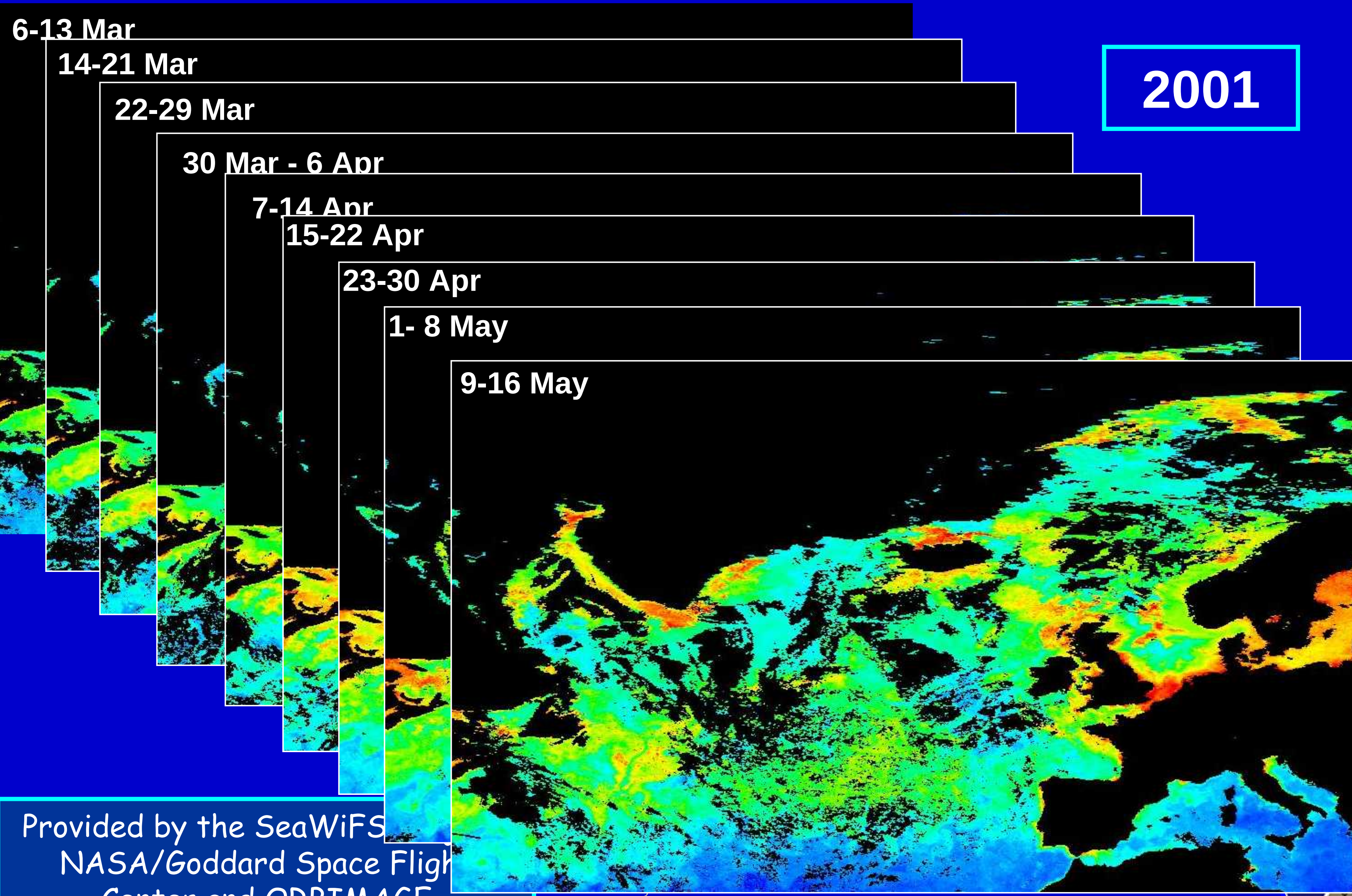
Global monthly composite of Chlorophyll-*a* distribution from SeaWiFS



July 2001

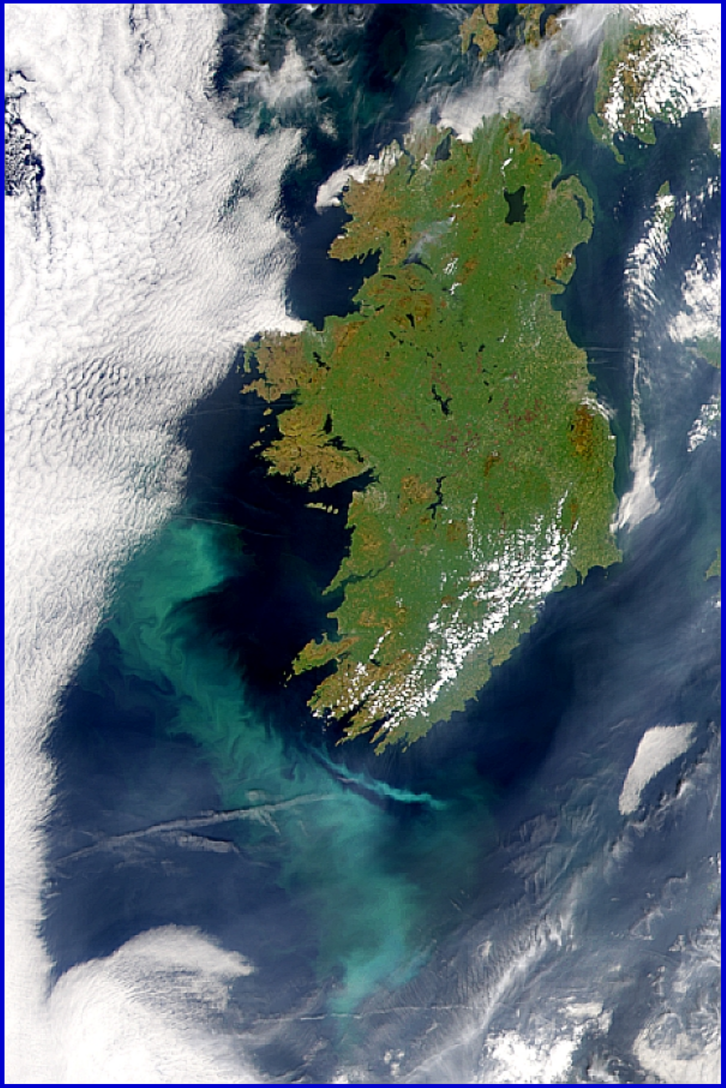
Tracking bloom development with SeaWiFS

2001

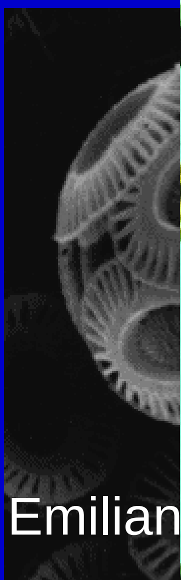


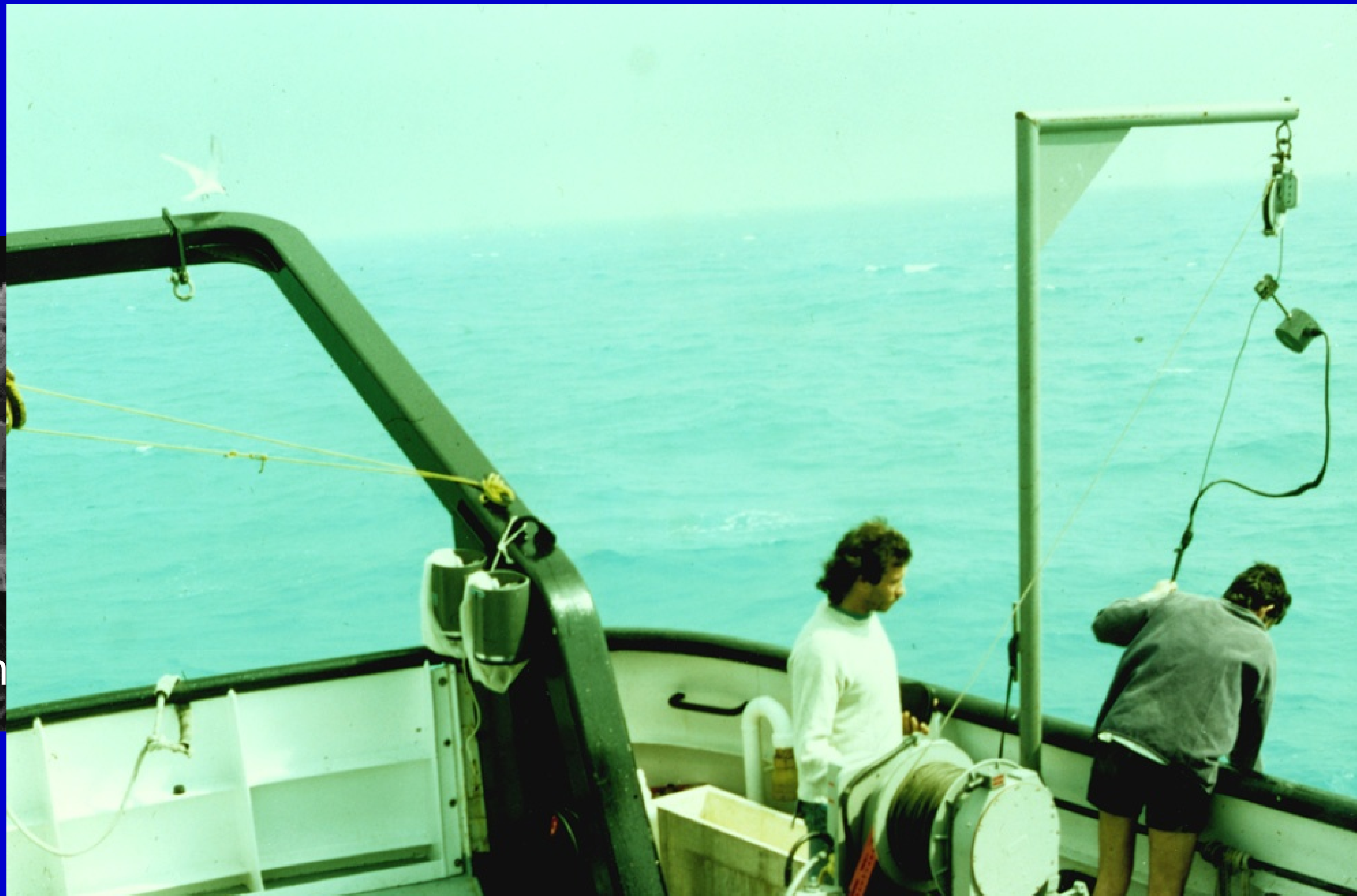
Provided by the SeaWiFS
NASA/Goddard Space Fligh
Center and ORBIMAGE

Coccolithophore bloom in the Celtic Sea



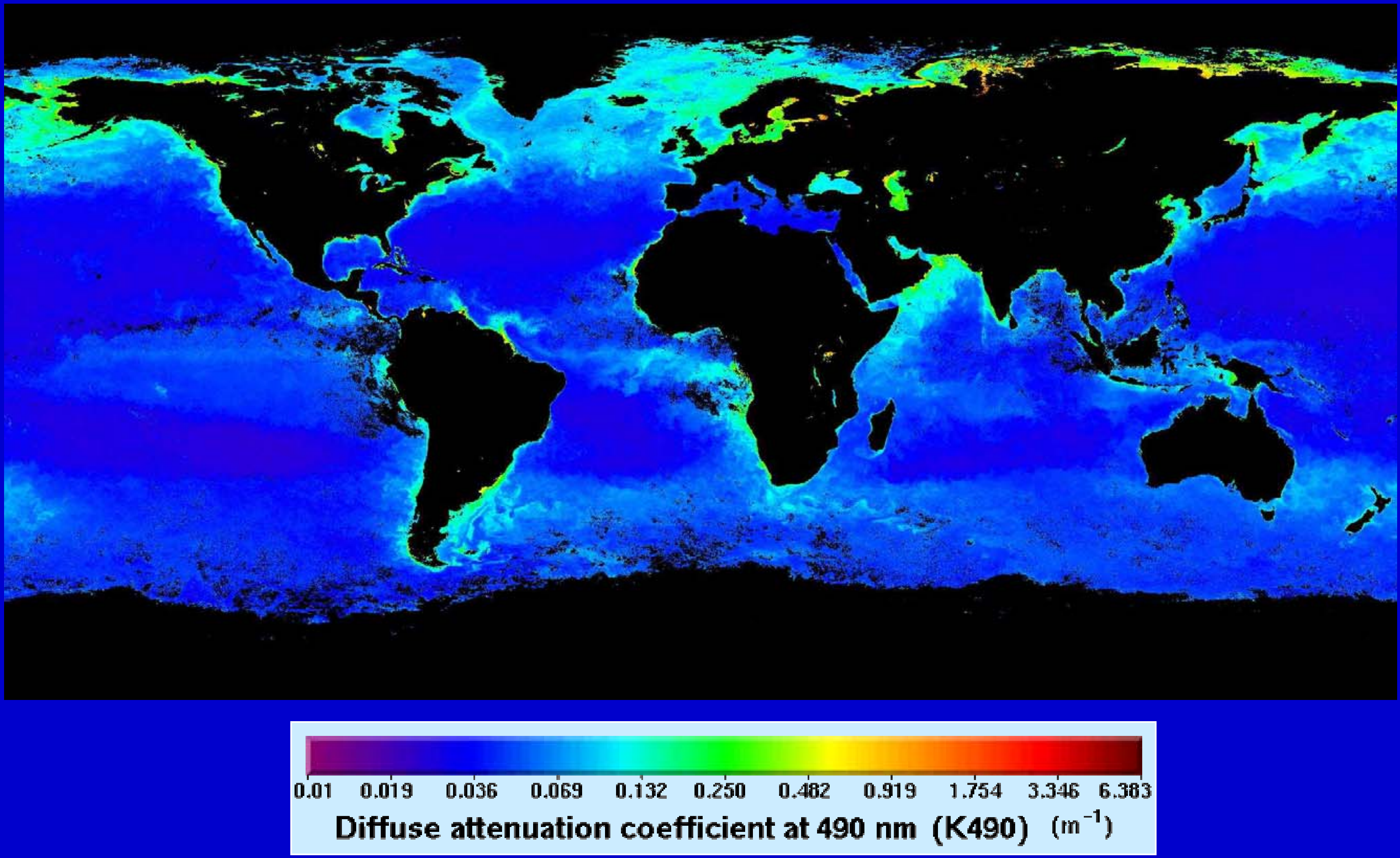
Coccolithophore blooms



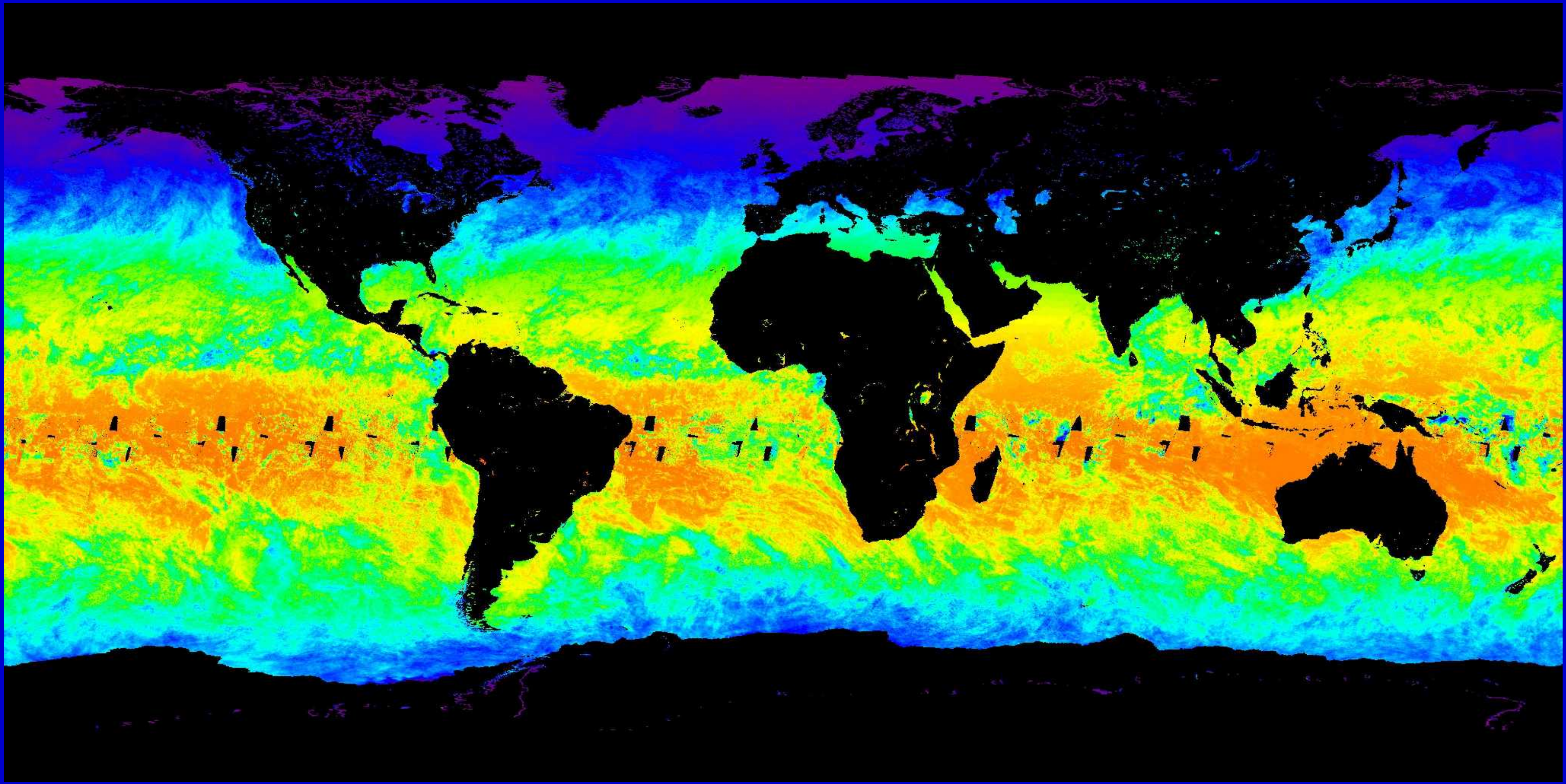


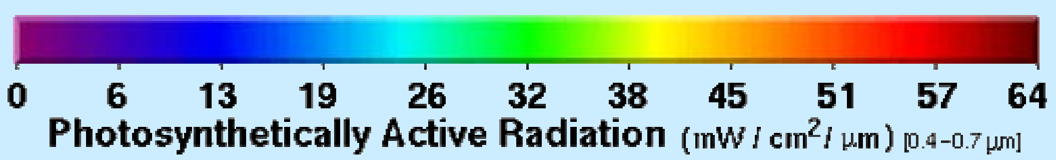
Dr Toby Tyrrell http://www.soes.soton.ac.uk/staff/tt/eh/satbloompics.html

Global map of K_{490} (diffuse attenuation coeff)



PAR derived from SeaWiFS



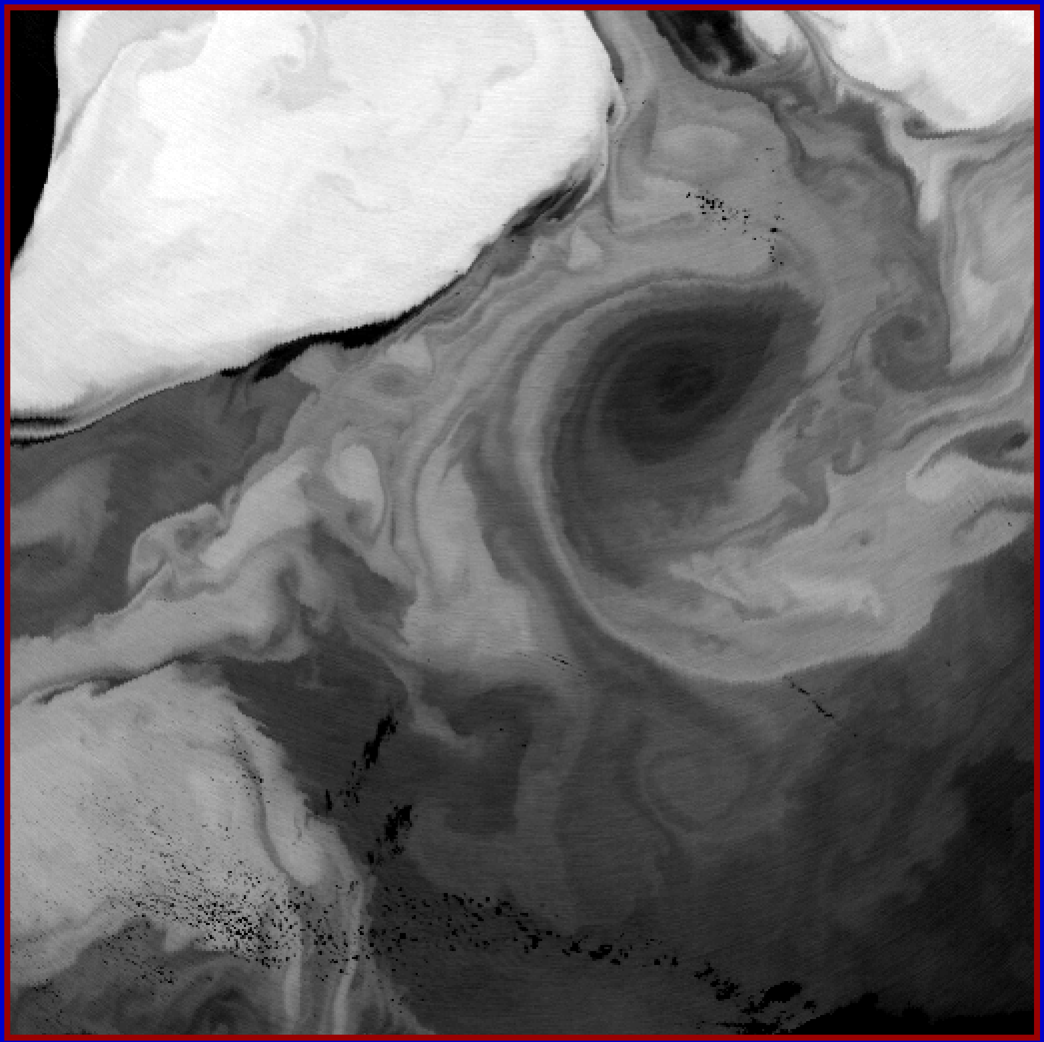


A conclusion on ocean colour

- Development lags behind other remote sensing methods
- Inherently difficult to retrieve ocean variables accurately and confidently
- But the rich information content has considerable potential = a scientific and technical challenge
- Just beginning to use ocean colour products in ocean models
- A challenging subject for future generations of young researchers !

Measuring sea surface temperature by radiometers on satellites

A mesoscale eddy in the South Atlantic



Apparent sea surface temperature in the South Atlantic from an infra-red sensor

Cooler **Warmer**

The image size is 500 x 500 km.

The data set consists of 1/4 million precise measurements of temperature .