Ocean Colour Processing and Products

Overview of the steps involved in processing optical satellite data for ocean applications

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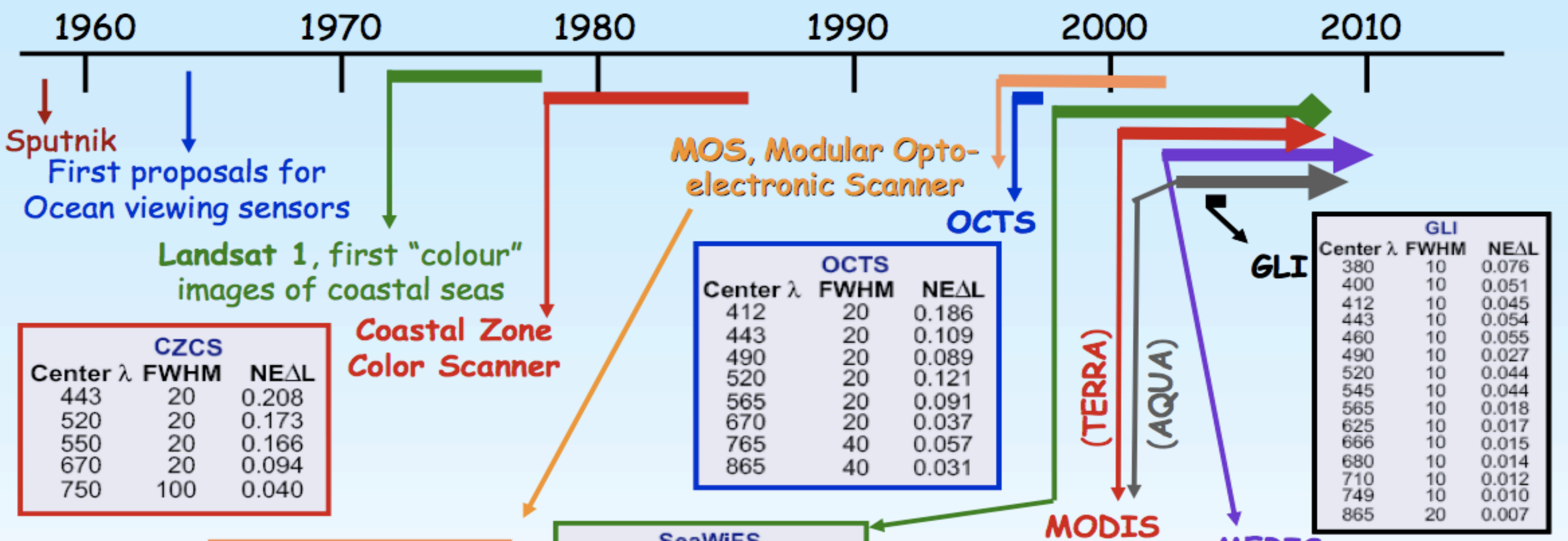
With thanks to Ian Robinson for much of the material

Ocean colour sensors - progress milestones



CZCS Center λ	FWHM	NEΔL
443	20	0.208
520	20	0.173
550	20	0.166
670	20	0.094
750	100	0.040

MOS Center λ	FWHM	NEΔL
408	10	0.192
443	10	0.124
485	10	0.148
520	10	0.141
570	10	0.150
615	10	0.105
650	10	0.141
685	10	0.088
750	10	0.102
815	10	0.034
870	10	0.033

OCTS Center λ	FWHM	NEΔL
412	20	0.186
443	20	0.109
490	20	0.089
520	20	0.121
565	20	0.091
670	20	0.037
765	40	0.057
865	40	0.031

SeaWiFS Center λ	FWHM	NEΔL
412	20	0.092
443	20	0.077
490	20	0.056
510	20	0.049
555	20	0.043
670	20	0.031
765	40	0.019
865	40	0.015

MODIS Center λ	FWHM	NEΔL
412	15	0.048
443	10	0.032
488	10	0.025
531	10	0.018
551	10	0.019
667	10	0.008
678	10	0.007
748	10	0.009
870	15	0.006
469 *	20	0.145
555 *	20	0.127
645 **	50	0.170
858 **	35	0.123

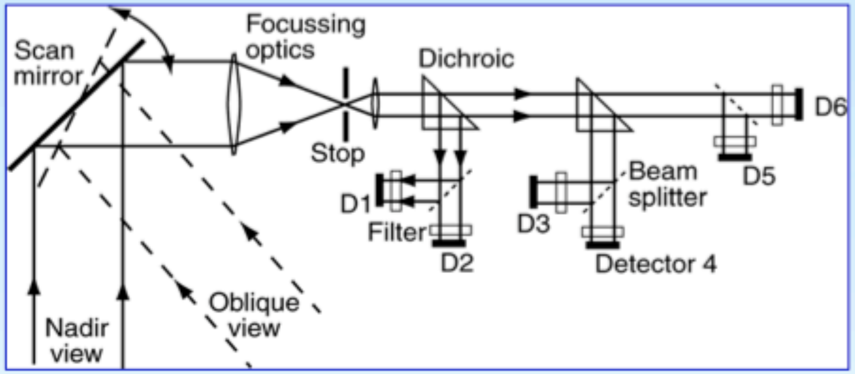
MERIS Center λ	FWHM	NEΔL
412.5	10	0.026
442.5	10	0.025
490	10	0.022
510	10	0.019
560	10	0.016
620	10	0.014
665	10	0.013
681	7.5	0.014
709	9	0.011
779	14	0.008
870	20	0.007
890	10	0.011
900	10	0.010

GLI Center λ	FWHM	NEΔL
380	10	0.076
400	10	0.051
412	10	0.045
443	10	0.054
460	10	0.055
490	10	0.027
520	10	0.044
545	10	0.044
565	10	0.018
625	10	0.017
666	10	0.015
680	10	0.014
710	10	0.012
749	10	0.010
865	20	0.007

For details of all ocean colour sensors see:-
http://www.ioccg.org/sensors_ioccg.html
or Report No.1 at http://www.ioccg.org/reports_ioccg.html

Progression of Visible waveband sensors

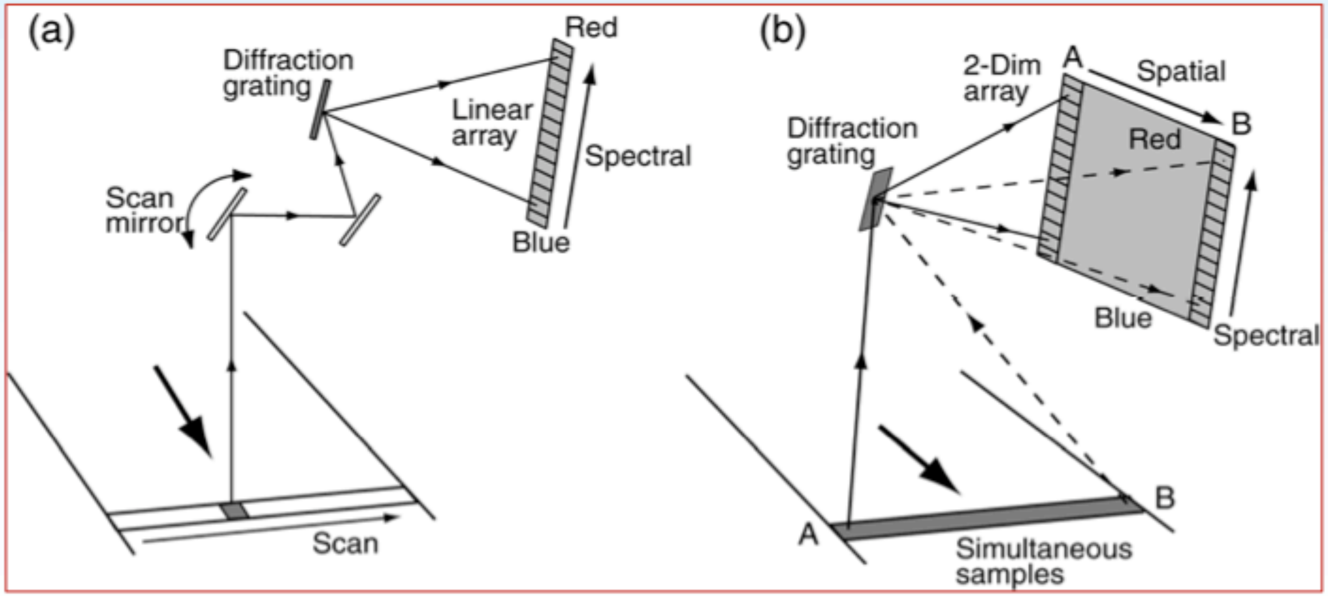
Simple multi-spectral scanner



E.g. Landsat Multi-spectral scanner,
Landsat thematic mapper
Coastal Zone Color Scanner

Spectroradiometer: (a) linear detector array (b) 2-D array

E.g. MODIS, MERIS



Wavebands for important ocean colour sensors

Note the bands common to most sensors:

440 nm

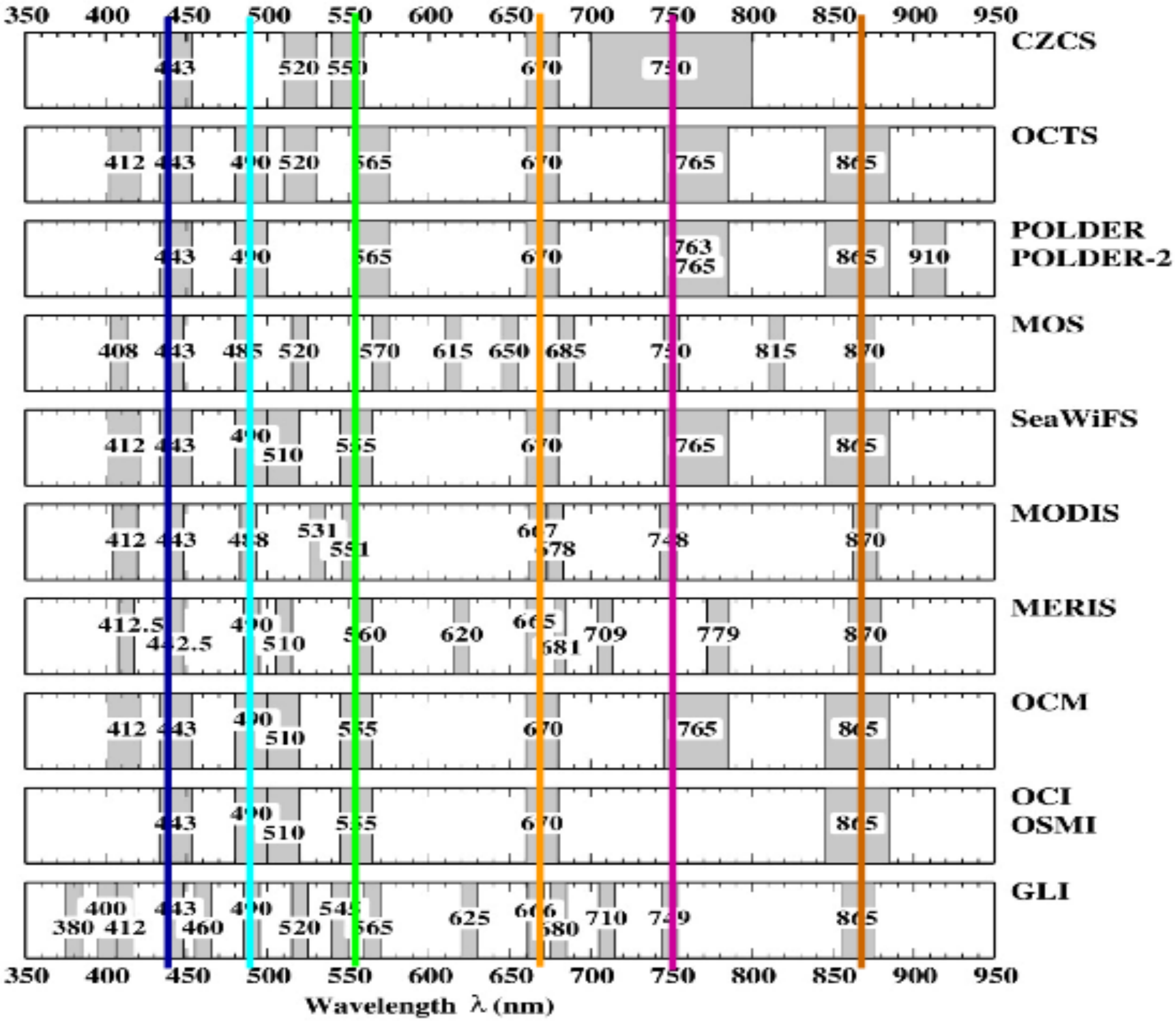
490 nm

550-565 nm

670 nm

750 nm

870 nm



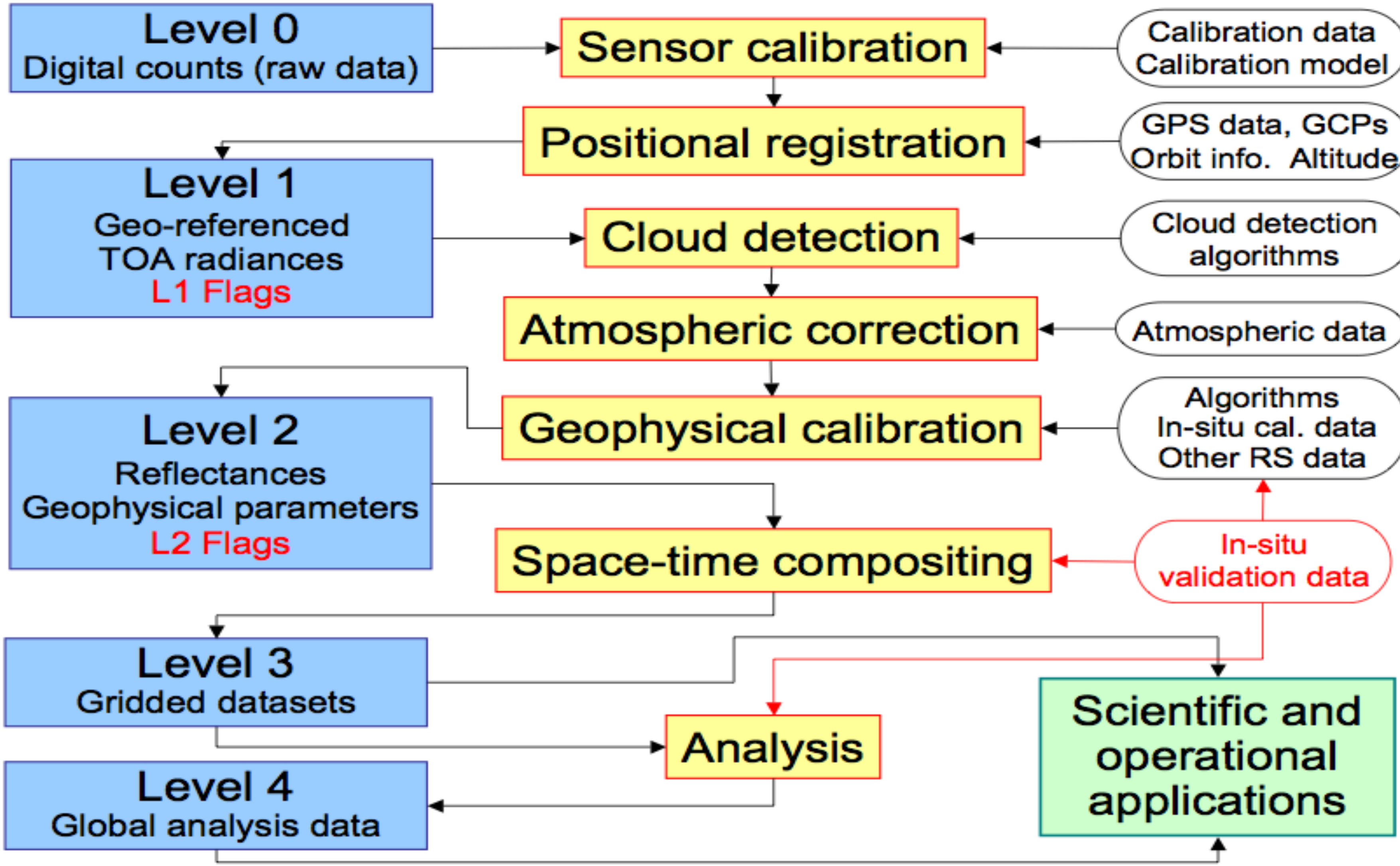
The "Ground Segment" of an EO Mission

- Those aspects of the remote sensing operation that are based on the ground:
  - Spacecraft Operations
  - Sensor Management (pre- and post-launch.)
  - Acquisition of "raw" data
  - Primary data processing (algorithm development, calibration, product archiving, product validation)
  - Data dissemination
  - Extended processing to Level 3 products and beyond.
- The purpose of this lecture is to:
  - Give an overview of the infrastructure (in addition to the satellite and sensors) needed to deliver useful E.O. data products
  - Distinguish between the different "levels" of data that you may encounter

Data acquisition

- Receive all data transmitted from satellite
  - Receiving station network
    - High latitude locations for Polar Low Earth Orbit satellites (LEOs)
      - E.g. Alaska, Kiruna (N. Sweden) earth see over half of all orbits
      - Svalbard sees ALL orbits of all polar orbiters
      - Mobile stations e.g. Antarctic
    - Data relay satellites
      - Relay data from every orbit to a central ground station
    - Local stations world-wide
      - Low – mid latitude stations see only a small fraction of orbits
      - For high resolution data that is not recorded on board
- Handling received data
  - Log all acquisitions
    - Use of a good database assists in reprocessing
  - Archive all raw data (level 0)
    - Long term storage commitment: secure; duplicate; independent.
  - Transmit data to processing stations
    - Speed of onward despatch is essential for operational processing
    - Use fibre optic land lines or satellite direct broadcast

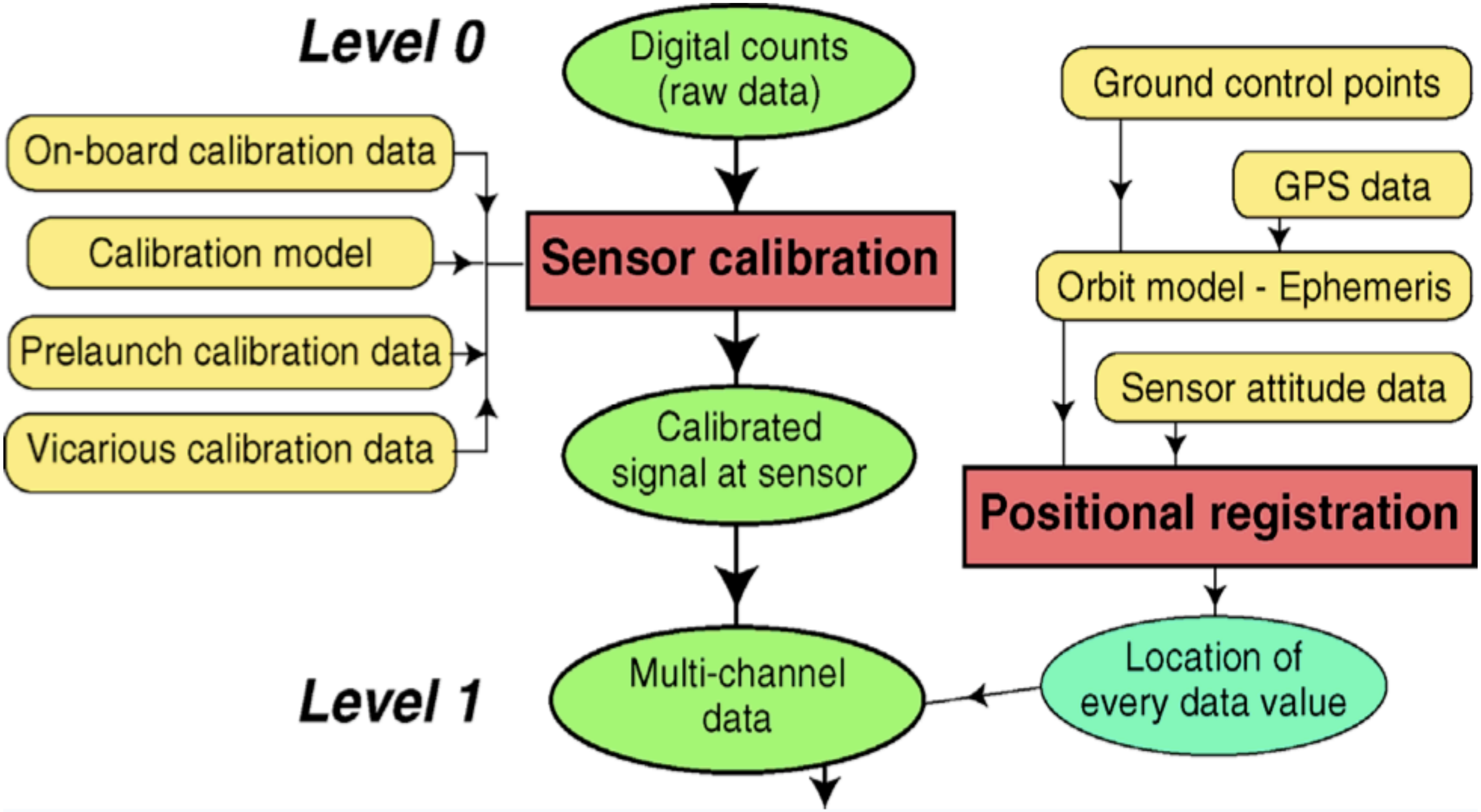
Overview: processing steps and products



Primary data processing & distribution

- Processing and Archiving Facilities (PAF)
  - Separate facilities for each sensor
- Process data to generate level 1 and 2 data (see next slides)
  - "Closed" facilities (e.g. ESA sensors)
    - Confidential processing software
    - Published processes and algorithms
  - Open facilities (e.g. NOAA and NASA sensors AVHRR, MODIS)
    - Open access to software
    - Processing can be distributed
- Archive L1 and L2 data
  - Good database essential for efficient access and tracking reprocessing
- Distribute L1 and L2 data
  - Serve all data products openly
  - Supply on order to selected users
  - Sell some L2 data products to commercial users ?
- Reprocessing
  - As additional information becomes available
    - Refined algorithms
    - Better calibration of sensors

Processing from Level 0 to 1

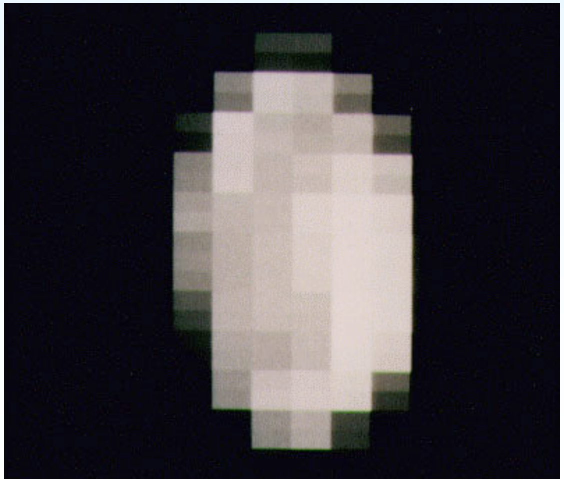


Sensor calibration

- Sensor converts received radiation to an electric response that is digitized for transmission.
- Sensor calibration inverts this by calculating radiances from raw counts. This requires:
  - A calibration model (mathematical expression) for converting the raw digital counts back into radiance
  - Calibration coefficients characterizing instrument performance at different radiances and wavelengths
  - Post launch estimates of calibration drift based on in-flight measurements of targets with known, constant radiance properties (e.g. reference panel, Moon)
- Output: TOA radiances + calibration flags
- Carried out by space agencies, but users need to be aware of calibration changes

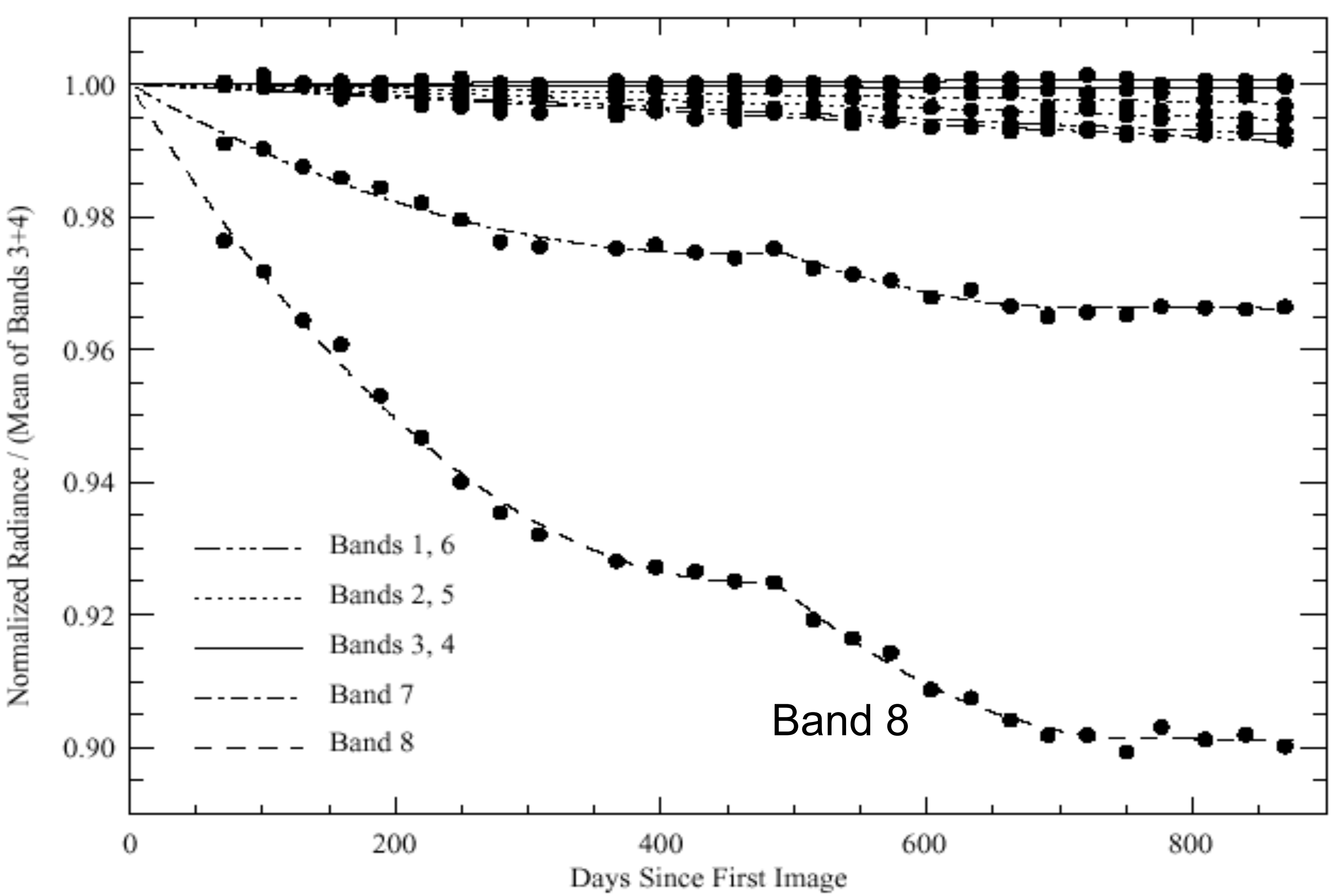
Lunar Calibration (e.g. SeaWiFS)

Allows for correction for long-term sensor degradation



- Constant target - no change
  - No atmosphere between moon and satellite - no correction needed
  - Same side of moon towards Earth
  - No weather or biology to change radiance characterstics over the satellite life time
- Lunar Viewing Geometry
  - SeaWiFS FOV = 1.6 x 1.6 mrad
  - Distance to Earth = 705 km
  - Distance to Moon = 384400 km
  - Nadir pixel size on Earth:
    = 705 x 0.0016 = 1.1 km
  - Nadir pixel size on Moon:
    = 384400 x 0.0016 = 615 km
  - Diameter of Moon = 3478 km (~ 6 pixels)

Correction for long-term detector degradation



Calibration: what you need to be aware of

- Calibration drift may mean reprocessing
  → new processing version
- May also mean changes to algorithms used in software distributed by space agencies
  - e.g. SEADAS (NASA), BEAM (ESA)
- Important to be aware of updates on space agency reprocessing (new versions) and software updates. (published by e-mail or on sensor websites).

Some recommendations:

- Use the latest processing version where possible
- Take care when comparing images from different processing versions (avoid if at all possible)

Geo-referencing

- The locations of pixels in a satellite image are given geographical cooridnates (lat/lon) corresponding to their position on the ground
- Geo-referencing (geo-location) produces a **tie point grid** of pixels within the image that have a precise location on the ground (every 16 pixel, every 16 row).
- Calculated from orbit parameters, time, altitude and look-angle of each sensor element. Accuracy: 1 - 2km.
- May be refined and made more accurate using ground control points (GCPs) visible and with known location.
- Tie-point grids (+ GCPs) are used when geo-correcting (mapping to a standard map projection) in L2-3 processing.

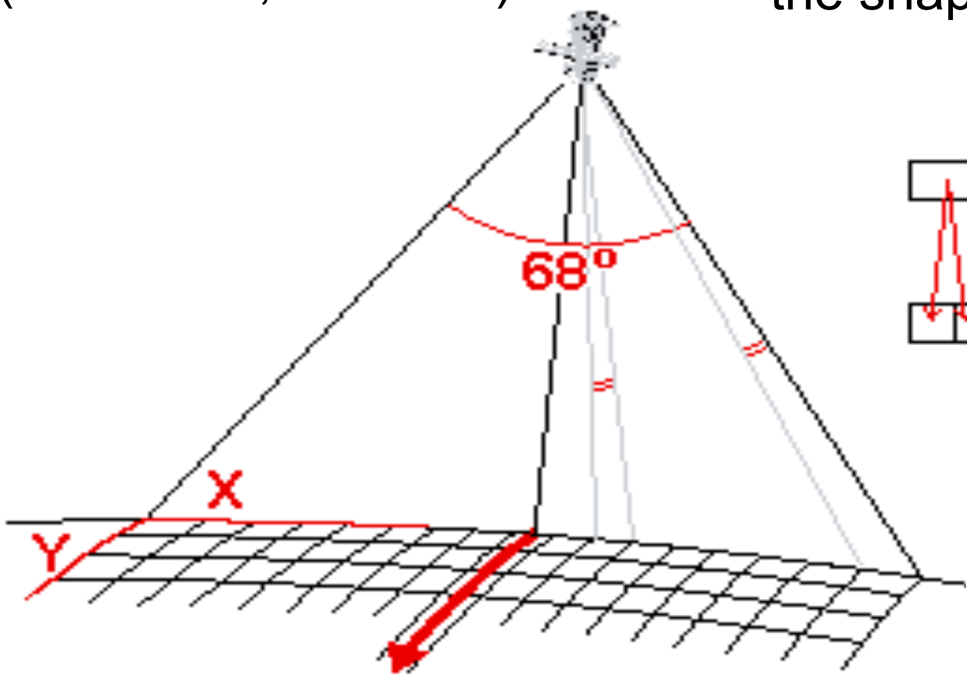
The MERIS product grid

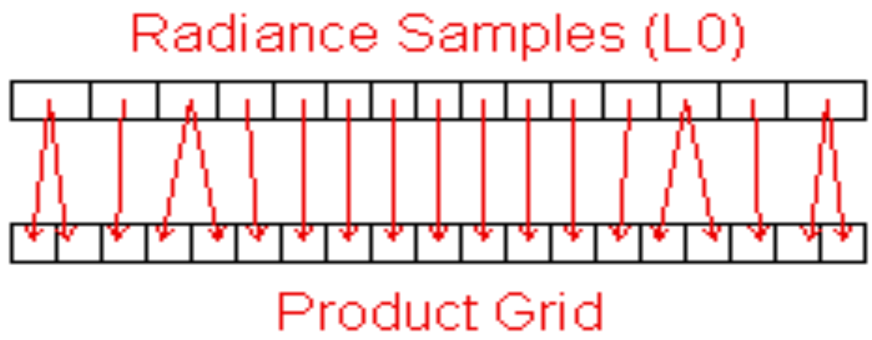
Swath width: 1150km
Across-track resolution:
- Nadir: ~260m
- Edge: ~390m

Along-track: 292m
(frame rate, $\Delta t \approx 0.44$s)

Geo-location of a pixel depends on

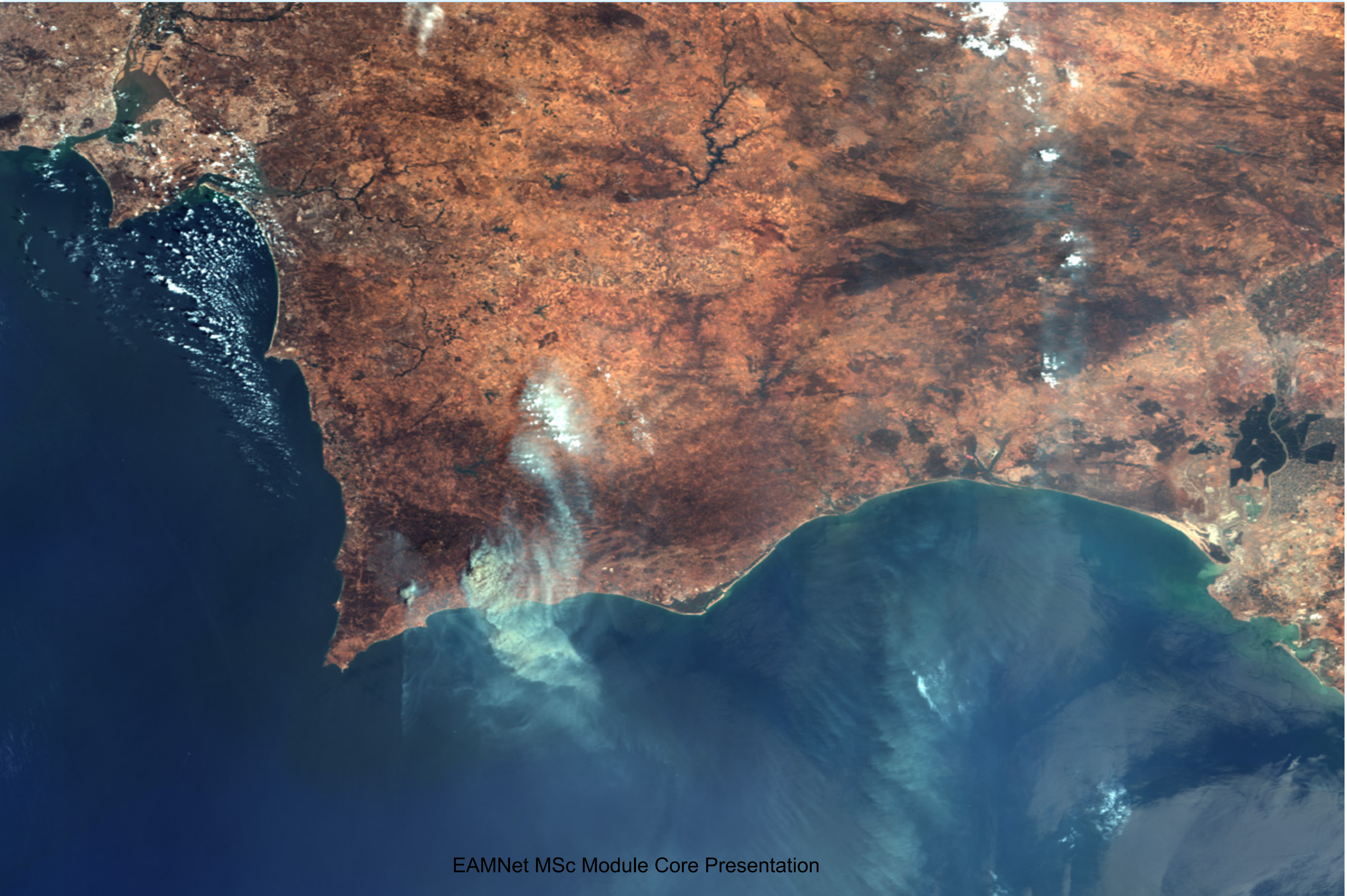
- position of Envisat at the time of acquisition,
- the orientation of the 5 camera modules
- the optics of each module.
- the shape of the Earth,



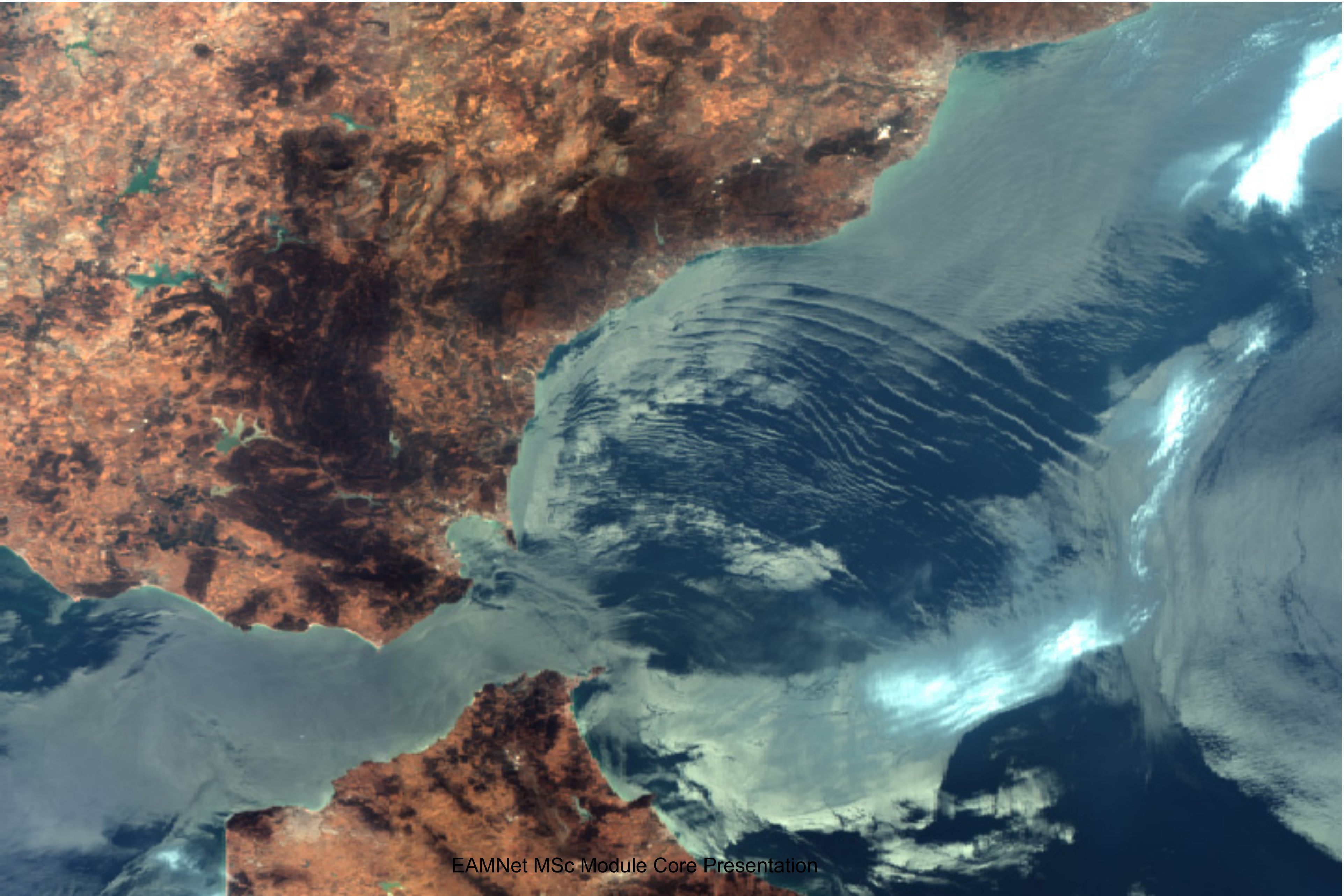


Radiance samples cover a wider area near the edges of the swath than at nadir, so some edge samples give rise to 2 pixels in the product grid. These are flagged in the L1A (top of atmosphere) product.

Example level 1 data (MERIS)

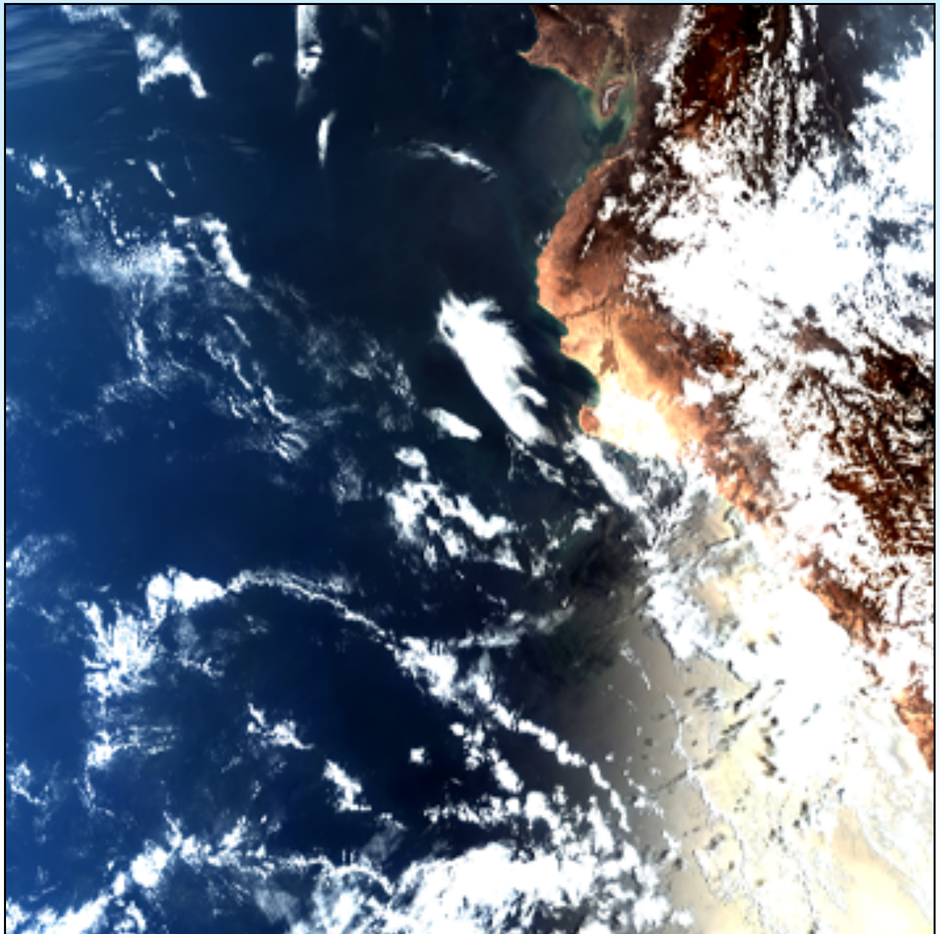


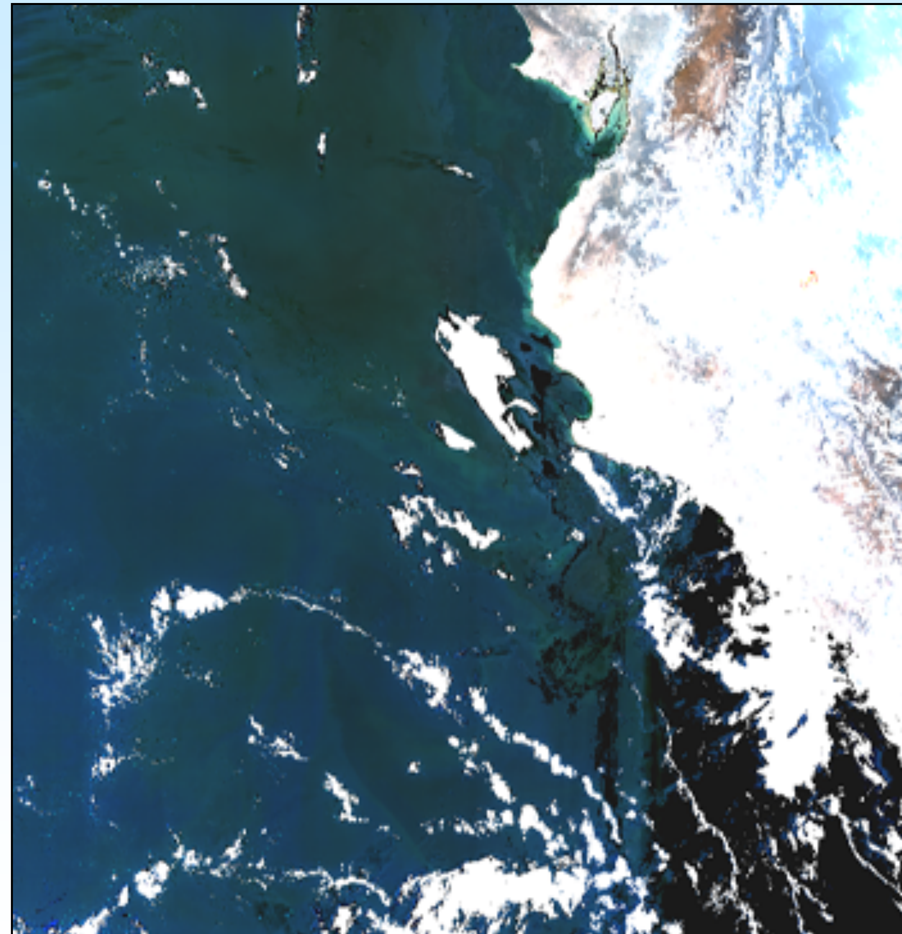
Example level 1 data (MERIS)



Atmospheric correction

L1: TOA radiance → L2 (1a): Reflectance



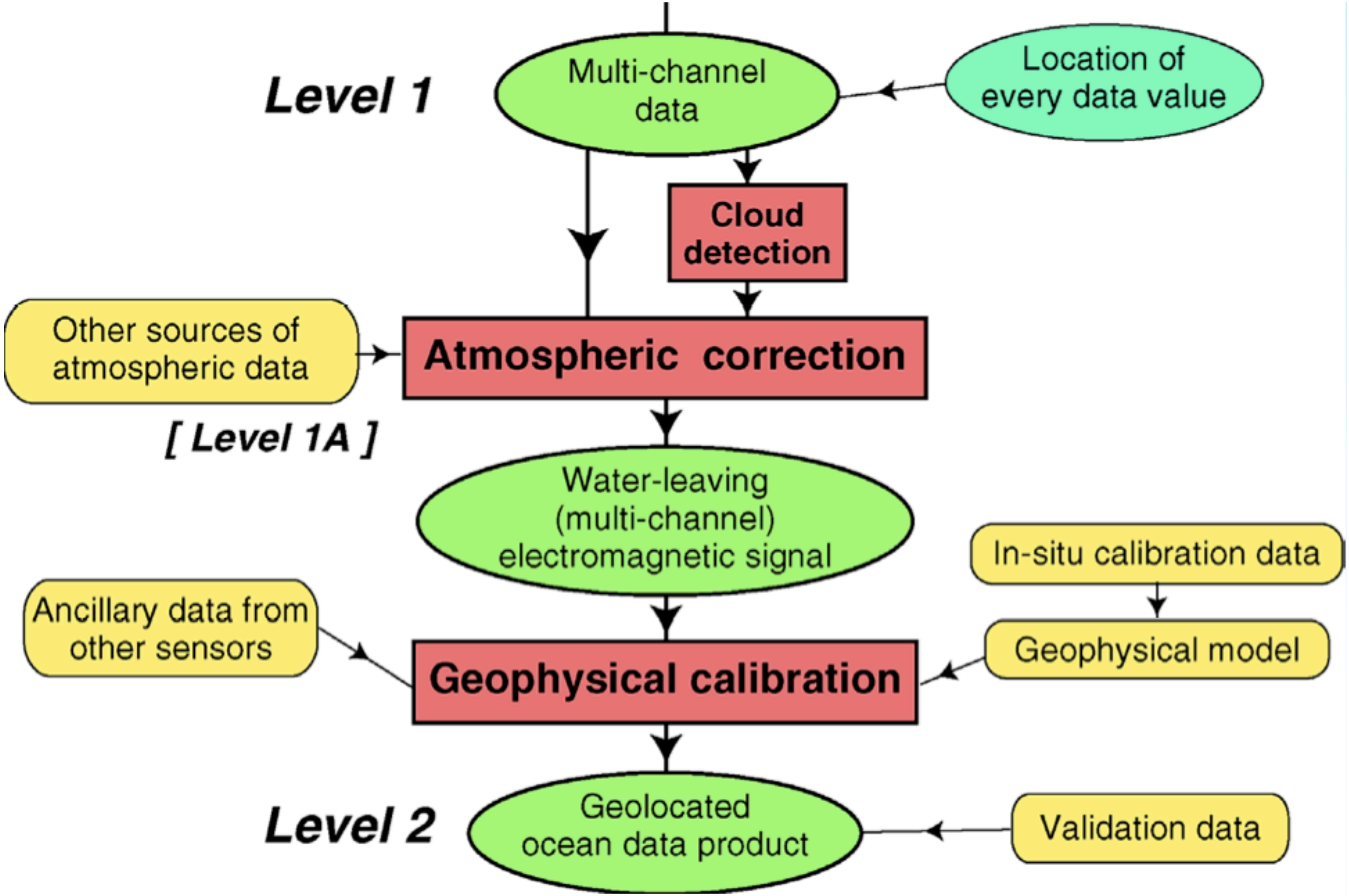


MERIS image from the coast of Peru corrected for cloud, sun-glint and path radiance

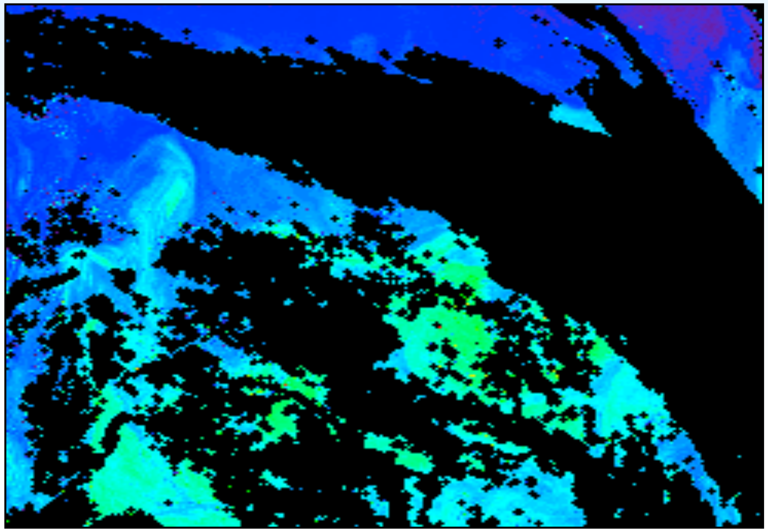
Algorithm development

- Required for atmospheric correction and geophysical parameter retrievals
- A crucial component of the processing chain
  - Interface between scientists and data managers
    - # Reviewed by the mission's Science Advisory Group (SAG)
    - # May be based on special science study contracts
    - # Operational software system built by software contractors
  - The essential link between raw and useful data products
    - # Based on user requirements
    - # User feedback is essential
  - Precise documentation is vital
    - # Scientific principles: in ATBD (algorithm theoretical basis document)
    - # Provides an "audit trail" for users to understand the data products
- Closely linked to instrument development
    - # Pre launch development
    - # Post launch adjustment / calibration during commissioning phase
    - # Ongoing validation, in principle throughout the sensor's operational lifetime

Processing from Level 1 to 2



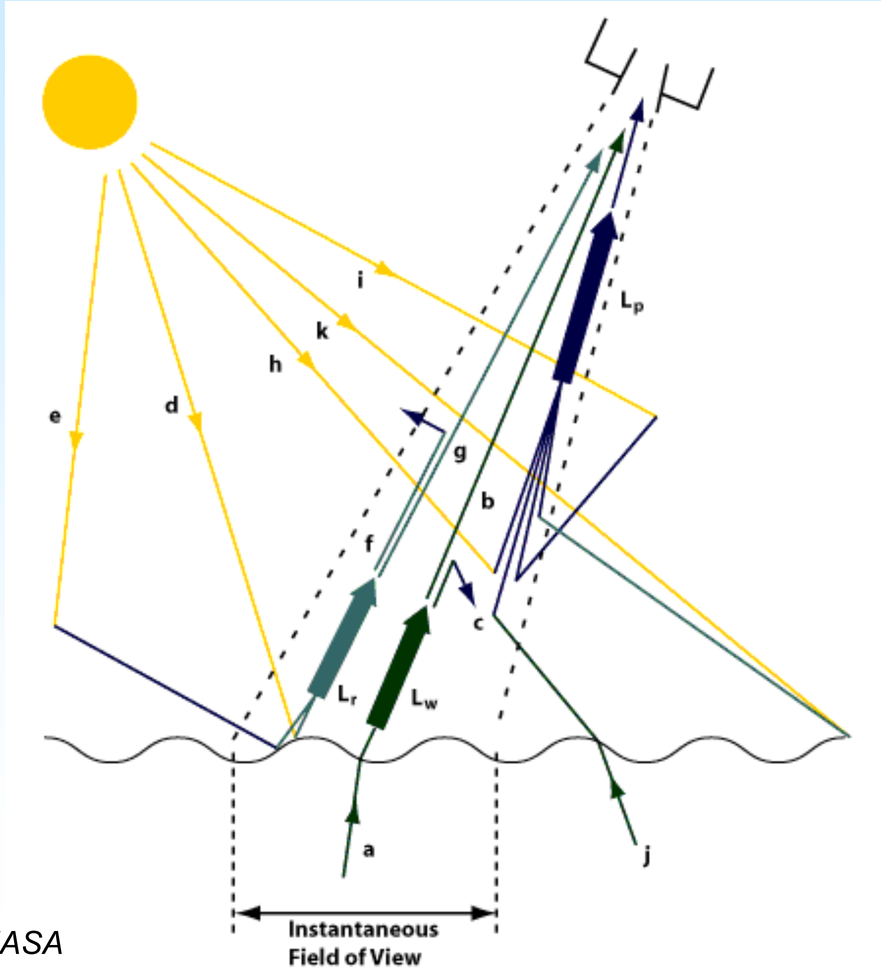
Cloud detection



- Cloud reflectance >> ocean/ land reflectance
- If reflectance exceeds a threshold value, a cloud flag is raised for the pixel
- Threshold based on TOA reflectance in a NIR band
- Sub-pixel cloud may not be detected by this method
  - May show up as anomalous chlorophyll values
  - May be flagged with a product confidence flag

Contributions to TOA radiances

$$Lt = Lr + (La + Lra) + tLwc + TLg + t\ Lw$$



NASA

Lt total radiance reaching satellite.

Lw water-leaving radiance to be retrieved at each wavelength.

TLg **sun glint** - direct reflectance of the solar radiance from the sea surface. (avoided through in SeaWiFS.)

tLwc contribution due to "white"-capping, estimated from statistical relationship with wind speed.

Lr contribution due to molecular (Rayleigh) scattering *can be accurately computed.*

La + Lra contribution due to aerosol and Rayleigh-aerosol scattering, estimated in NIR from measured radiances and extrapolated to visible using aerosol models.

Atmospheric correction steps

- Cloud detection
- Rayleigh correction - for molecular (Rayleigh) scattering and absorption by gases - e.g. ozone
- Application of land/sea masks (aerosol correction over sea only)
- Sun-glint identification
- White-cap detection
- Correction for scattering by aerosols (Mie scattering)
  - Determine aerosol type (continental / marine)
  - Determine aerosol optical depth
  - Calculate signal contribution from aerosol scattering

OUTPUT :

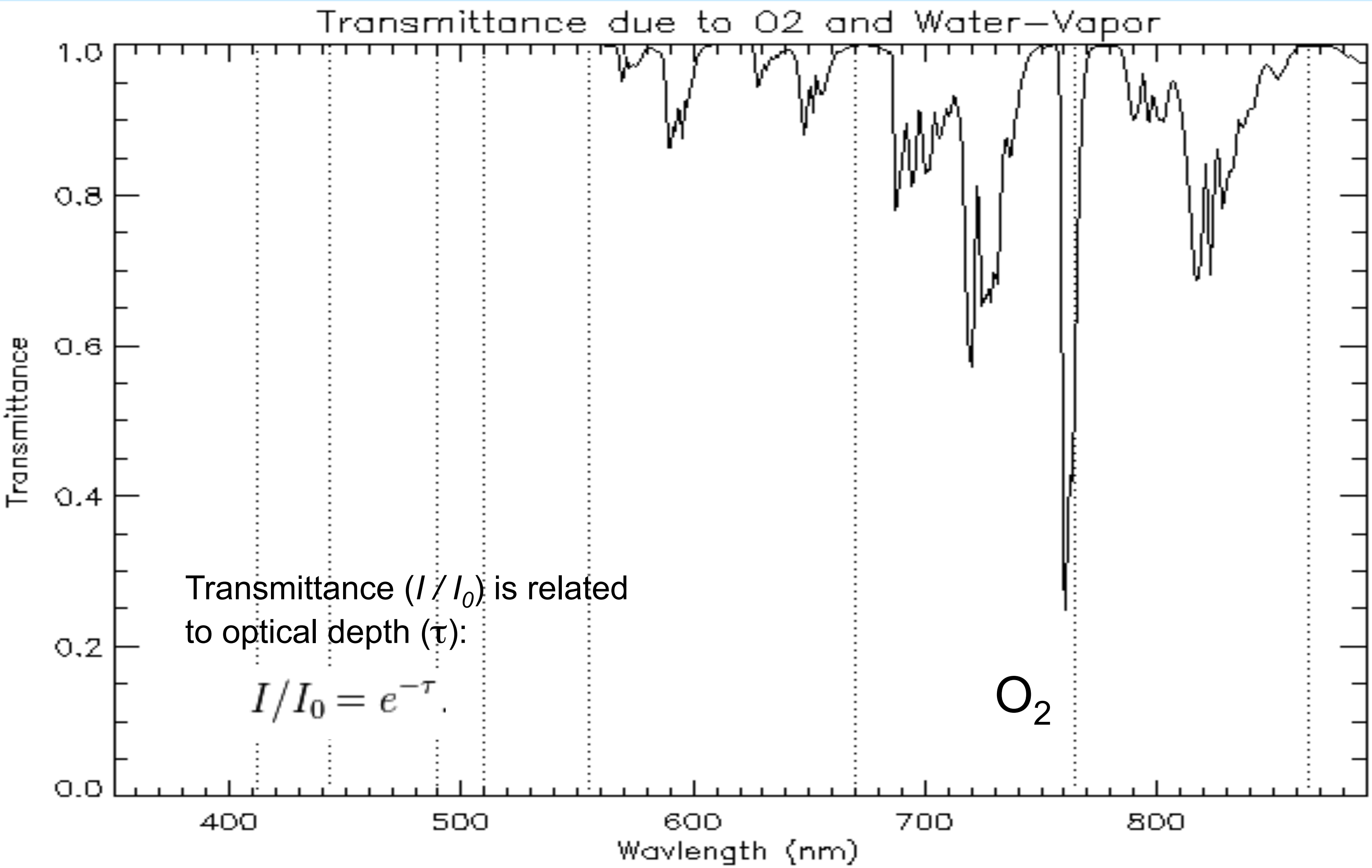
- Reflectances (ESA) or normalised water-leaving radiances (NASA)
- Level 2 confidence flags / cloud and glint masks

Rayleigh correction

Correction for absorption and scattering by gases

- Sometimes treated separately from aerosols because
  - Molecular composition of atmosphere generally uniform and known
  - Scattering and absorption coefficients are well known and do not generally change
  - Ozone absorption varies with season by can be retrieved from climatology or using data from atmospheric sensors designed to measure this.
- Rayleigh optical thickness, $\tau_m(\lambda)$ is due mainly to scattering by air molecules
  - Although at some (known) wavelengths absorption occurs
- Rayleigh path radiance calculated from $\tau_m(\lambda)$ and viewing angle, (θ,ϕ) for each pixel across track.

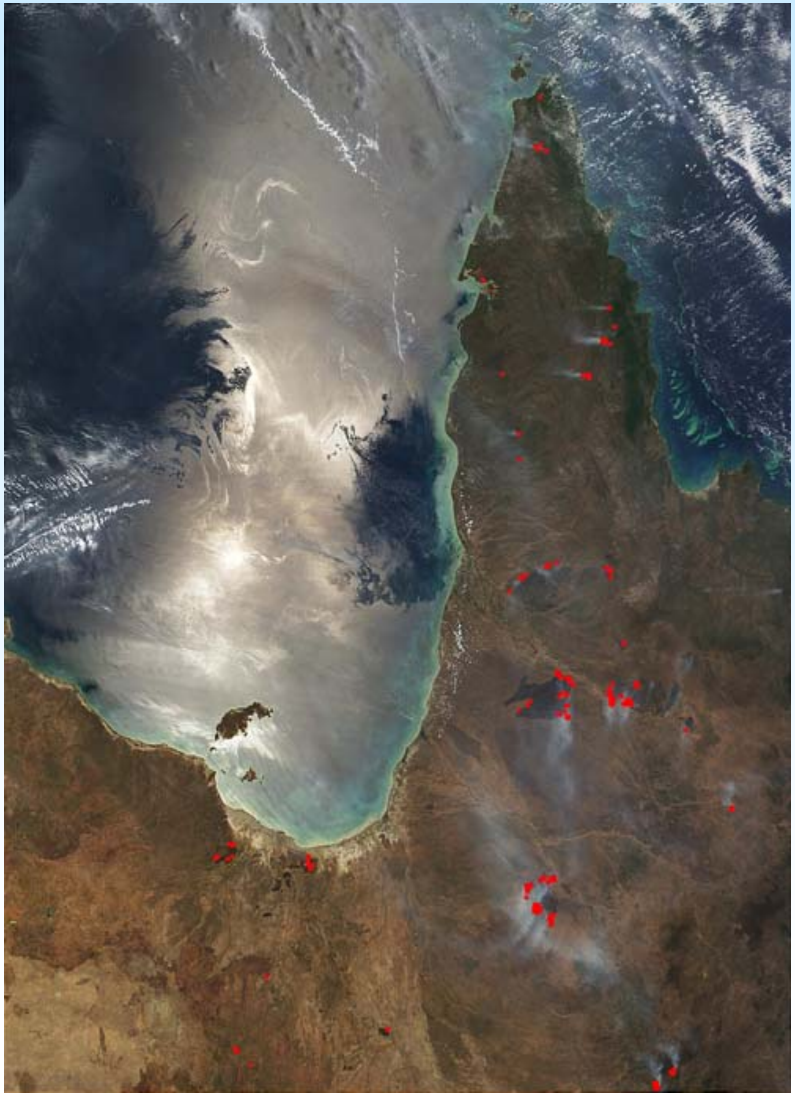
Atmosphere optical depth



Transmittance (I / I_0) is related to optical depth (τ):

$$I/I_0 = e^{-\tau}.$$

Identifying and correcting for sunglint



Reflection of sunlight into FOV

- Avoided by choice of viewing angle
- Steeper waves => more glint

Sky-glint:

- 2-3% except at high wind speed, near swath edge.
- Correction included in Rayleigh and aerosol corrections

Corrections strategies:

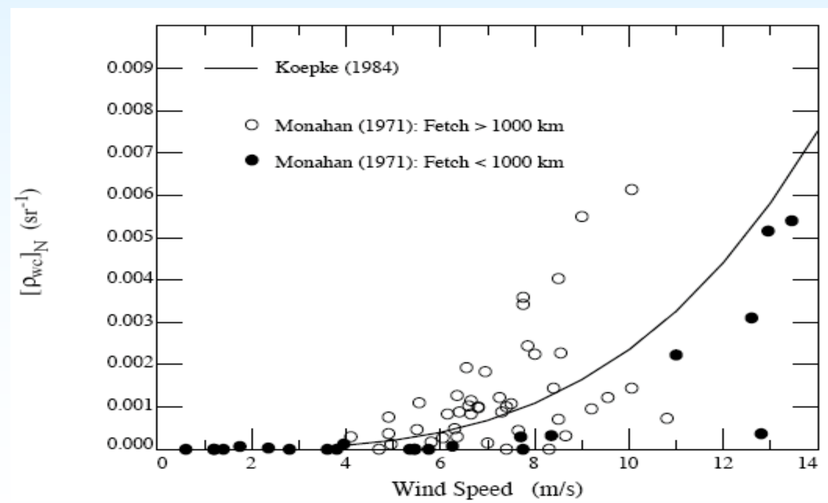
- High glint correction: threshold value for TOA radiance
- Medium/low glint: correction from:
  - Look angle (θ,ϕ), sun angle (θ_s,ϕ_s)
  - Wind speed and wave slope statistics
  - Fresnel reflectance coefficient

OUTPUT: Glint flags

Whitecap correction

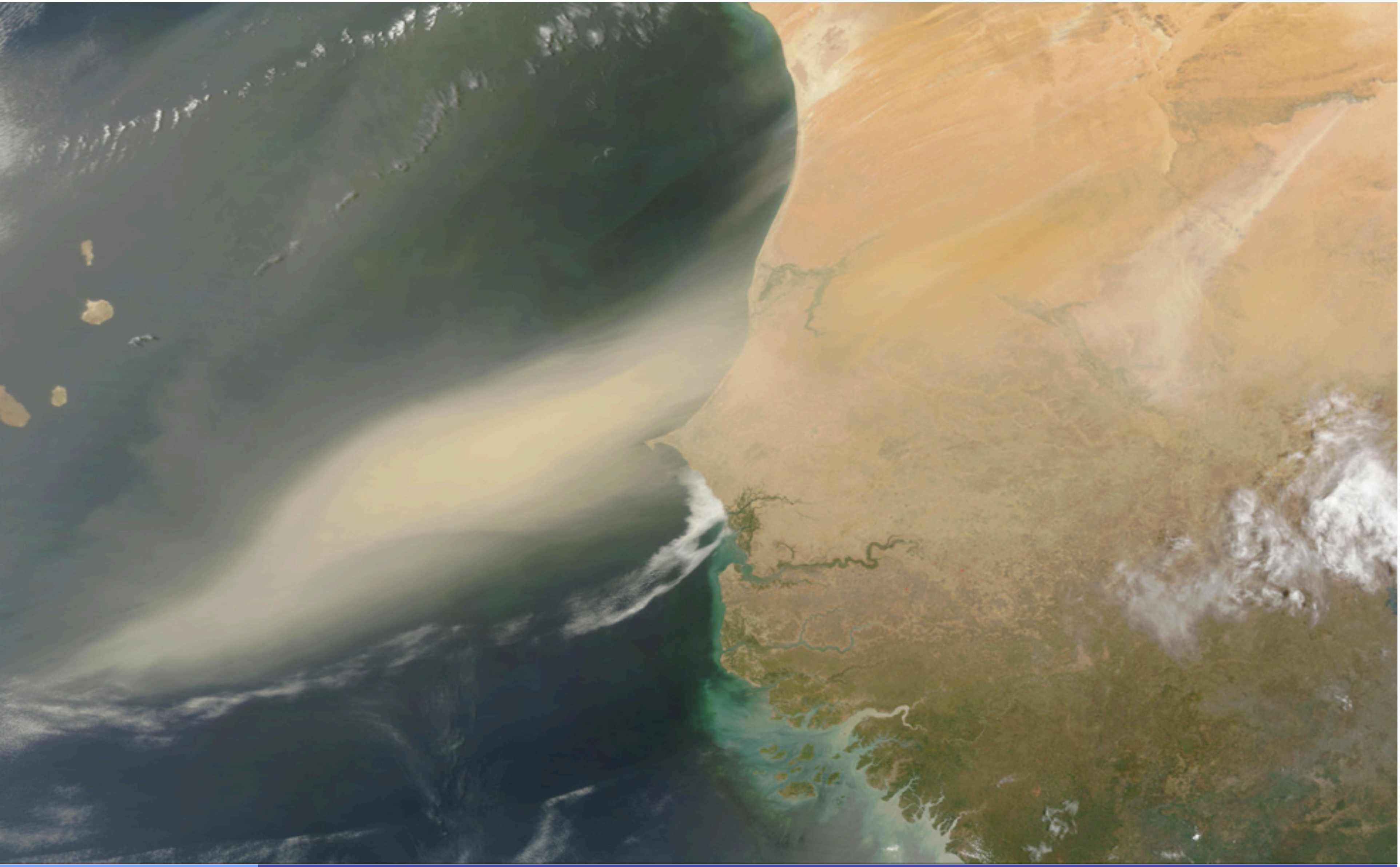
- Foam / bubbles from breaking waves
- Bright - increases upwelling radiance
- Spectrally similar to direct sunglint
- Affects aerosol correction so must be removed from signal first
- Normalised whitecap reflectance a function of wind speed:

$$[\rho_{wc}]_N = 6.49 \times 10^{-7} W^{3.52}$$

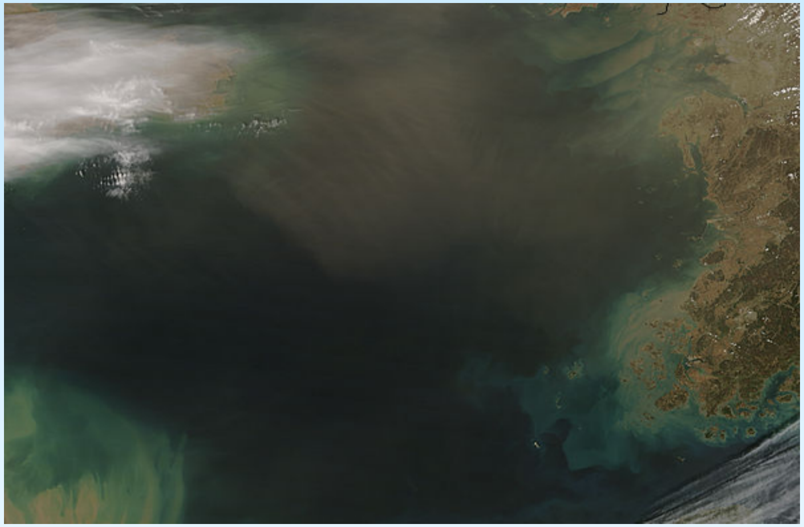


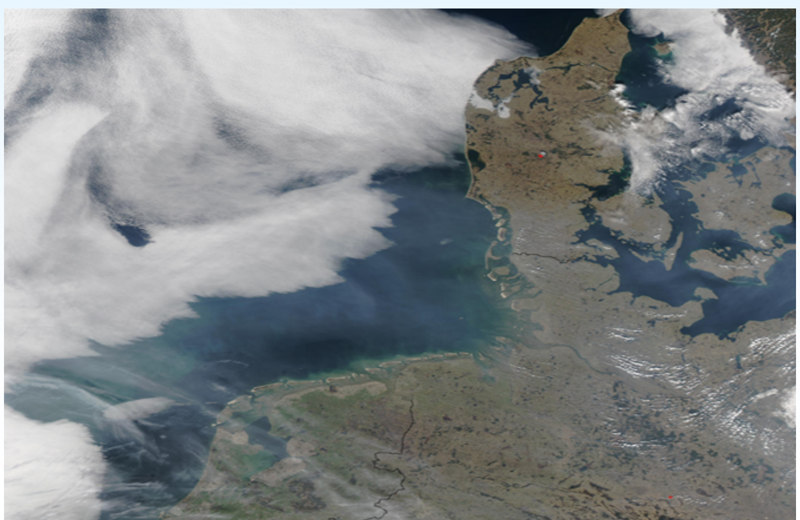
Source: http://modis.gsfc.nasa.gov/data/atbd/atbd_mod17.pdf

Continental aerosol example (MODIS L1 data)



Determining aerosol type and model to use





- Continental aerosol
  - Dust, smoke, smog
  - Absorbs radiation across a wide range of wavelengths
  - Variable scattering and absorption properties
- Marine aerosols
  - Mainly water vapour
  - Non-absorbing except for defined, narrow bands
  - Scattering properties determined by size distribution
- Aerosol type determines choice of aerosol model used in the aerosol correction

Estimating the aerosol contribution

Based on look-up-tables (LUT) of radiance for all bands

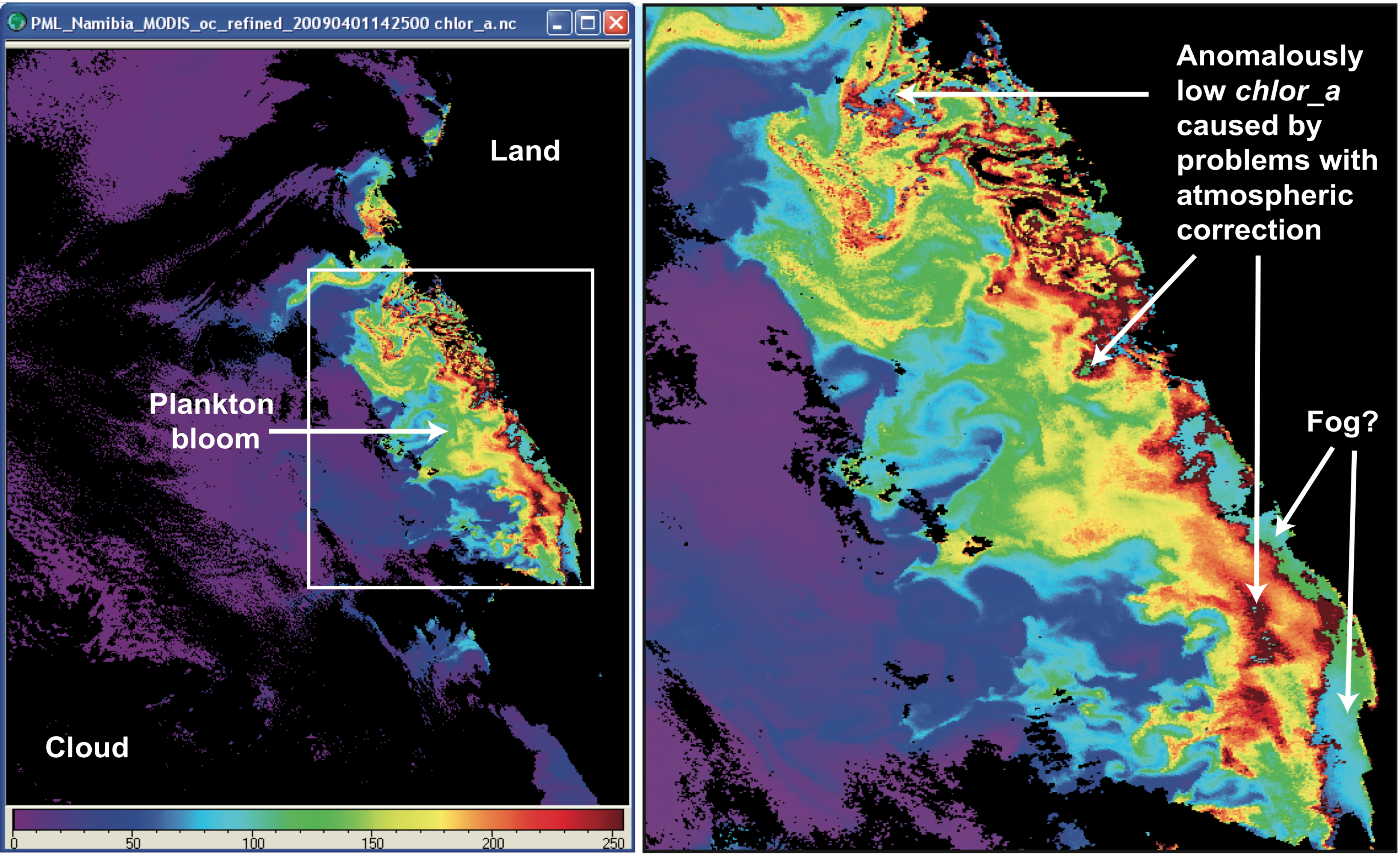
- computed from atmospheric radiative transfer models using different aerosol types (continental or marine or mixed c-m)
- Continental aerosols:
  - Absorption calculated from concentrations and absorption coefficients of different constituents (dust, smoke, pollution haze)
- Marine aerosols:
  - Assumes no absorption except in narrow water absorption bands
  - Scattering coefficient, *b*, and scattering phase function β^* calculated from size-distribution of water-droplets, (a function of atmospheric humidity and wind-speed)

Uses TOA spectral radiance in 2 NIR bands (778 and 765 nm)

- Compares these to LUT and finds values for all other bands
- 'Dark pixel' assumption: High water absorption coefficient - no water-leaving radiance, only surface and atmosphere contributions
- Causes problems when particle scattering in the water is high - plankton blooms / high concentration of suspended sediment.

OUTPUT: **Water-leaving reflectances**, L2 confidence flags

Example of atmospheric correction problems

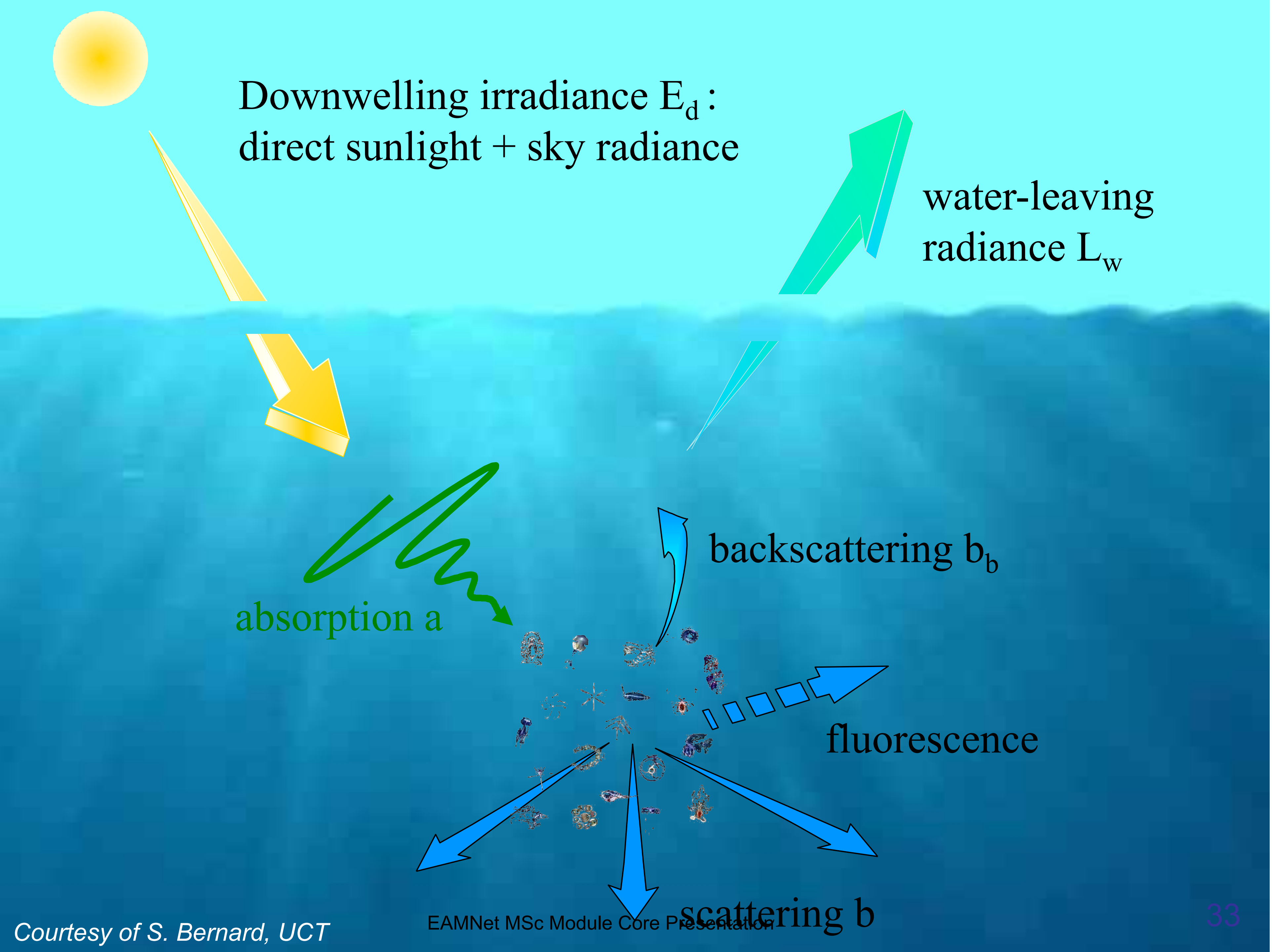


Deriving chl-a and other geophysical parameters

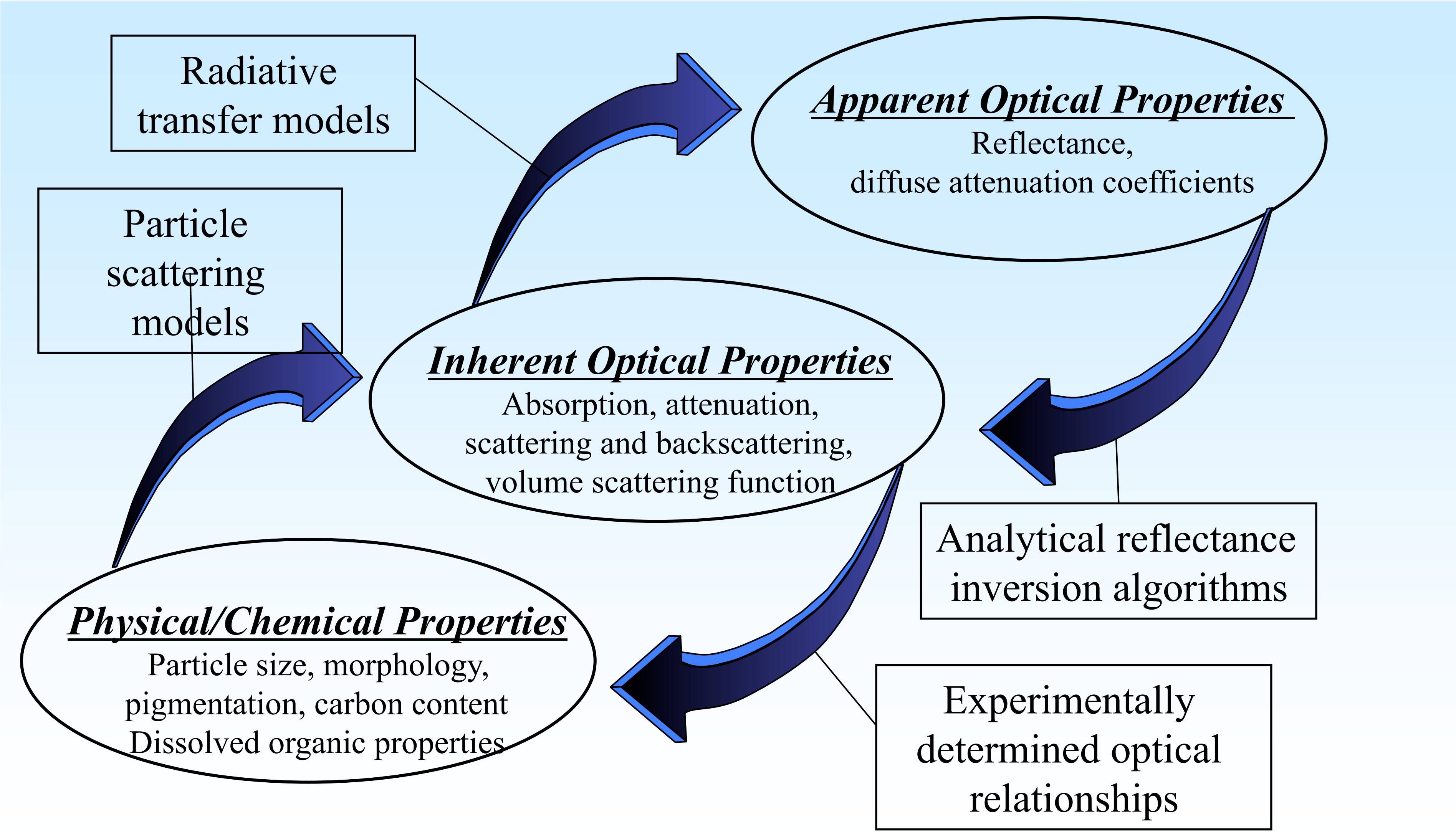
- Geophysical algorithm development
  - Initial algorithms developed analytically or with model data sets, + data from airborne sensors or other satellites
  - Validation against in-situ data from ships, buoys, platforms and airborne campaigns
- Algorithms applied to spectral reflectances (esa) normalised water-leaving radiance (nasa)

TYPICAL OUTPUT

- Pigment concentrations (chlorophyll-a)
- Total suspended particulates, yellow substance
- Diffuse attenuation coefficient (K)
- Photosynthetically available radiation (PAR)
- Aerosol optical thickness at 865nm (thau865)
- L2 confidence flags


Downwelling irradiance E_d :
direct sunlight + sky radiance
water-leaving
radiance L_w
absorption a
backscattering b_b
fluorescence
scattering b
Courtesy of S. Bernard, UCT

In-water optics and algorithm development



Courtesy of Stewart Bernard

Algorithms for chlorophyll retrieval

- Inversion of semi-analytical models using *in-situ* data
  - Single and multiple band-ratio algorithms
- Look-up tables
  - Generated with forward numerical modelling of radiative transfer through water using IOP's obtained from *in-situ* measurements
- Neural net algorithms
  - Relate R_{rs} to concentrations via non-linear equations
  - Training sets created by forward numerical modelling, using IOP's from in-situ measurements of selected cal/val sites
  - Non-linear mapping of satellite measurements to parameters of interest through neural net training

  - Example: MERIS algorithm for Case 2 water (Doerffer)

Validation: testing and improving accuracy

- Goal: < 35% error for global Case 1 waters
- Validation with satellite in-situ 'match-up' data
- How representative is the algorithm?
  - Accuracy at different concentrations
  - Performance in different regions
  - Effect of different water types
- Need to consider
  - The *in-situ* data used to develop and validate algorithm
  - Performance of alternative algorithms
  - Are there regions where the accuracy is reduced?
  - When to use other algorithms

Two main types of seawater

Case 1

Optically active constituents:

- Phytoplankton cells with pigments
- Their breakdown products
  - correlate with pigment concentrations.

Case 2

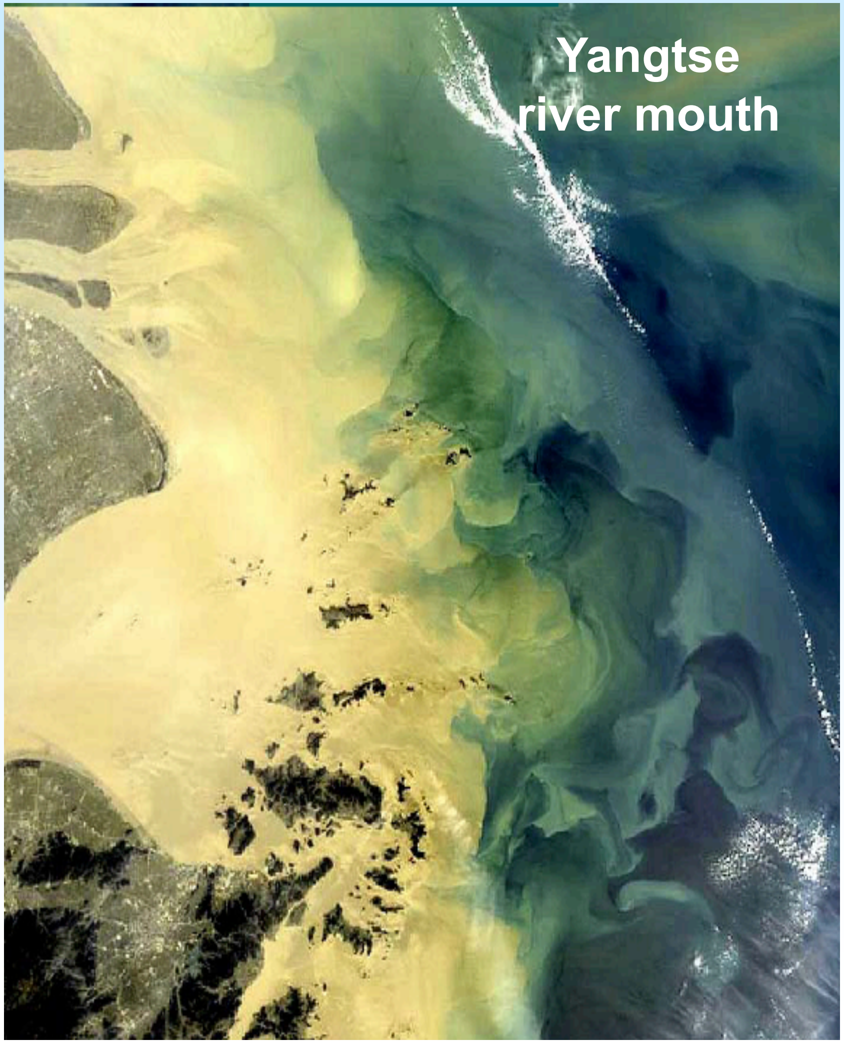
Optically active constituents:

- Phytoplankton cells
- Sediment particles
- Coloured Dissolved Organic Matter from land run-off

Particle scattering and CDOM absorption **do not correlate** with chlorophyll concentration

MERIS algal-2 algorithm

an attempt to solve the Case 2 problem



MERIS bands for SPM

- 3 red bands: - 620, 665, 681
- One NIR band 709 nm
- Water flagged as Case 1 or Case 2 based on NIR radiances
- **CASE2_S flag**

Neural net algorithm

- developed using model data
- tested and further developed with in-situ data from North Sea
- Uses 8 bands 412-709 nm
- Poor atmospheric correction of red bands causes problems for algorithm performance

Flags

Lelvel 0
Digital counts (raw data)

Level 1
Geo-referenced TOA radiances
L1 Flags

Level 2
Reflectances / normalised water-leaving radiances
Geophysical parameters
L2 Flags

Level 3
Global gridded datasets

- Raised during processing L0 - L1 - L2
- Different types
  - Class flags: Land, ocean, cloud
  - Quality (confidence) flags:
    - Were tests for glint or whitecapping positive?
    - Did any of the algorithms fail or give anomalous results?
  - Science flags
    - Additional information relevant to image interpretation and analysis
- Used in masks when processing to L3
  - Should this pixel be included in composite?
  - Avoid bad quality data, but also avoid bias
    - selective removal of high or low values that are have been incorrectly flagged

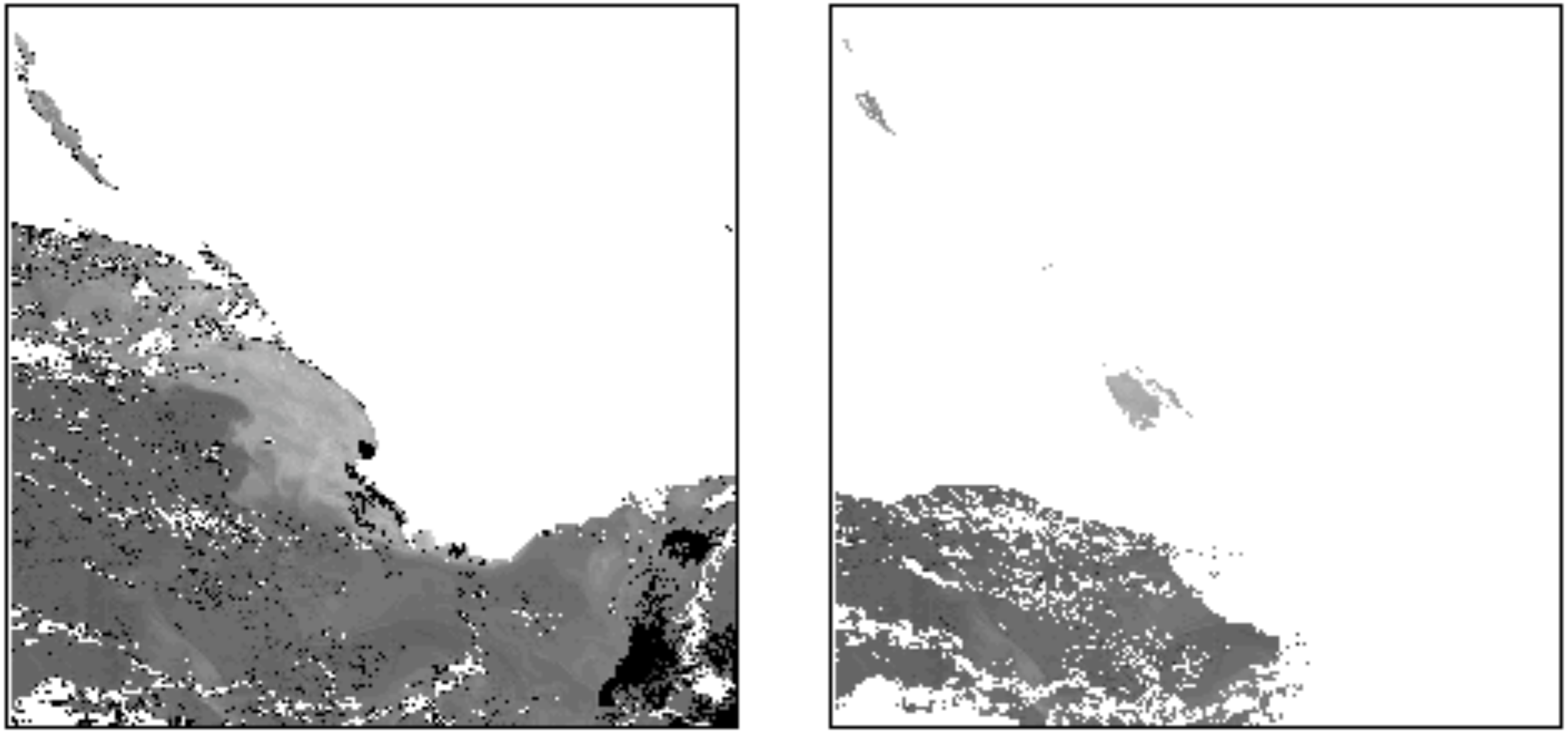
An example of using MERIS L2 flags

Class flags applied:

Cloud and land masked

Class flags + confidence flag

- Anomalous reflectance values / failure of atmospheric correction

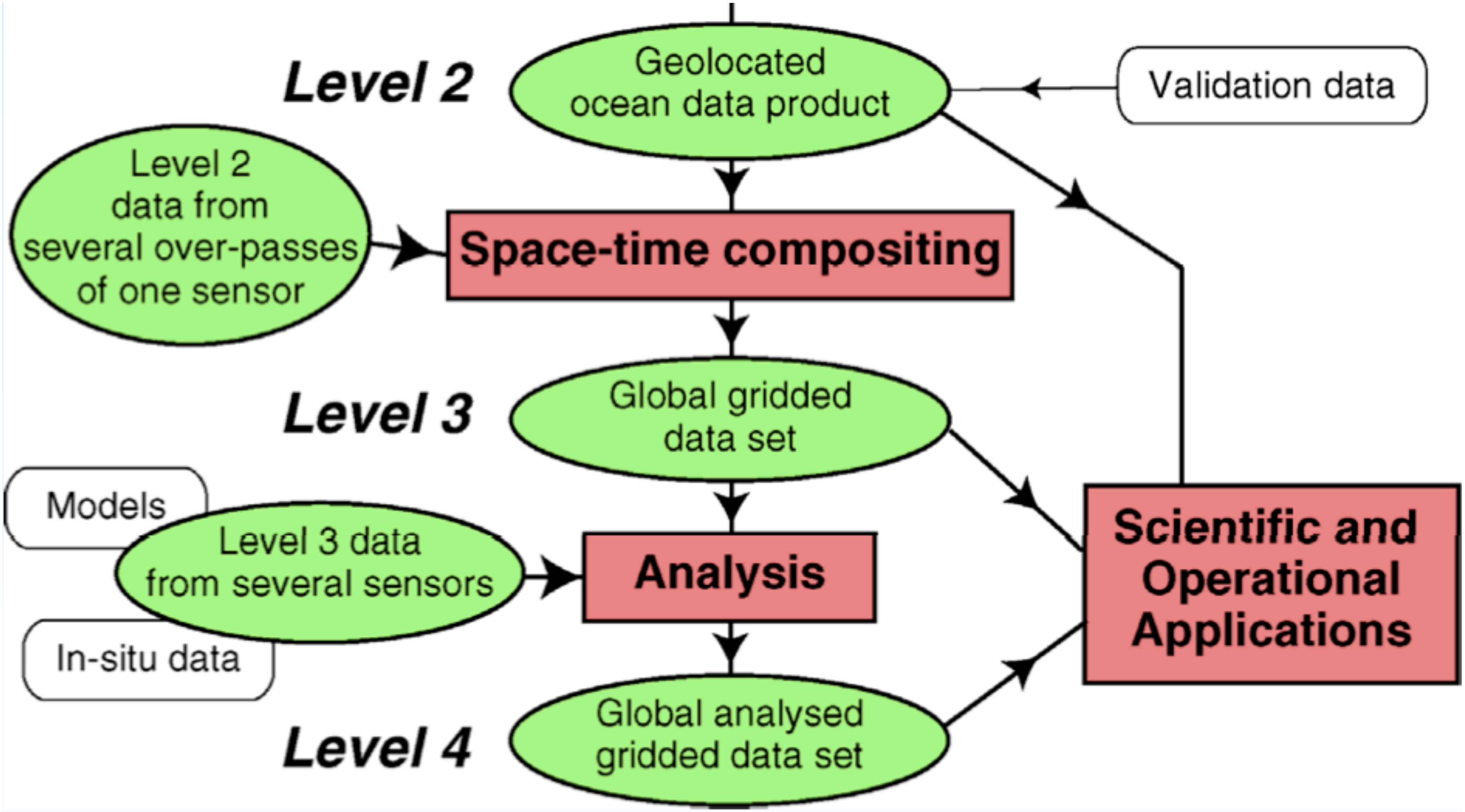


Coccolithophore bloom in the Benguela LME

Additional processing to level 3

- Global EO gridded data products from individual sensors
  - # Originally performed by scientists and users,
  - # Now often part of the Space Agency activity
- Changed resolution
  - # Typically reduced spatial and temporal resolution
  - # Averaging within larger space-time bins can improve accuracy
- Dissemination of level 3 data
  - # Commercial or restricted products
    - Purchase data or buy subscription
    - Scientific users submit proposals
  - # Open access (this is now typically available for most datasets)
    - Data available via Internet (www web page access; download by ftp sites
    - Distributed on CD-ROM
- Validation of level 3 products

Additional processing to level 3



Summary (1)

- Atmospheric correction essential before applying algorithms for geophysical parameters - chlorophyll, SPM etc.
  - Flagging for clouds, glint and white caps (foam)
  - Absorption and scattering by atmospheric gases
  - Absorption and scattering by aerosols (water droplets, dust)
    - Uses TOA radiances in near infrared to determine aerosol type and select algorithm to use
- Global chlorophyll algorithms based on 443:550 ratio
  - work well for open ocean, except at high chl-a
  - Serious over-estimate of chl-a near coasts due to SPM and CDOM
- Case 2 algorithms (MERIS algal2)
  - Simultaneous calculation of chlorophyll-a, suspended particulates and yellow substance
  - Only validated with limited (mainly North Sea) in-situ data
  - Case 2 flag triggered by highly scattering blooms

Summary (2)

- Processing to level 3
  - Removing data flagged as suspect
  - Resampling to a common grid using a standard map projection
  - Combining several images from the same sensor
  - Automated processing with standard algorithms
  - => global/regional gridded data
- Processing to level 4 - analysis products
  - Combines data from several sensors
  - Validation with in-situ data
  - Using models to interpolate and fill gaps
- Validation with in-situ data essential to assess accuracy of global products in different regions and seasons