IOCCG Training Course on Ocean Colour Remote Sensing

Uncertainties in ocean colour remote sensing

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IOCCG
International Ocean Colour research Coordination Group

Helmholtz Zentrum Geesthacht (was GKSS)

Geesthacht is close to Hamburg, North Germany

Institute of Material Research
Institute of Polymer Research
Institute of Coastal Research
Staff: ca. 750
furthermore on the campus: Brockmann Consult

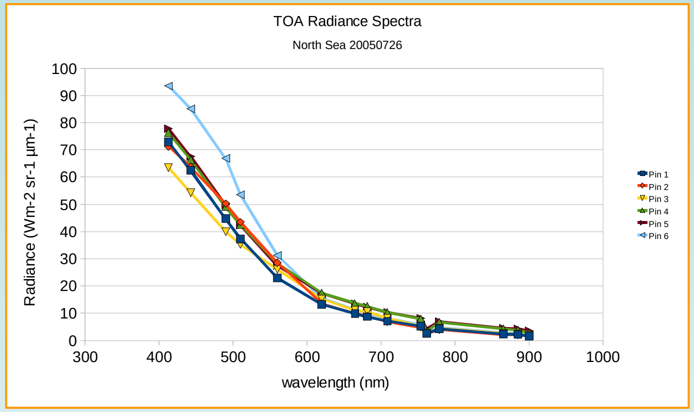
Why this lecture?

- Coastal colour remote sensing is a difficult task, it can lead to failures and large uncertainties.
- Conditions for failures have to be identified.
- Uncertainties have to be quantified on a pixel by pixel bases.
- Methods have to be developed to reduce uncertainties
- Required error level depends on the application of RS data

Program for July 9 and 10

- Lectures
  - Sources of uncertainties
  - How to determine uncertainties
  - How to reduce uncertainties
- Exercises
  - Information content of ocean colour reflectance spectra
  - Regression statistics as the basis for algorithms and validation
  - Ambiguities and saturation effects
  - Sensitivity analysis
  - How to determine uncertainties when fitting data to a model

What determines the radiance spectrum at TOA



air molecules

different aerosols

thin clouds

contrails

Sky reflectance

Sun glint

foam

floating material

Suspended particles

dissolved organic matter

Vertical distribution

chlorophyll

Bottom reflection

different phytoplankton species

Colour Remote Sensing of complex water is not possible!

- Too many variables in water determine the system:
  - Different types of particles with variable size distribution, complex shapes of particles with different absorption/scattering properties
  - Different phytplankton types with different pigment composition, size distribution, scattering properties, phase functions
  - „dissolved“ material with different optical properties
  - For each component variable vertical distribution
  - In shallow water reflection of a bottom with variable optical properties
  - Rough sea surface with foam, partly floating material
  - Due to high absorption a very low reflectance in blue spectral range
- Atmosphere
  - High path radiance compared to water reflectance
  - Different and varying aerosols
  - Thin cirrus clouds and contrails, sunglint
  - Varying vertical distribution
  - Adjacency effect by land and clouds
  - Varying solar and observation angles
- Measured Variables
  - Only a limited number of spectral bands

Colour Remote Sensing of complex water is possible!

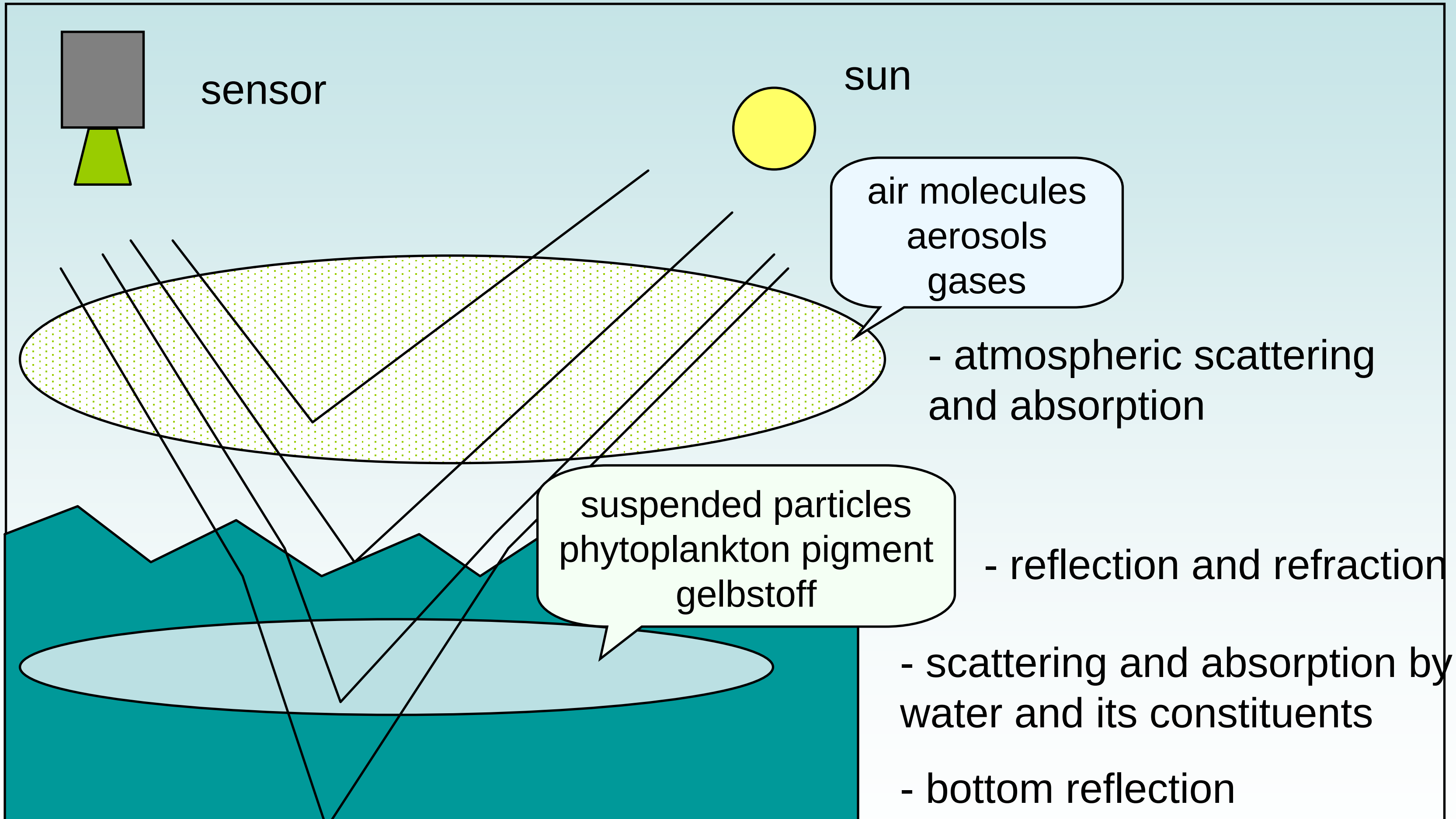
But:

- Restrict to a small number of components with similar optical properties
- Detection of special cases such as red tides, cyanobacteria
  - Exclude or develop special algorithms
- General knowledge about vertical distribution at different seasons
- Bathymetry to estimate possible bottom effects
- Determine penetration depth / z90 depth
- Determine scope of algorithm
- Develop algorithm to determine / flag out of scope conditions
- Determine uncertainties for each product

Atmospheric correction most challenging issue

- Develop special procedures for atmospheric correction over complex waters
- Problems: adjacency effects, floating material
- Determine conditions when AC leads to too large uncertainties

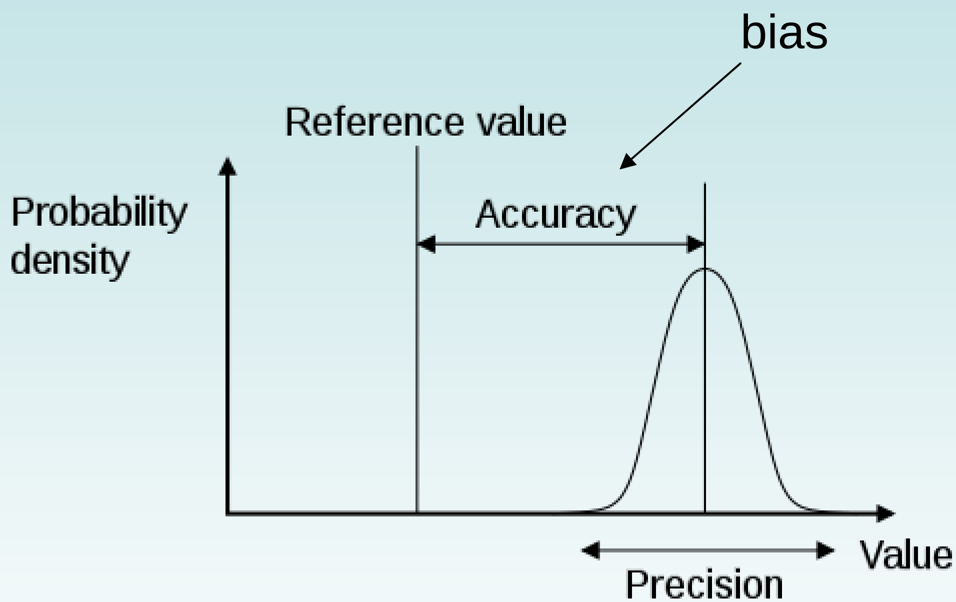
Basic principles of Water Color RS



Terms and Definitions

- Reliability
- Accuracy
- Precision
- Stability
- Reproducibility
- RMS error
- Bias
- Linearity

Accuracy and Precision



Scatter
Standard deviation

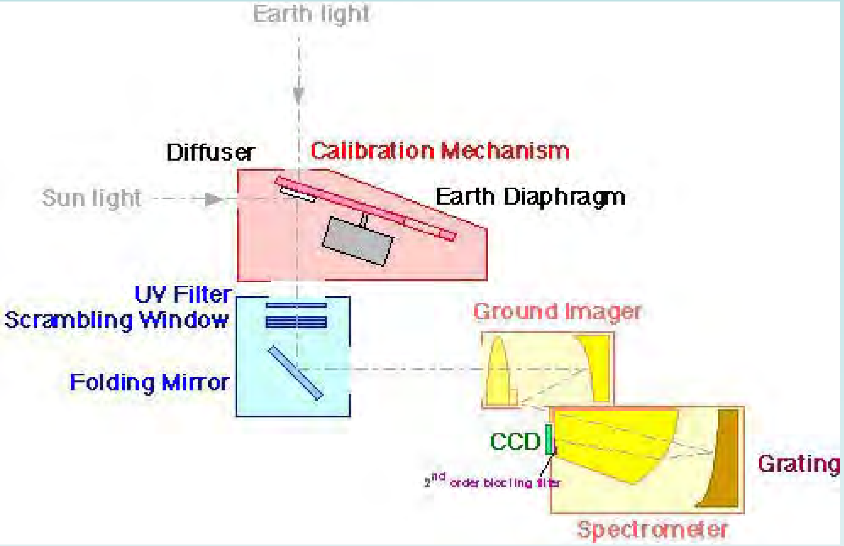
Uncertainties

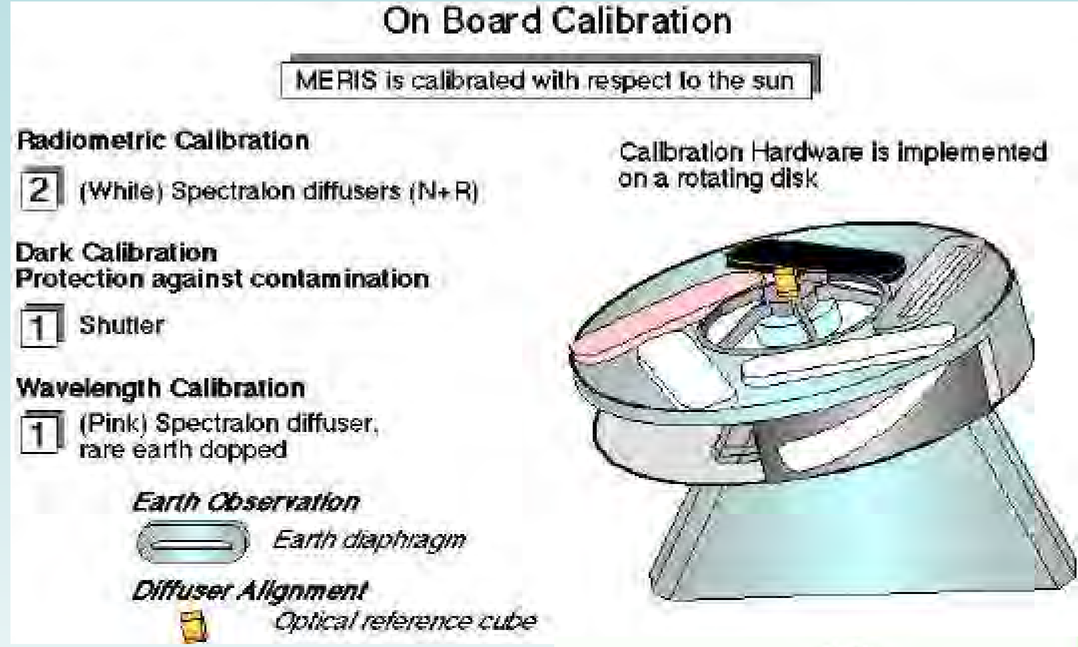
- **Calibration of a space sensor**
- Variability of atmosphere and specular reflectance
- Factors influencing the TOA radiance spectra
- The variability of water reflectance
- Uncertainty due to the bio-optical model
- Sensitivity, ambiguities and co-variances
- Strategies to determine out of scope conditions and uncertainties
- Conclusions

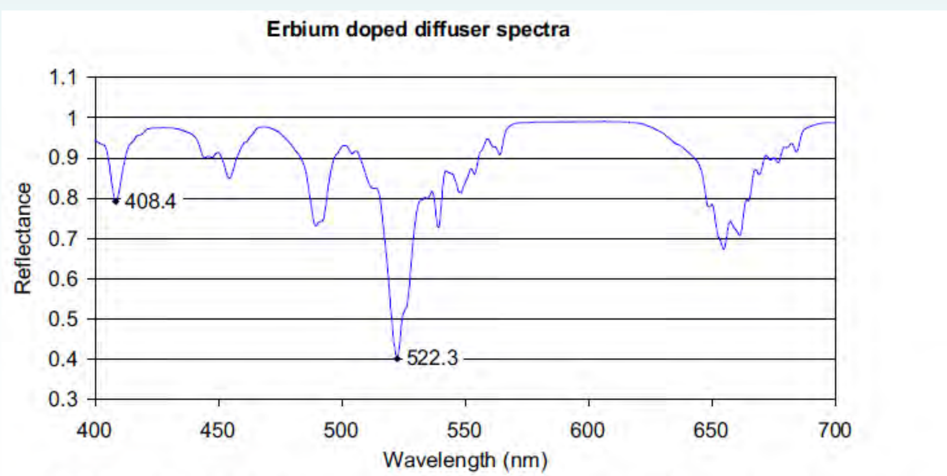
Calibration of the Space Sensor

- Overview
  - On board calibration
  - Vicarious calibration
  - Radiometric calibration
  - Spectral calibration
  - Dark signal
  - Linearity
  - stability

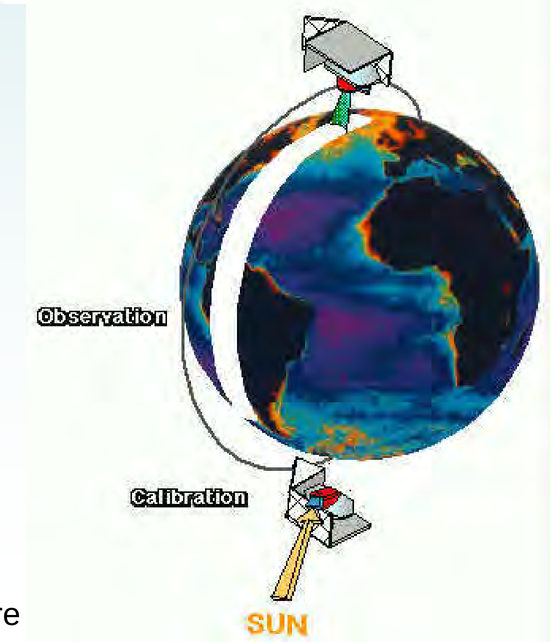
Calibration of MERIS



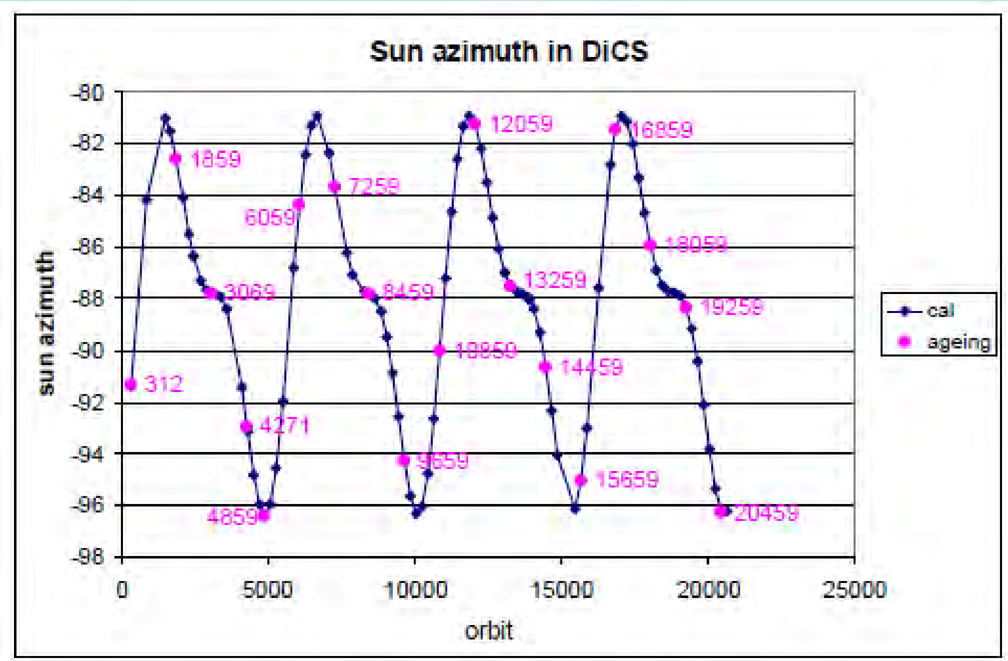


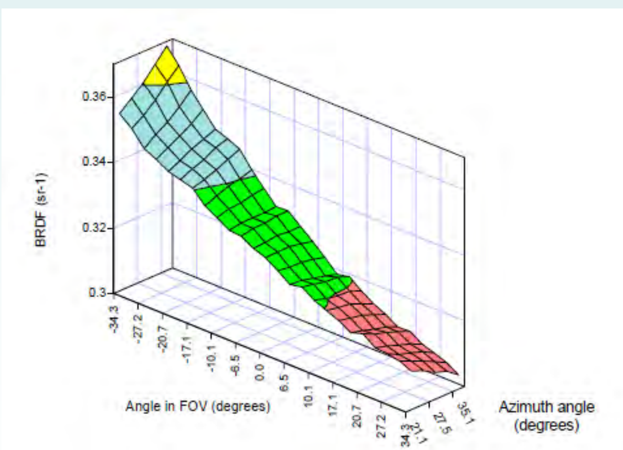


l: Erbium doped Spectralon™ Diffuser reflection spectrum.



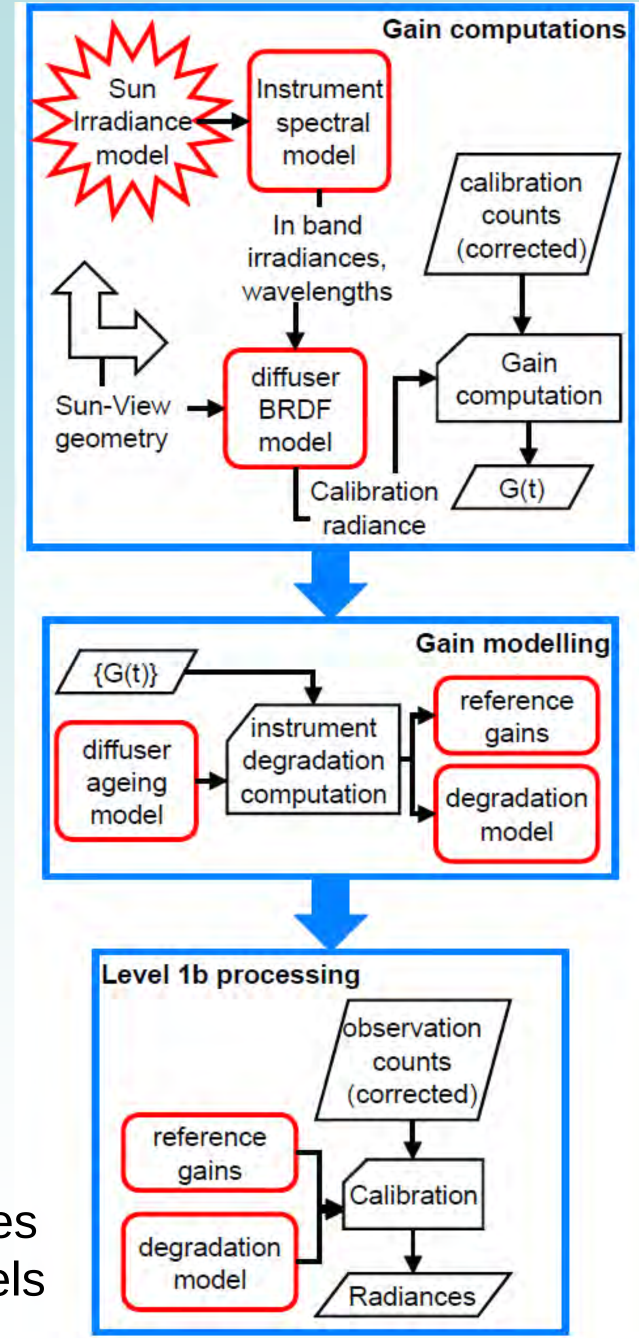
Calibration procedure





Diffuser plate 1 BRDF at 410 nm for four illumination conditions corresponding to different times throughout the year

Measurements of Diffuser 1 (blue diamonds) and diffuser 2 (red circles) are shown as Sun Azimuth angle vs. orbit number. Orbit scale can be converted into time with the approximate ratio of 5000 orbits per year.



Red indicates use of models

Bourg & Delwart, 2006

Long term Calibration

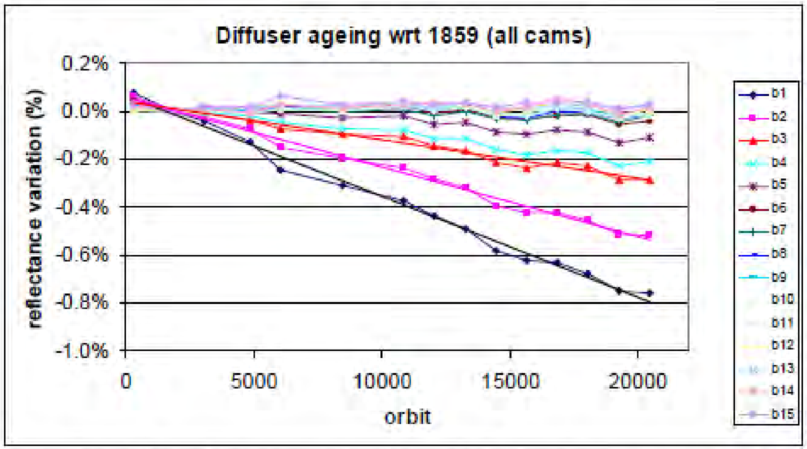


Figure 10: relative evolution of diffuser response ratio.

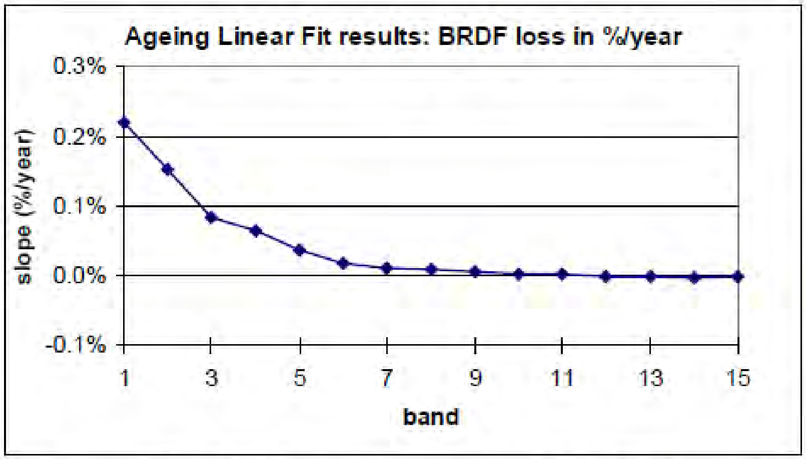
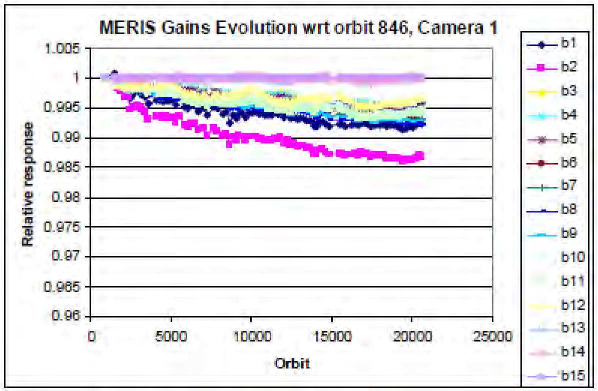
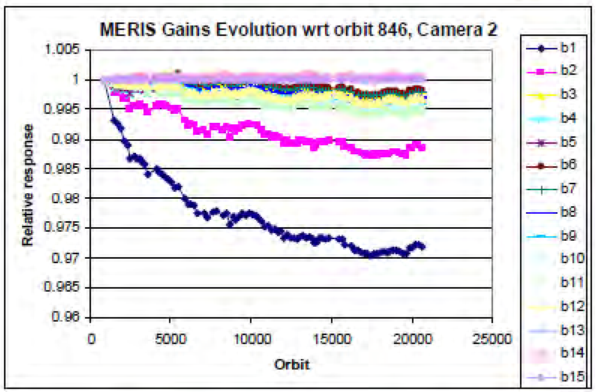


Figure 11: diffuser ageing rate at MERIS channels wavelength, in percent per year.

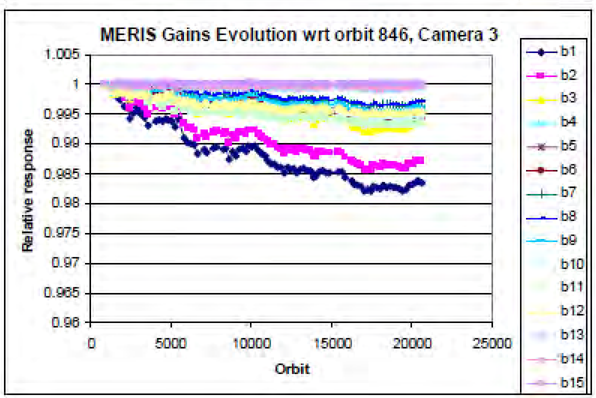
Long term gain development of MERIS



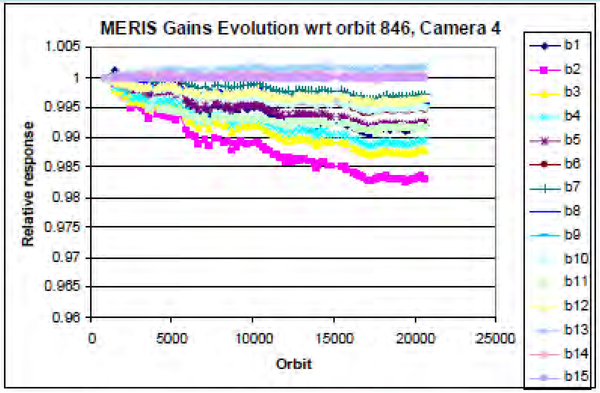
Camera 1



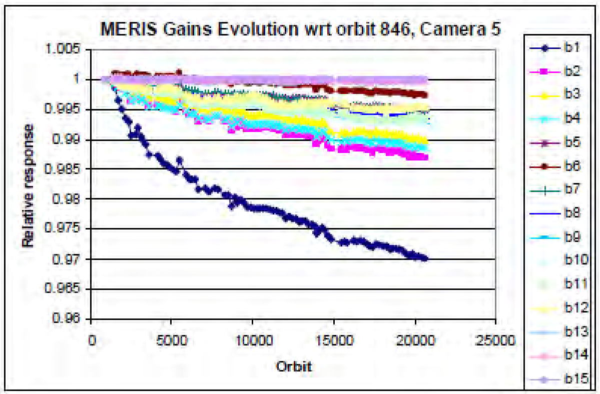
Camera 2



Camera 3



Camera 4



Camera 5

mean per camera optics degradation for all bands.
Cameras 1 to 5 from top to bottom.

Spectral calibration and smile effect MERIS

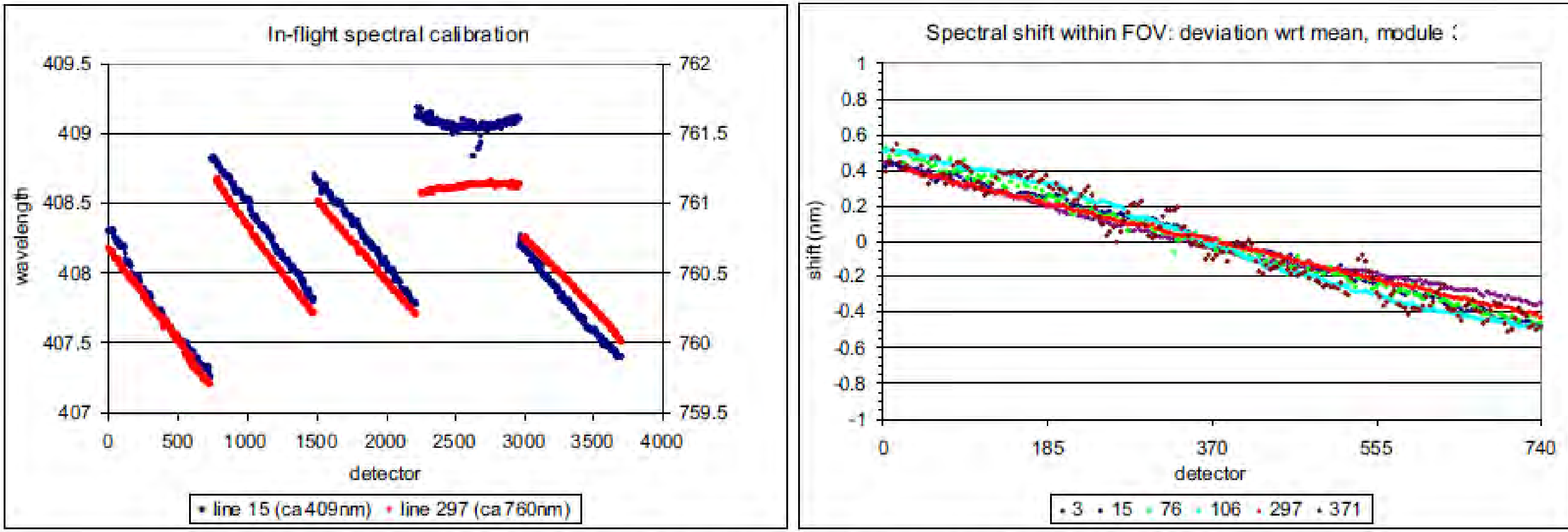


Fig. 12: Spectral calibration for all camera's field of view.

Delwart, Huot, Bourg & Brockmann

Sensor intercomparison

3.1.5 Inter-comparison of MERIS and AATSR

The top of the atmosphere reflectance measured simultaneously by MERIS and AATSR can be seen in fig. 10 below.

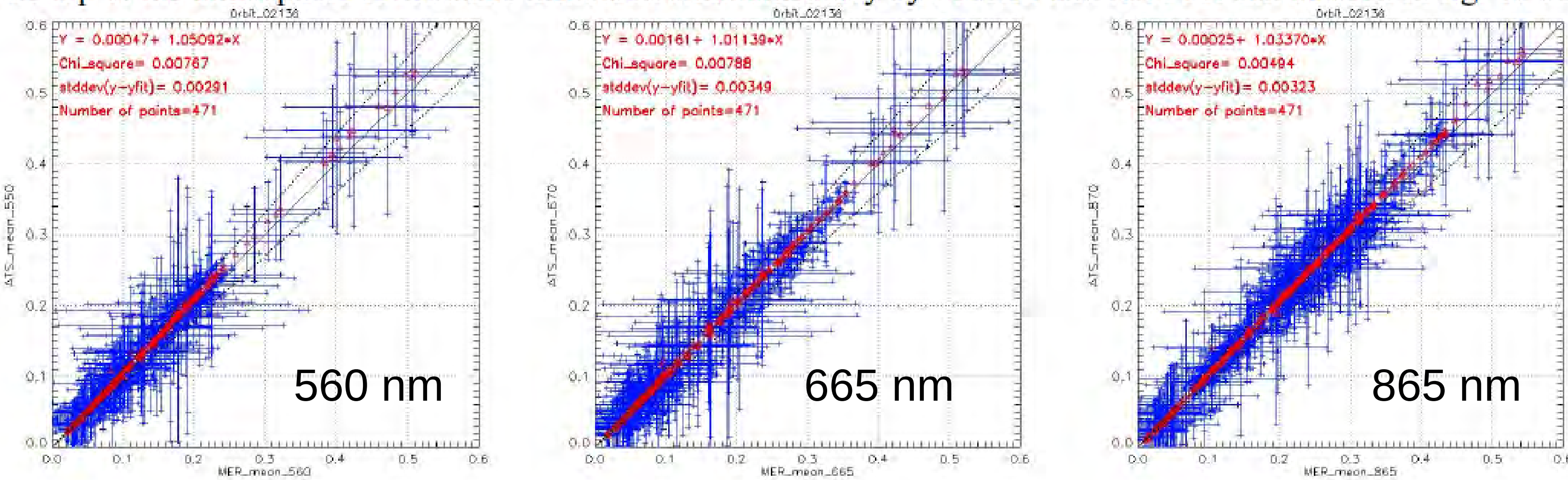
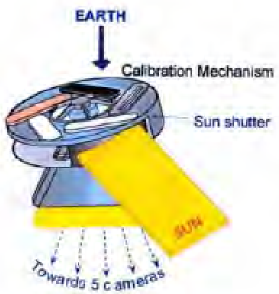


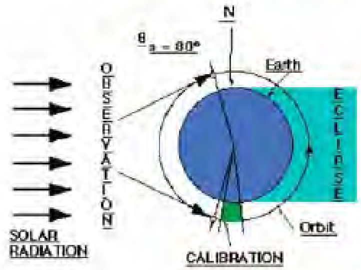
Fig. 10: Comparison of MERIS and AATSR Top of Atmosphere Reflectance on 28 July 2002.

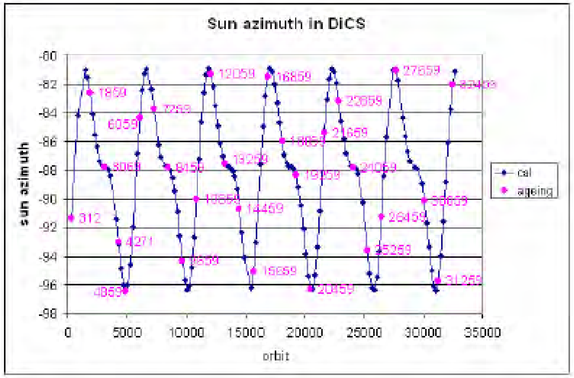
Fig 10 shows the average (red dot) and STD (error bar) computed over macro-pixels of 573 km^2 and compared over a complete orbit. These results shows that both instruments, which are both calibrated using diffusers, compare very well (<6%). It must however be noted that these are only preliminary results, that need to be confirmed statistically over a much larger data set.

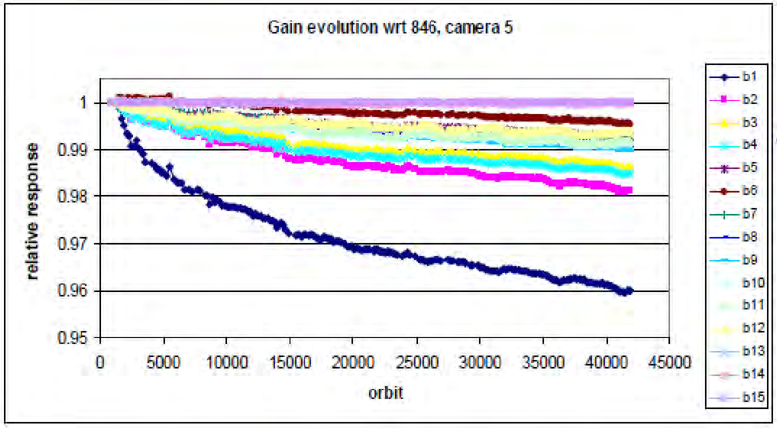
Level 1 radiometric *calibration*

Like MERIS, OLCI performs on board radiometric calibration :
- **Every 2 weeks routine with 1st diffuser**
- **Every 3 months with 2nd diffuser for ageing**









Space environment implies **ageing** of Diffuser and Optics

2nd diffuser to monitor diffuser-1 BRDF ageing

=> Diffuser Aging model

frequent calibration to monitor Instrument degradation

=> instrument degradation model

$$G(t) = G(t_0)\cdot\left(1-\beta\cdot\left(1-\gamma\cdot e^{-\delta t}\right)\right)$$

Degradation Model based on the SeaWifs model (Barnes et al.)

Maximum degradation of 4 % after more than 8 years in space

P. Goryl, ESA

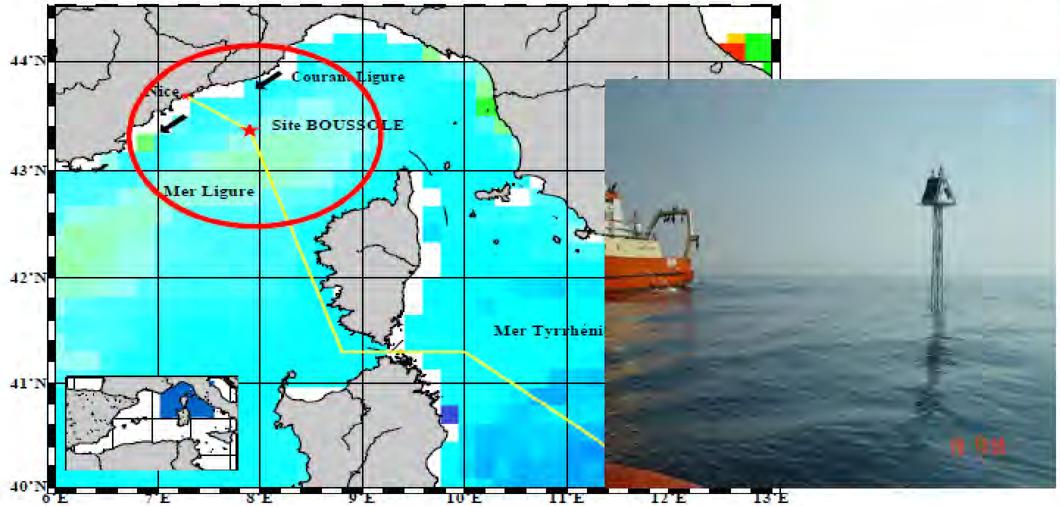
Vicarious calibration or adjustment

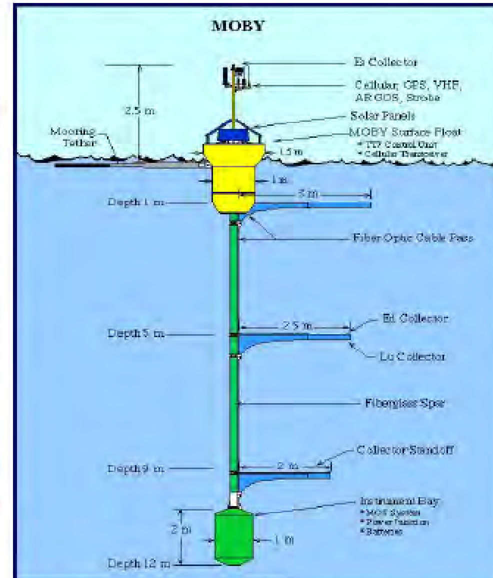
- Using well characterized and calibrated ground target
- Clear atmosphere
- Not only the sensor but the system *sensor / atmospheric correction* is calibrated

- Pros?

- Cons?

Adjustment in the visible





BOUSSOLE / MOBY used for:

→ adjustment in the visible

→ Validation

P. Goryl

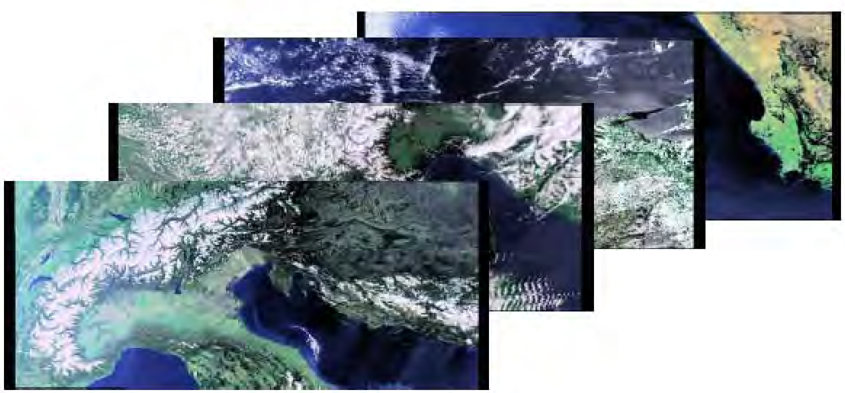
validation DataBase

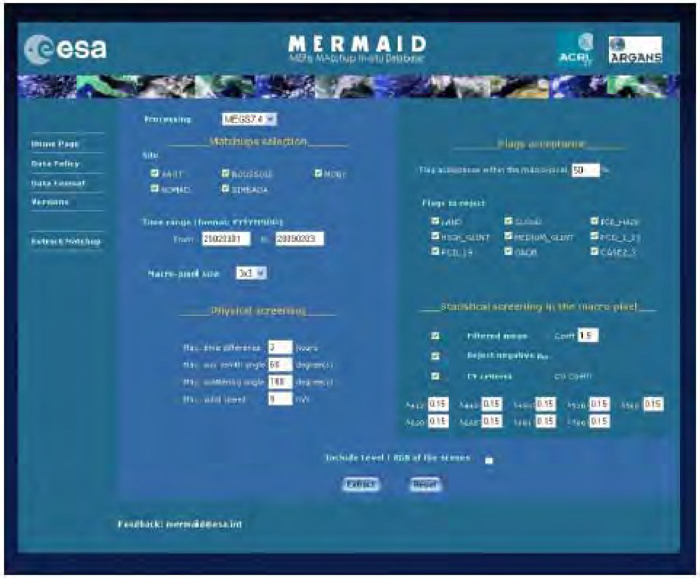
MERMAID

- A centralised database of concurrent MERIS acquisitions and in-situ optical measurements (protected by a standard data policy)

- Available to Ocean Colour researchers working within the MERIS mission: MERIS QWG, MVT and any collaborating PI

- Accessible on the web with a simple interface and standard data format





P. Goryl, ESA

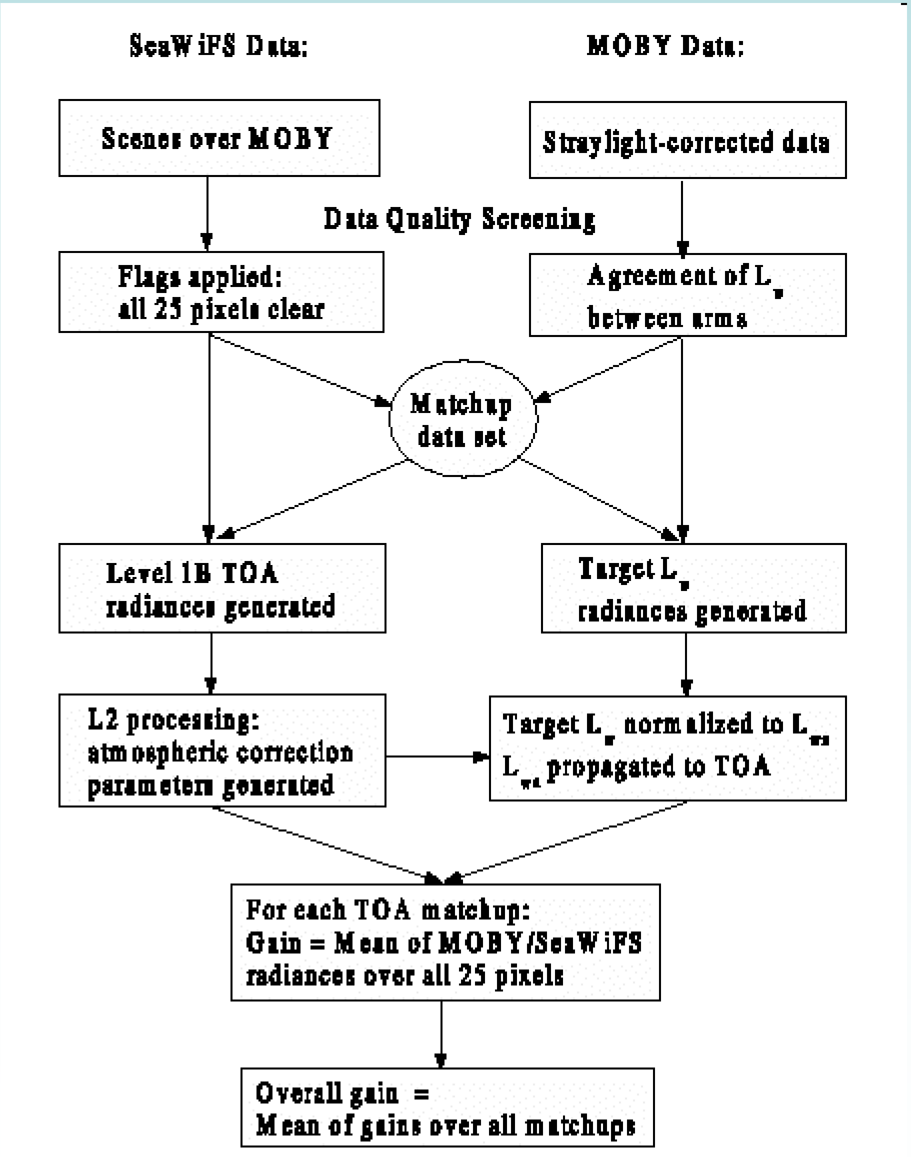
Vicarious calibration

- The top of the atmosphere (TOA) radiances for each band measured by MODIS or SeaWiFS are compared with MOBY (Marine Optical Buoy) insitu match-up radiance values that have been propagated to the TOA using the current atmospheric correction parameters.

- It is assumed that the values at MOBY have only small uncertainties and predict what the values measured at the satellite should be. Therefore the difference between the satellite values and the MOBY values gives us the calibration gains.

- Every time a change is made to the data processing methodology, the vicarious gains have to be updated. Once calculated, the gains are then utilized in the data processing stream.

- This diagram demonstrates how SeaWiFS (or MODIS) and MOBY data are used to compute the vicarious gains from ratios of TOA radiances.



http://oceancolor.gsfc.nasa.gov/VALIDATION/gains.html

Operational Vicarious Gain Coefficients

MODIS Aqua N=39	412 nm	443 nm	488 nm	531 nm	551 nm	667 nm	678 nm	748 nm	869 nm
Gain	0.9710	0.9848	0.9795	0.9870	0.9850	0.9797	0.9776	0.9855	1.00
Stdev	0.0086	0.0079	0.0071	0.0066	0.0057	0.0039	0.0042	0.0122	0.00

SeaWiFS N=147	412 nm	443 nm	490 nm	510 nm	555 nm	670 nm	765 nm	865 nm
Gain	1.0368	1.0132	0.9918	0.9982	0.9993	0.9729	0.9716	1.00
Stdev	0.0084	0.0084	0.008	0.0082	0.0079	0.0061	0.0086	0.000

http://oceancolor.gsfc.nasa.gov/VALIDATION/operational_gains.html

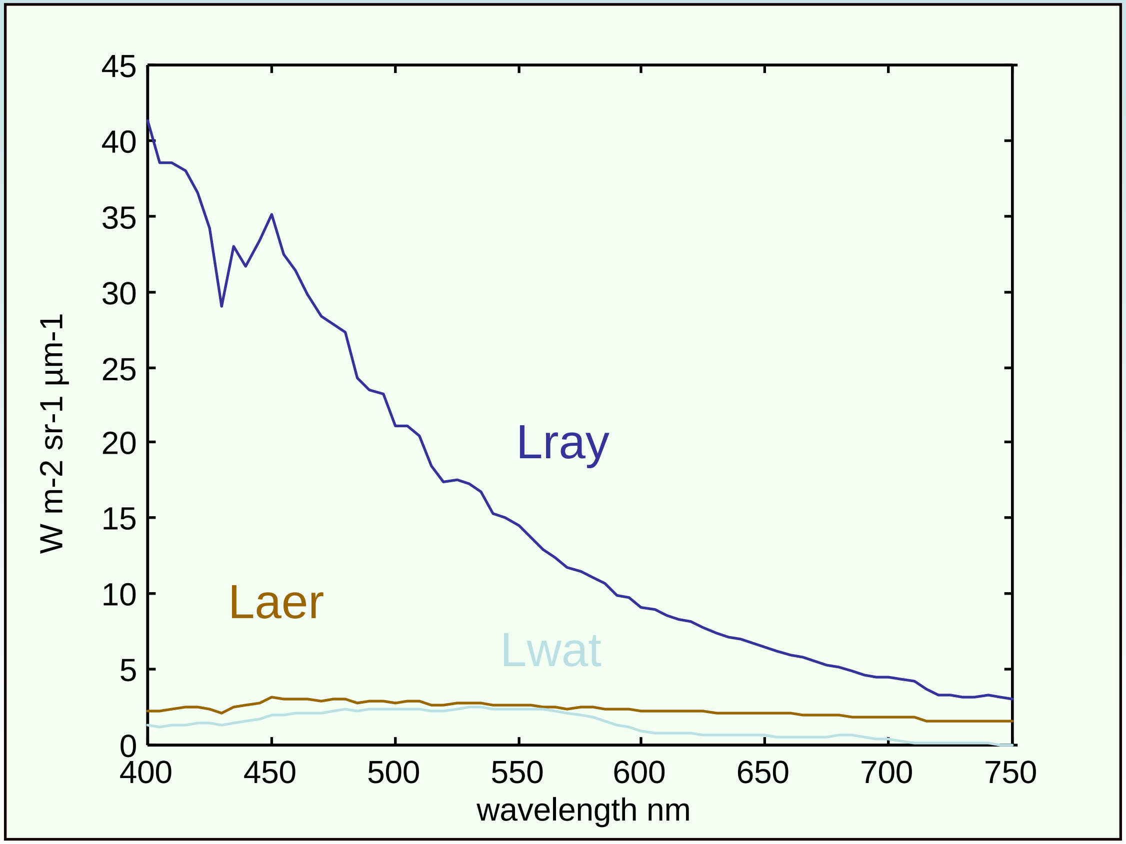
Conclusion calibration of sensor

- Requirement for radiometric calibration very high (~ 1% accuracy)
- Long term performance and stability has to be monitored
- Gains have to be adjusted
- Remaining issues (MERIS): non linearity dark signal, straylight
- To get water reflectances of high accuracy atmospheric correction has to be included (vicarious adjustment or calibration)
- Issues of vicarious calibration:
  - Angular problems, different sun zenith angles
  - Different aerosols
  - Accuracy of reference ground measurements

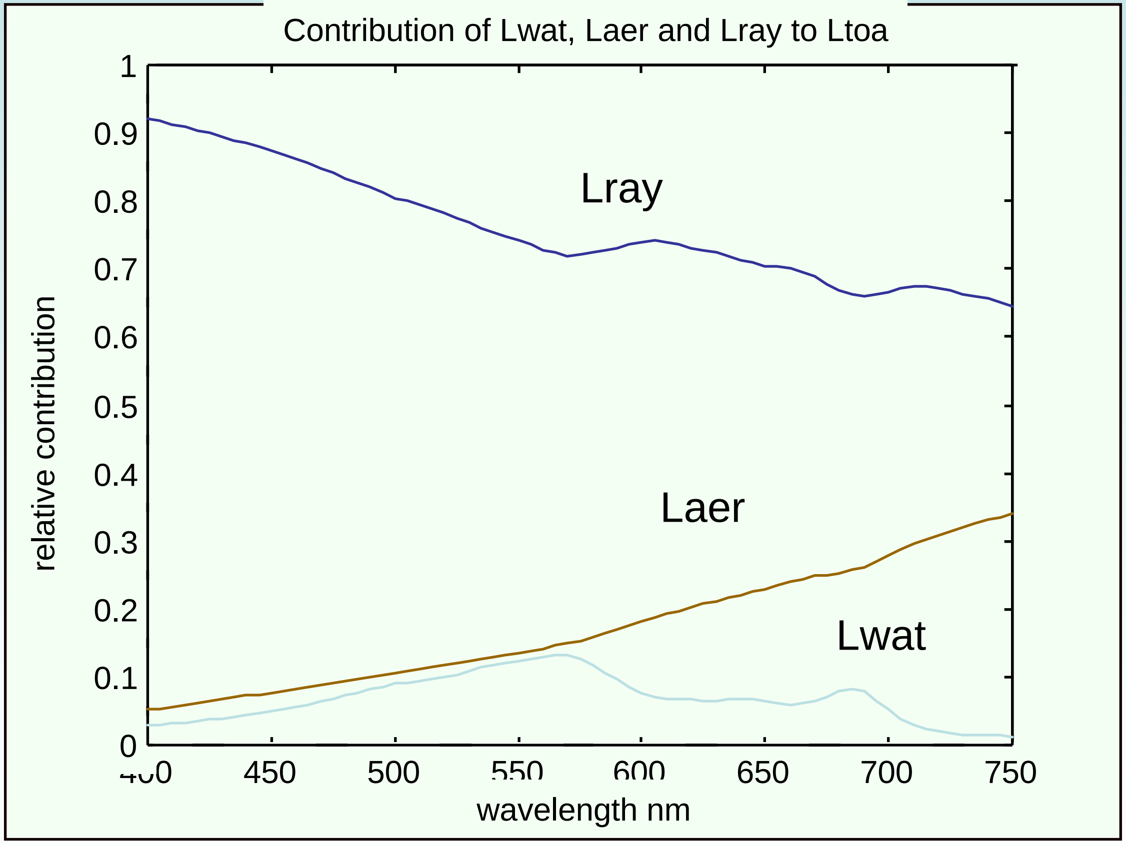
Atmosphere and water surface

- Large variety of aerosols
  - Use of selected aerosol types (models)
- Thin clouds (cirrus, contrails)
- Sub-pixel clouds
- Cloud shadows
- Absorption by atmospheric gases: water vapour, oxygen, ozone, NO2
- Foam and white caps
- Waves
- Sky and sun glint

Radiances at Top of Atmosphere (TOA)



The composition of the Radiance Spectrum at Top of Atmosphere



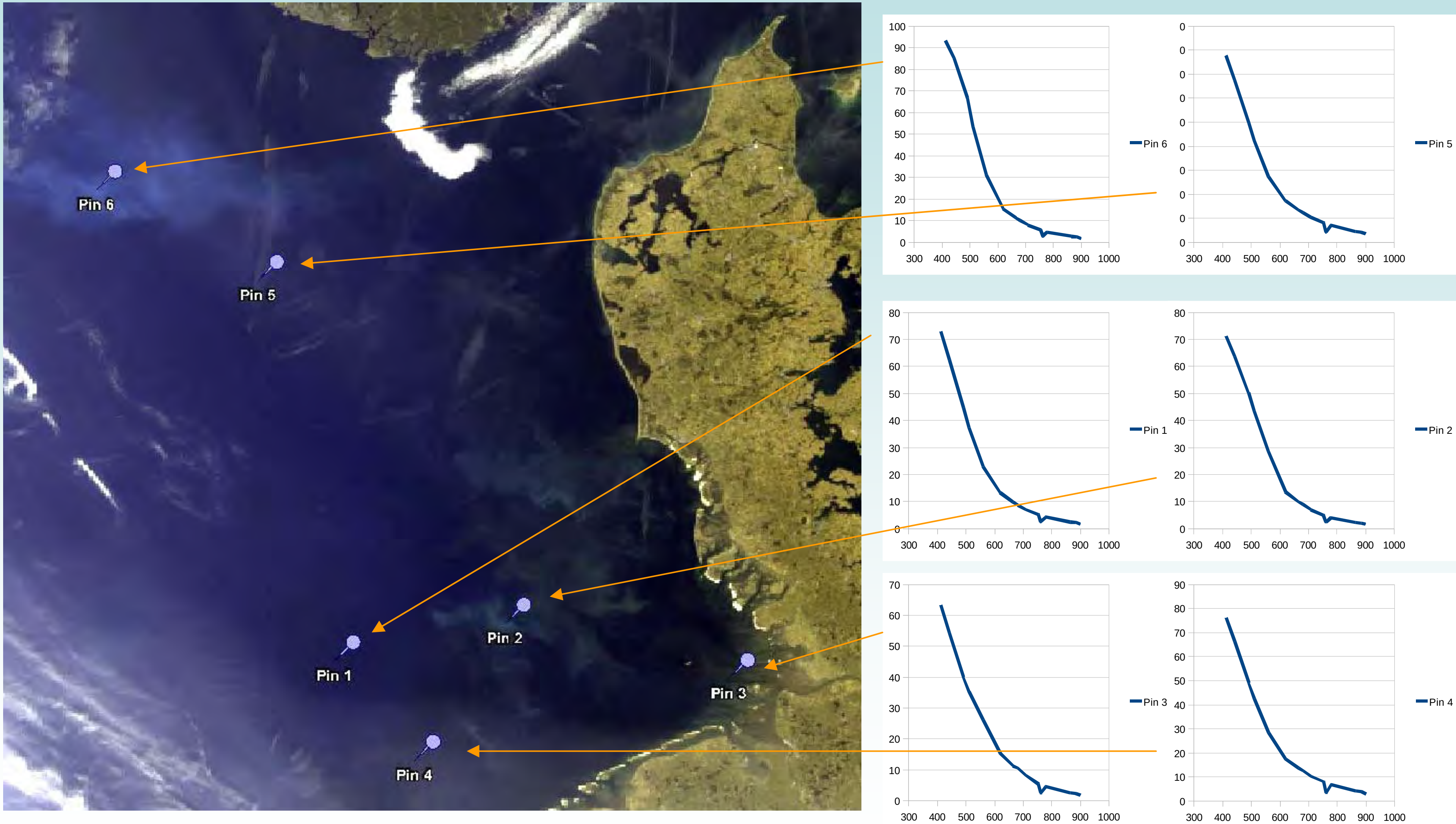
Relative contribution to TOA radiance

water leaving radiance: Lw

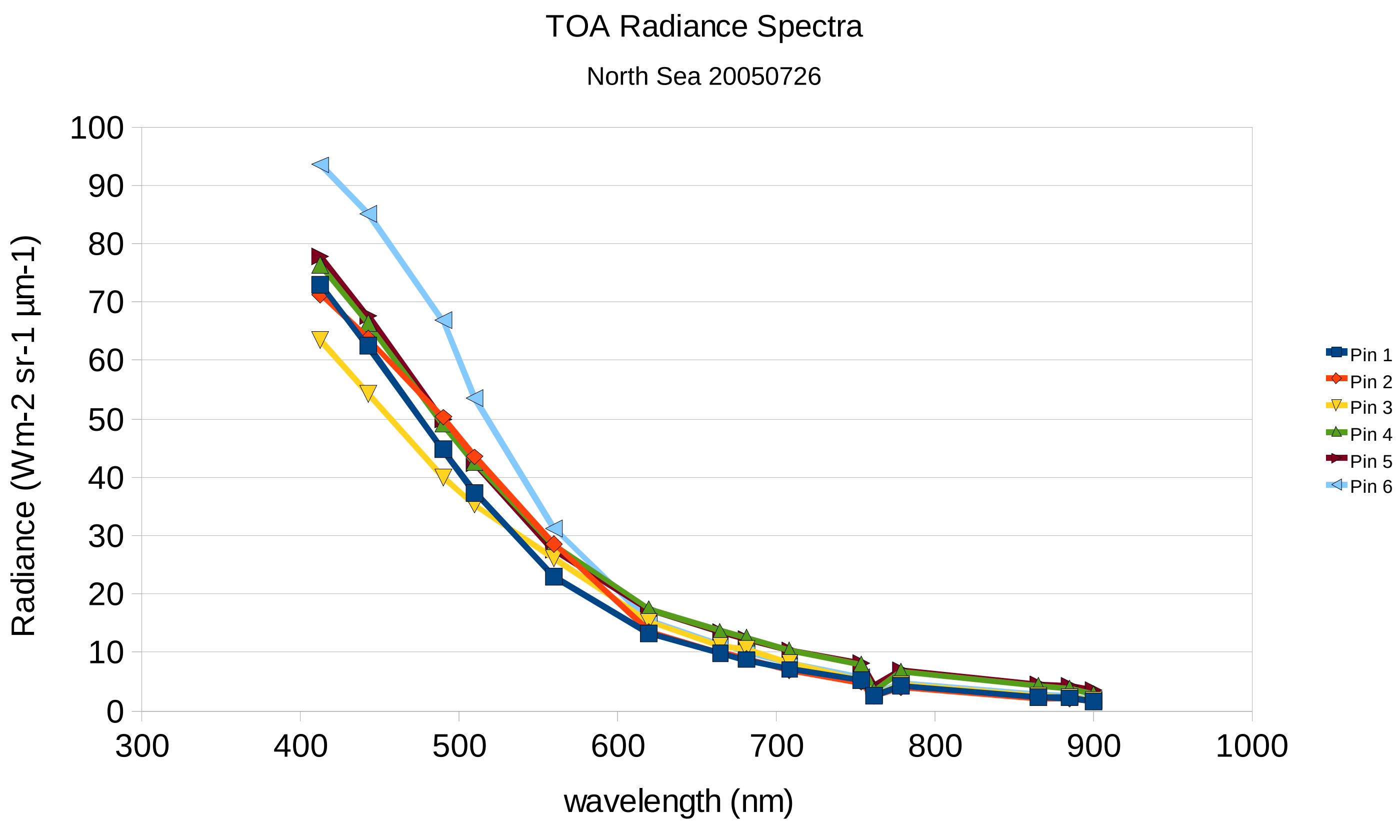
aerosol path radiance: Laer

Rayleigh path radiance: Lray

Spectral Variability top of atmosphere



The Information: radiance spectra at top of atmosphere

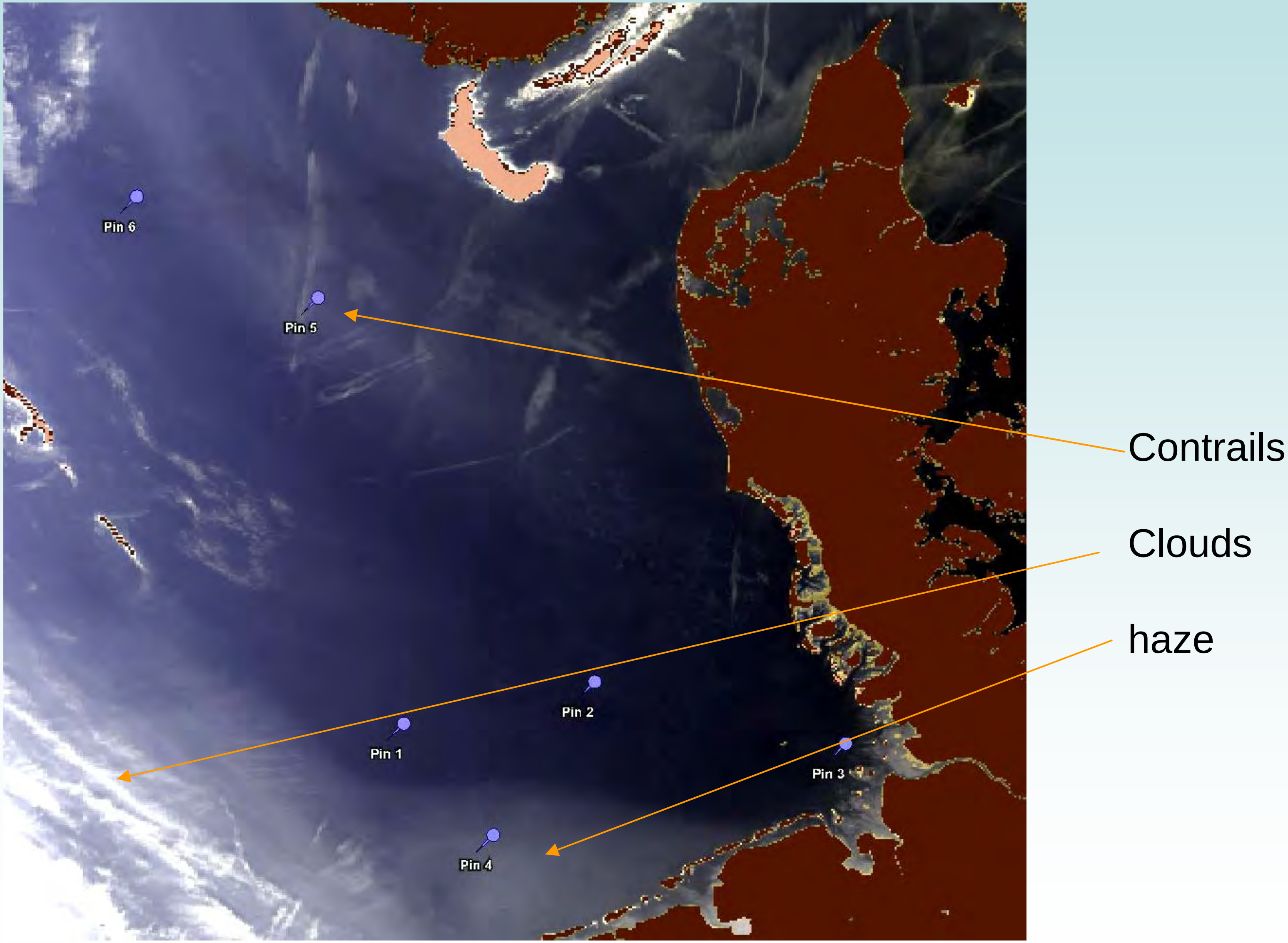


Aux data:

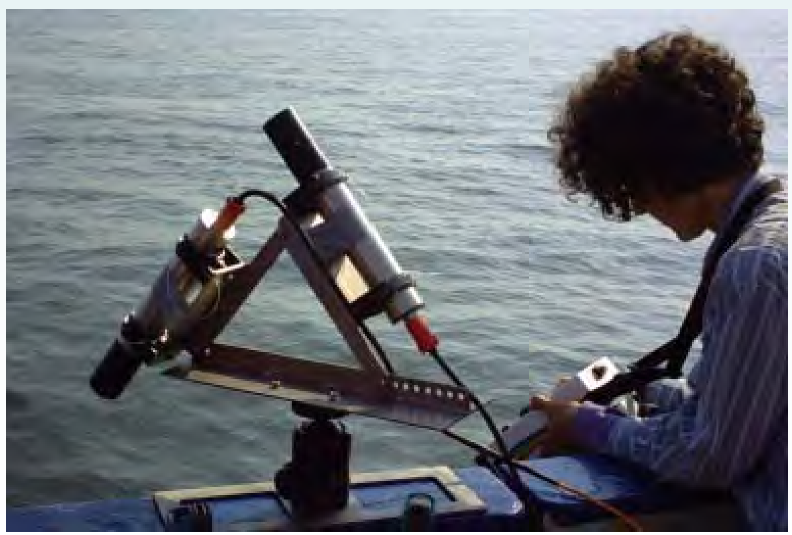
- Sun zenith angle
- Sun azimuth
- View zenith
- View azimuth
- Surface pressure
- Ozone
- Wind

- Expected ranges
- Knowledge about optical properties

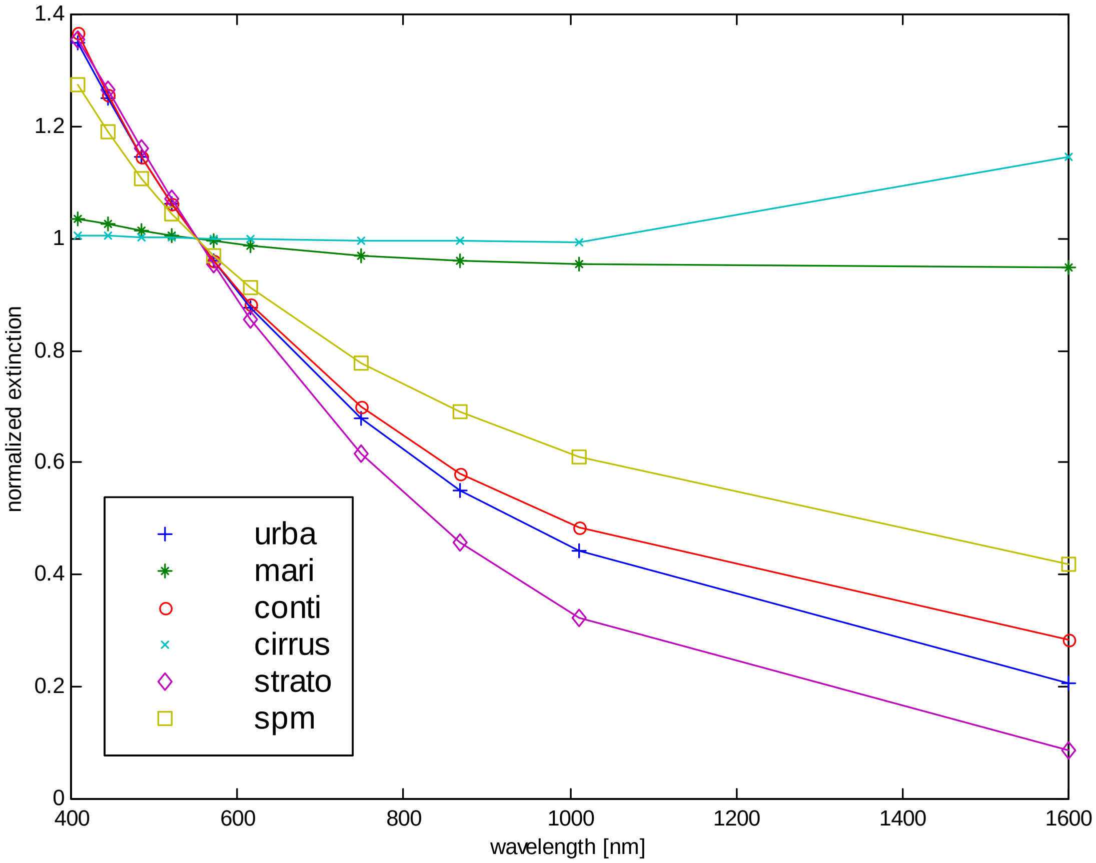
The dominant signal:
Path radiance reflectance over coastal water



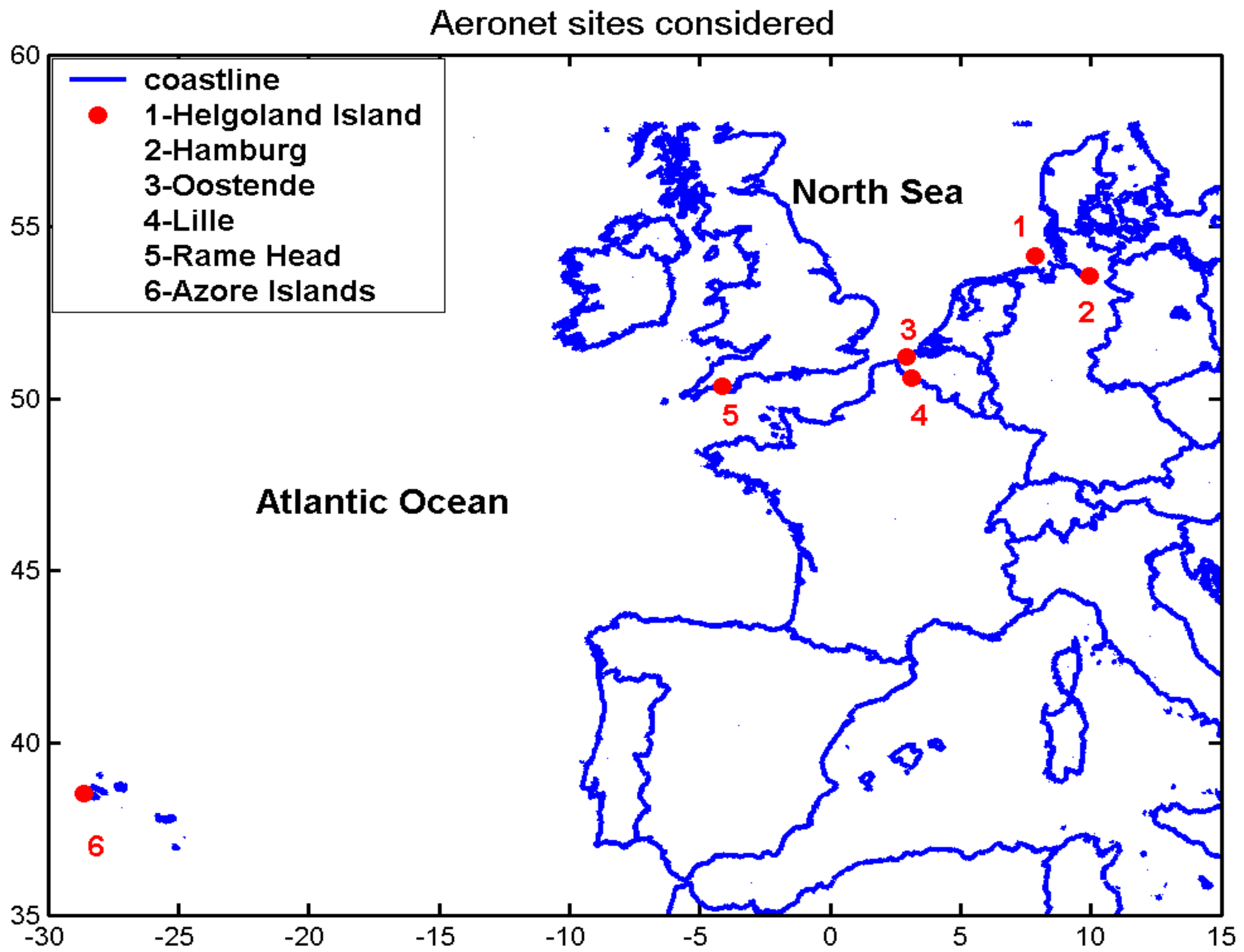
Instruments used for validation



Aerosol Extincion in Model Atmosphere

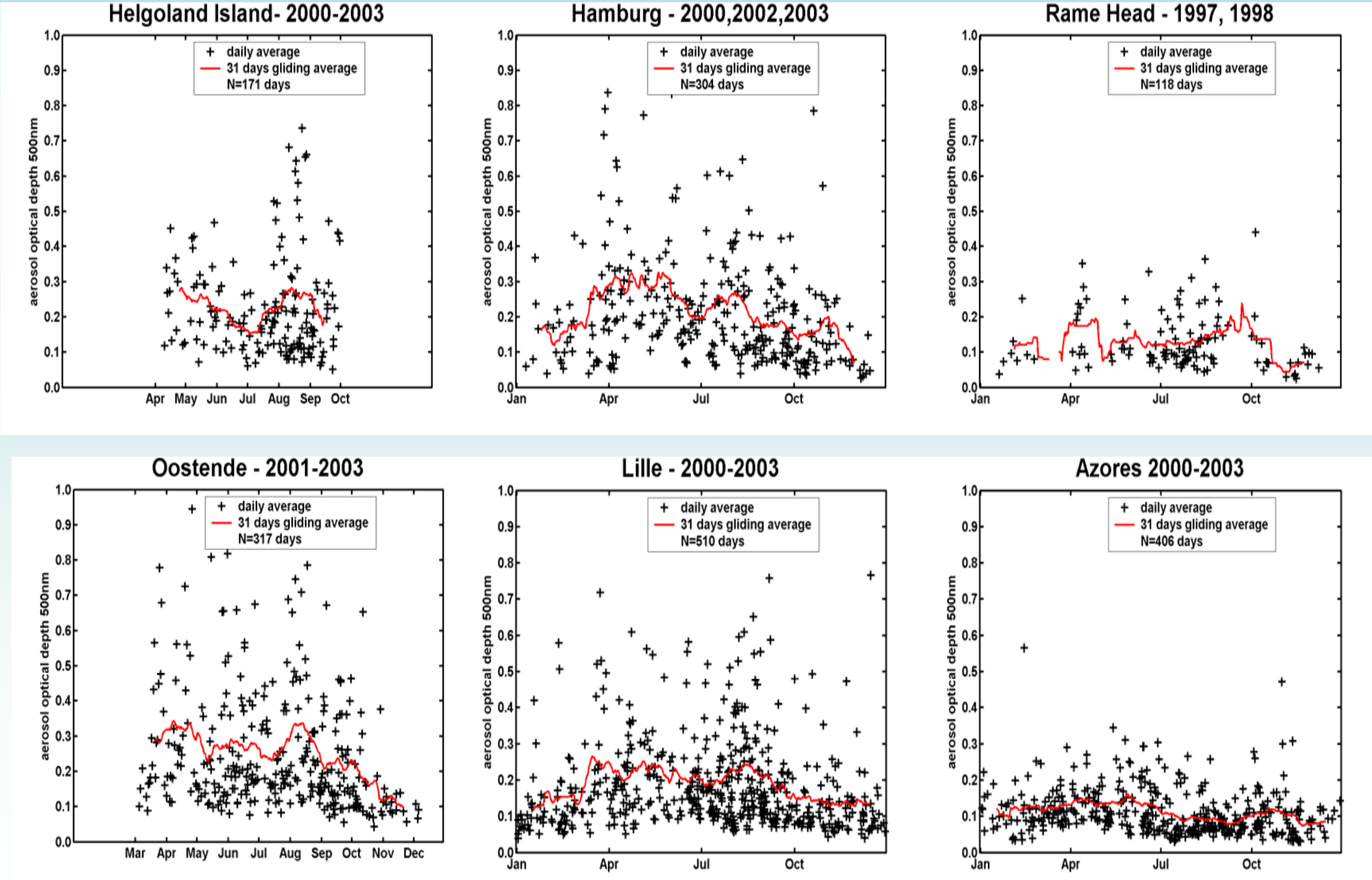


normalized at 550 nm, urban aerosol with 50%, maritime with 99% humidity

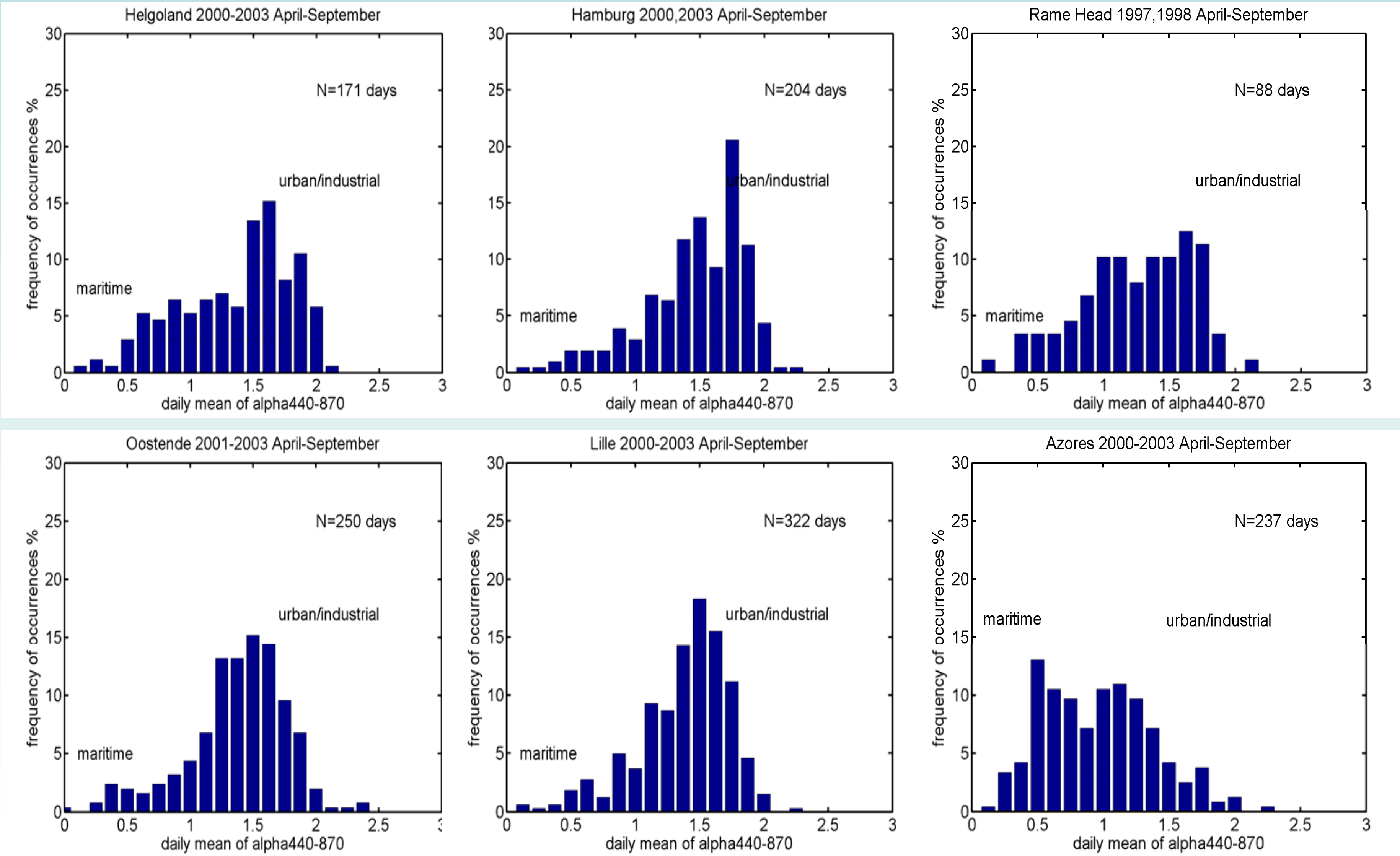


Aeronet sites considered
coastline
1-Helgoland Island
2-Hamburg
3-Oostende
4-Lille
5-Rame Head
6-Azore Islands
North Sea
Atlantic Ocean
1
2
3
4
5
6
60
55
50
45
40
35
-30
-25
-20
-15
-10
-5
0
5
10
15

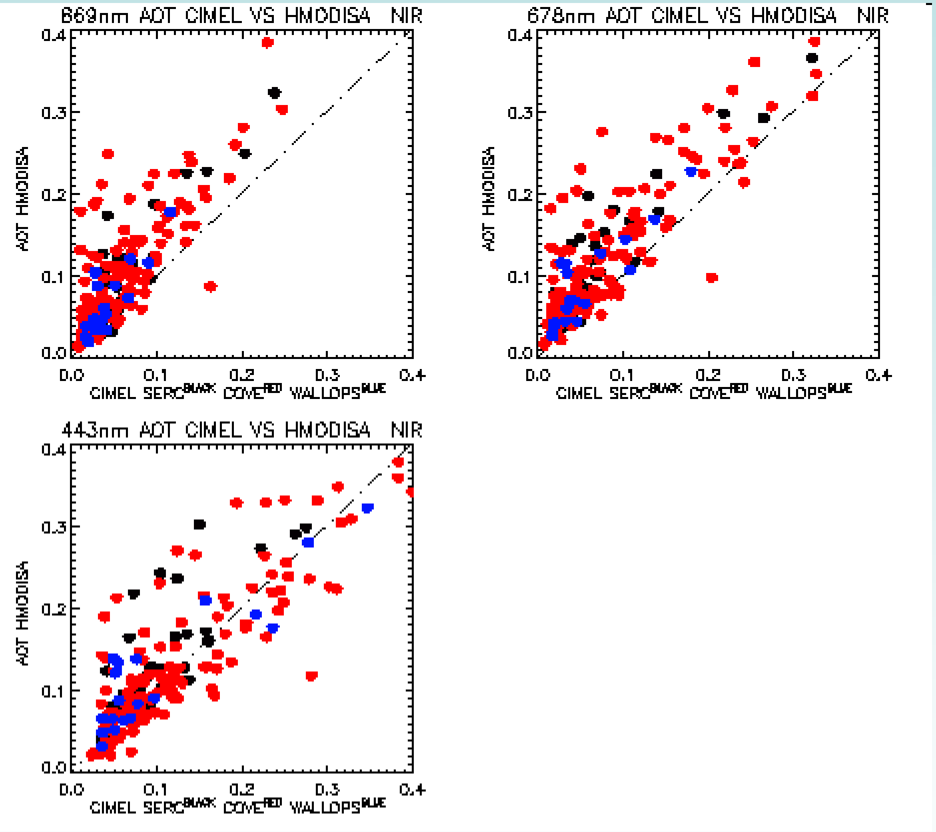
Annual variation of the Aerosol optical depth 500nm



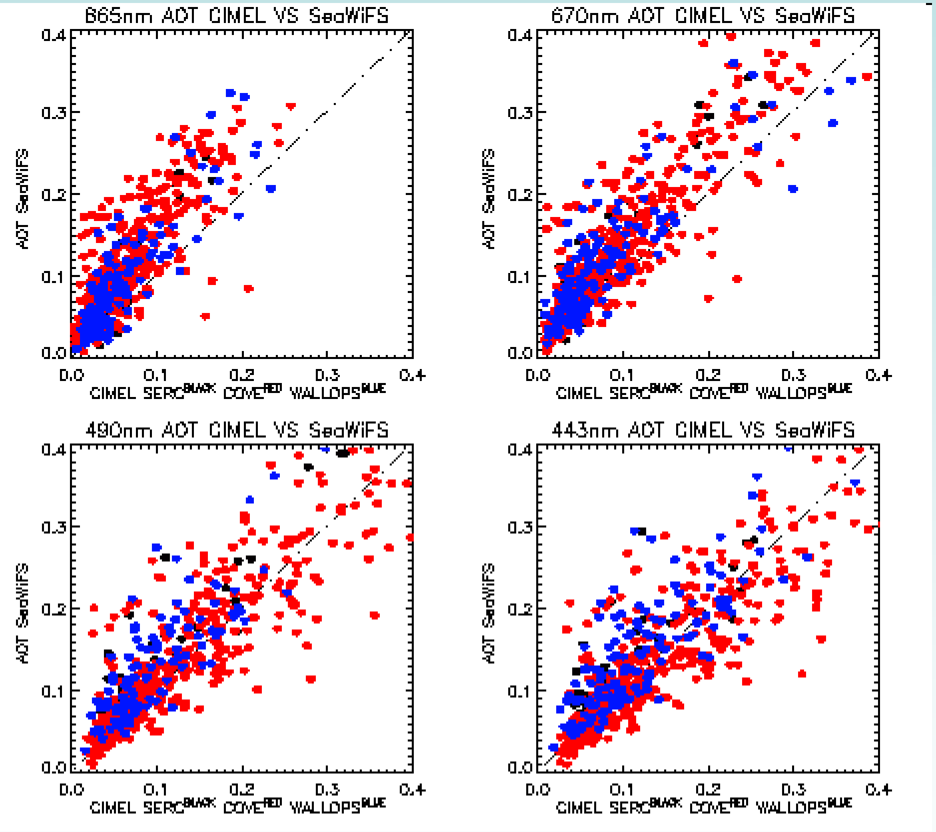
Frequency of occurrences for Angstrom parameter α440_870



AOT comparisons between MODIS-Aqua/SeaWiFS and AERONET CIMEL measurements



MODIS

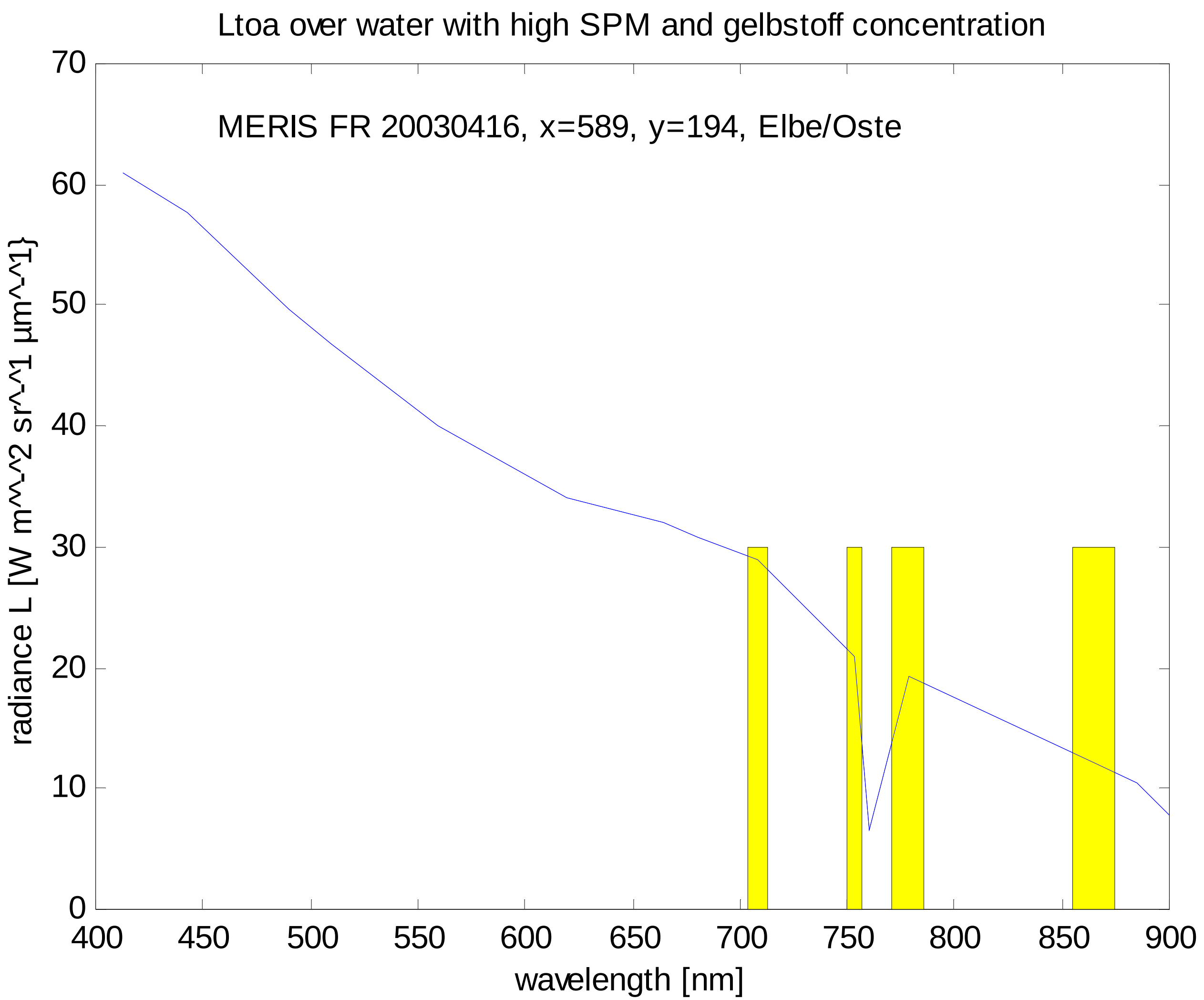


SeaWiFS

Operational processing and aerosol models

http://oceancolor.gsfc.nasa.gov/staff/ewa/aerosol.html

Bands for atmospheric correction



Aerosol models

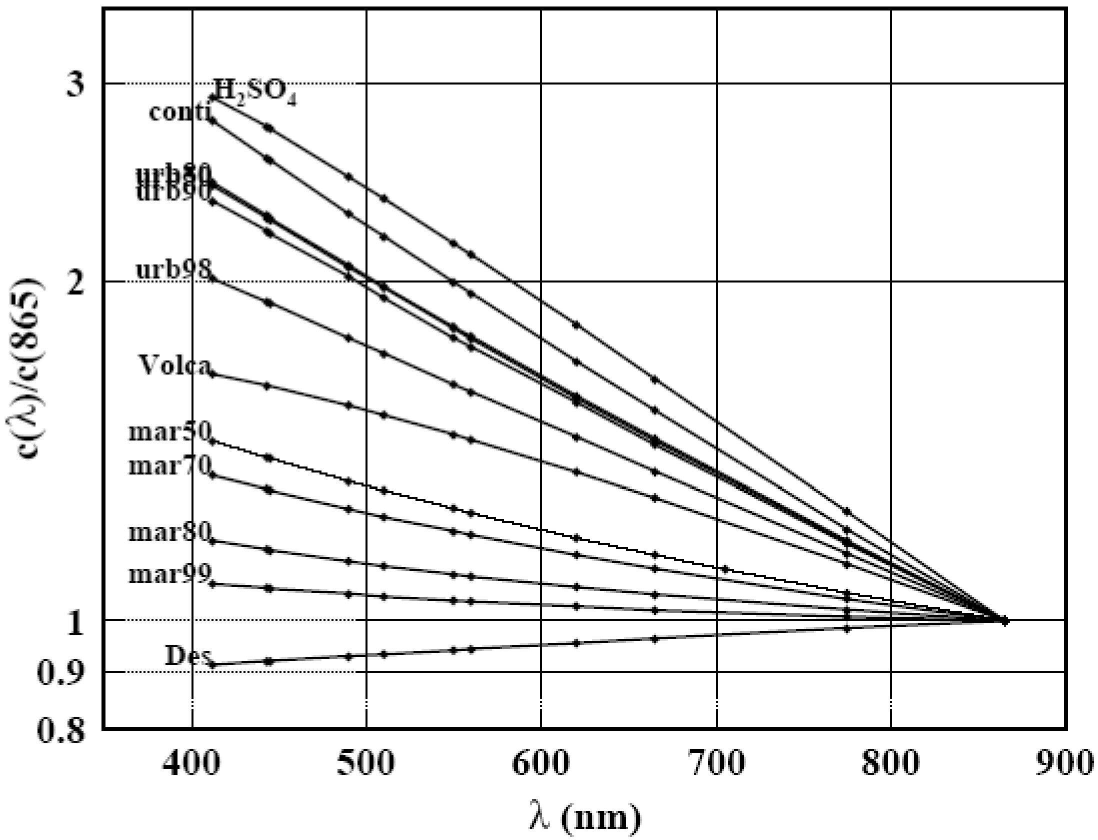
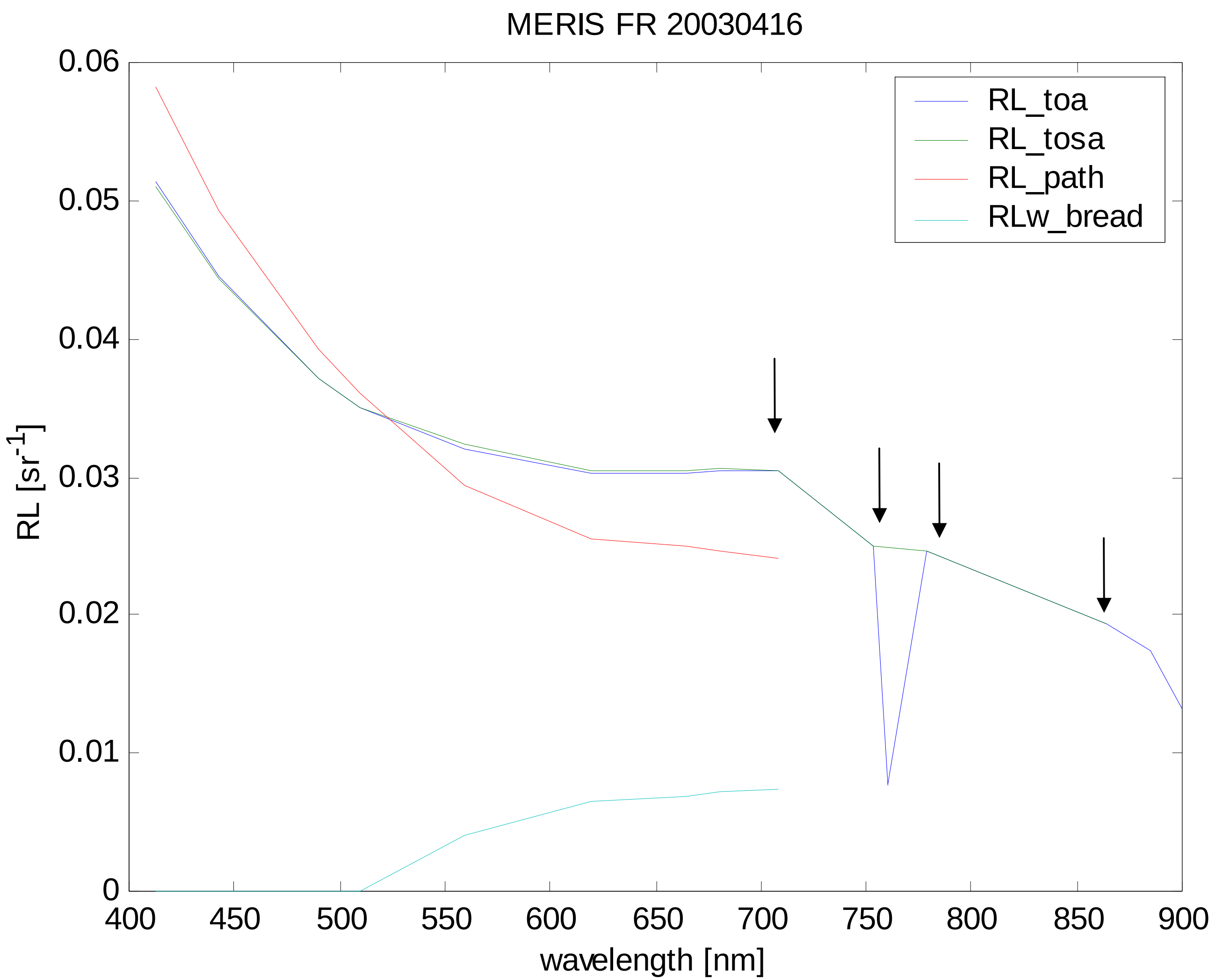


***Figure 3.5** : the ratio c(λ)/c(865) as a function of wavelength (linear-log scale), and for several aerosol models selected for the present study*

("mar" is the maritime model for various relative humidities, "urb" is the urban model, etc..).

Antoine & Morel, MERIS ATBD

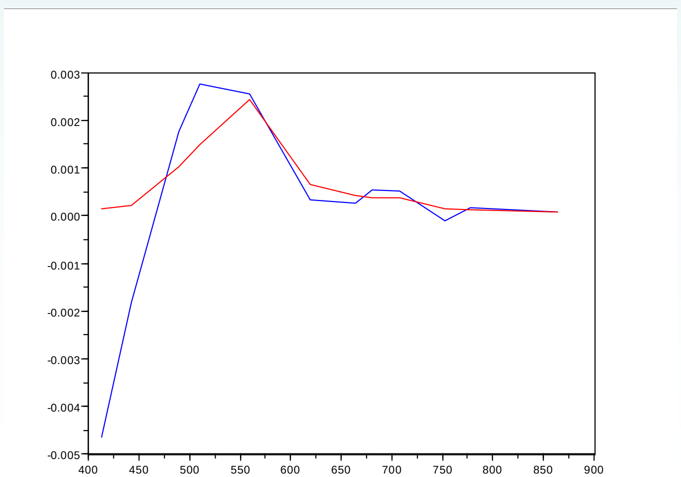
Strange Spectra producing negative reflectances

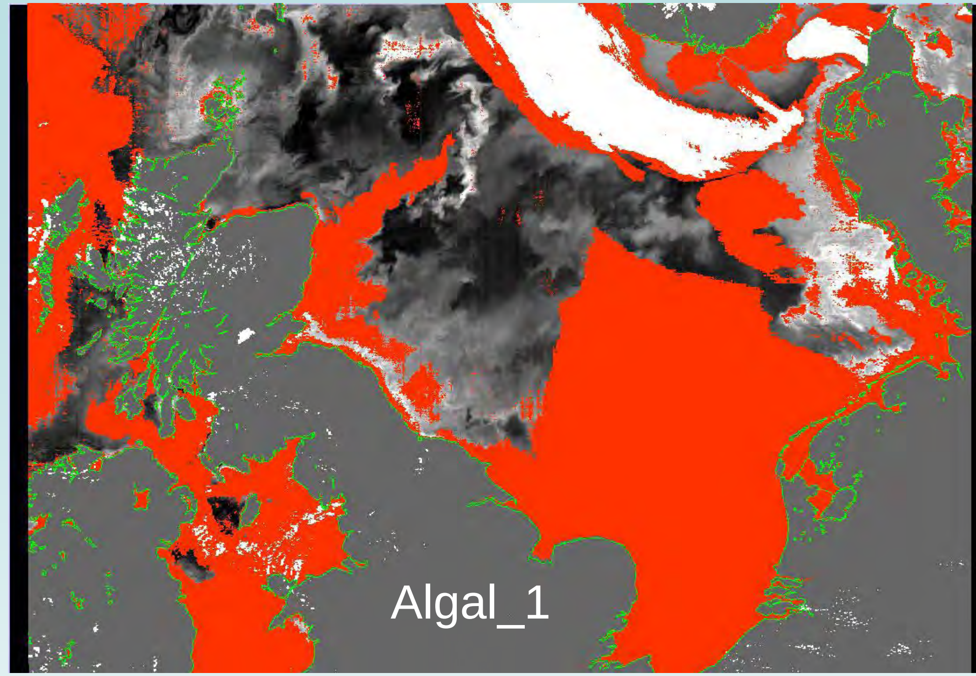


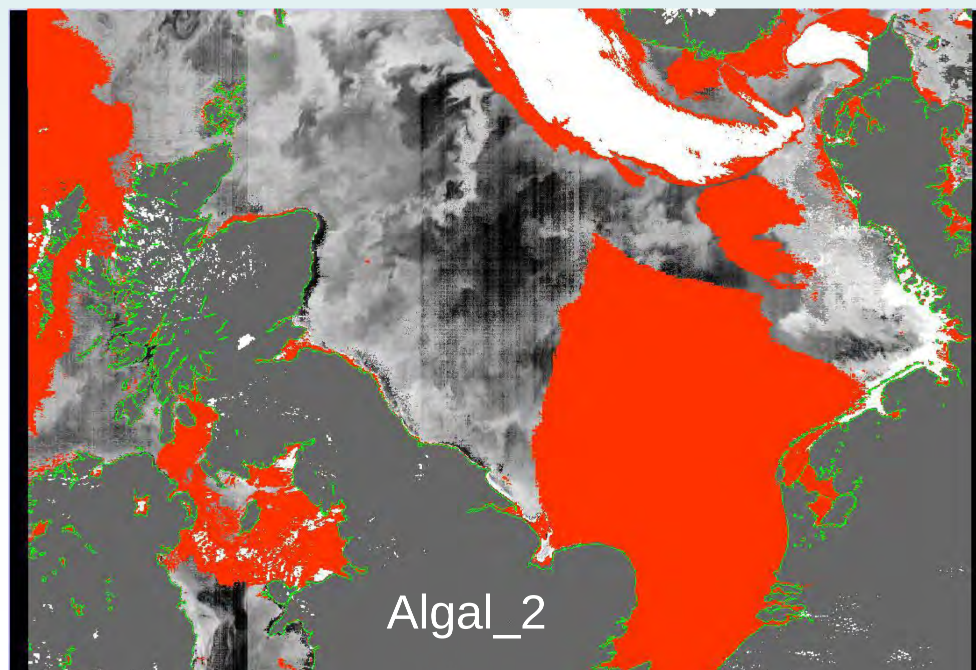
Main Problems

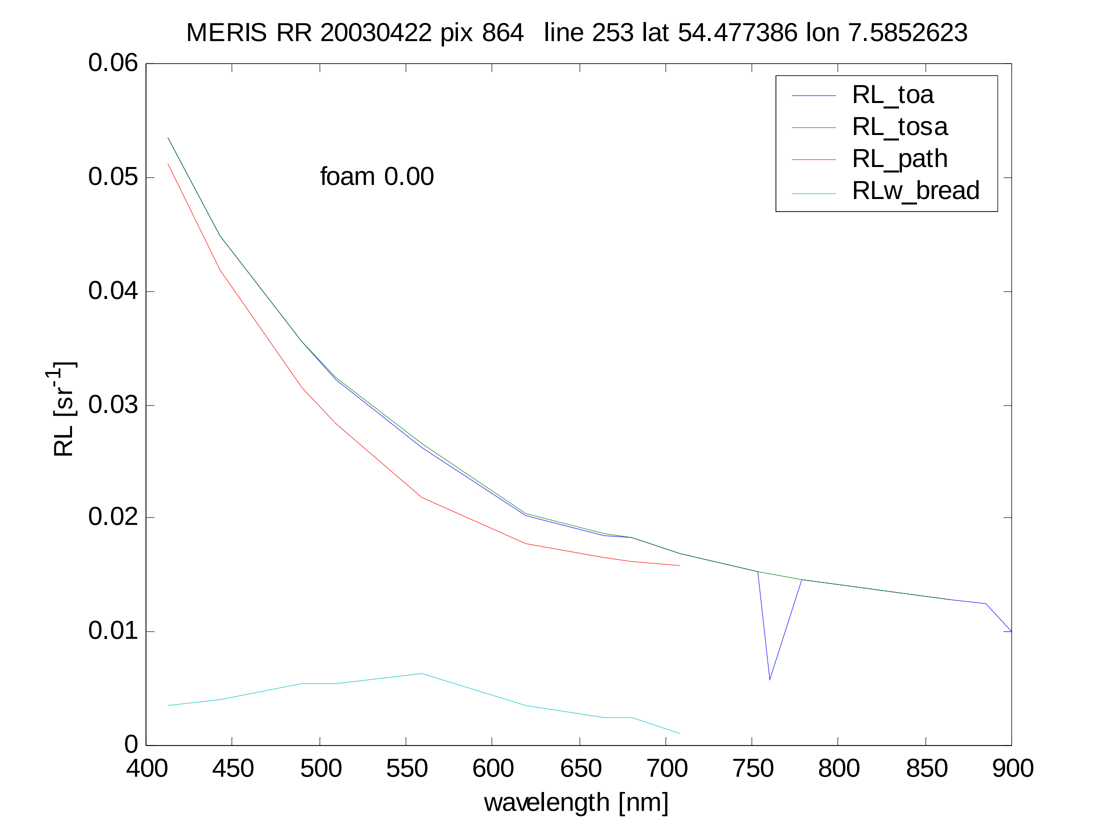
- Atmospheric correction often not sufficient for all 9 bands
- Partly bands 1-2 negativ, or bands 7,8,9 noisy (in case 1 water)

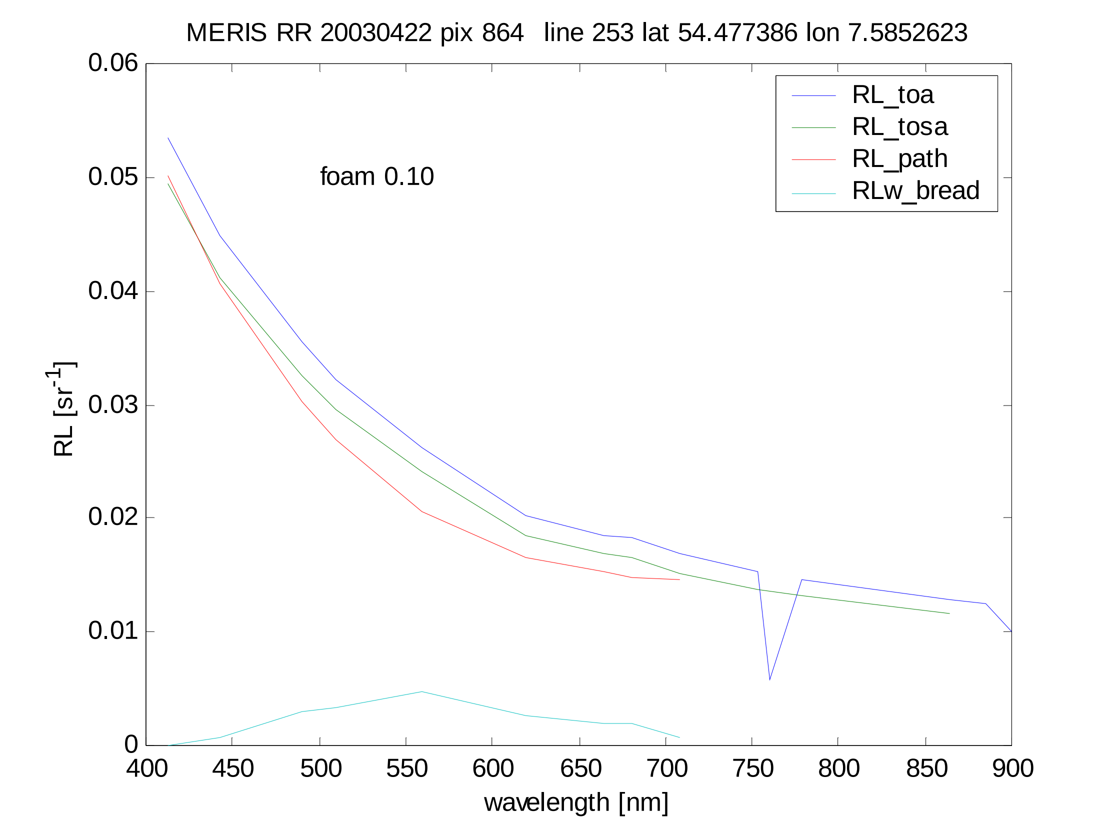
- Result:
  - Noise in data
  - Wrong ys or chl data

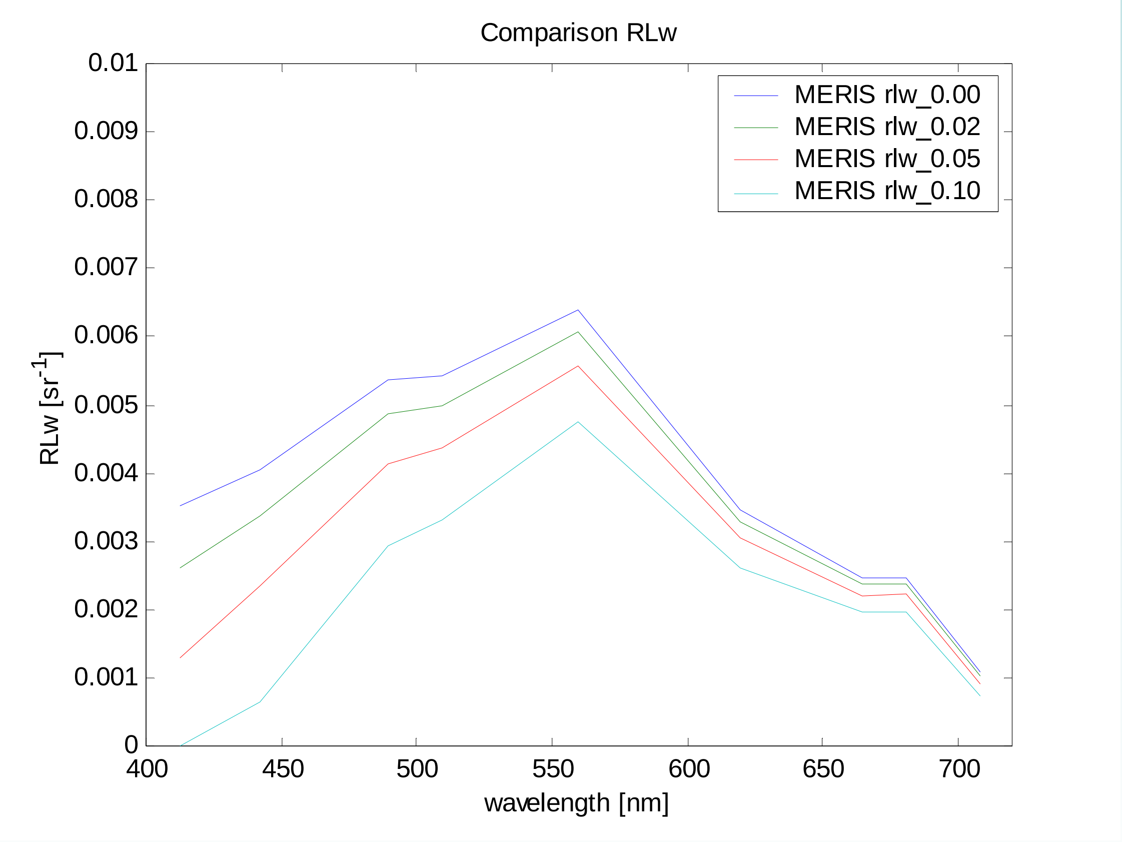






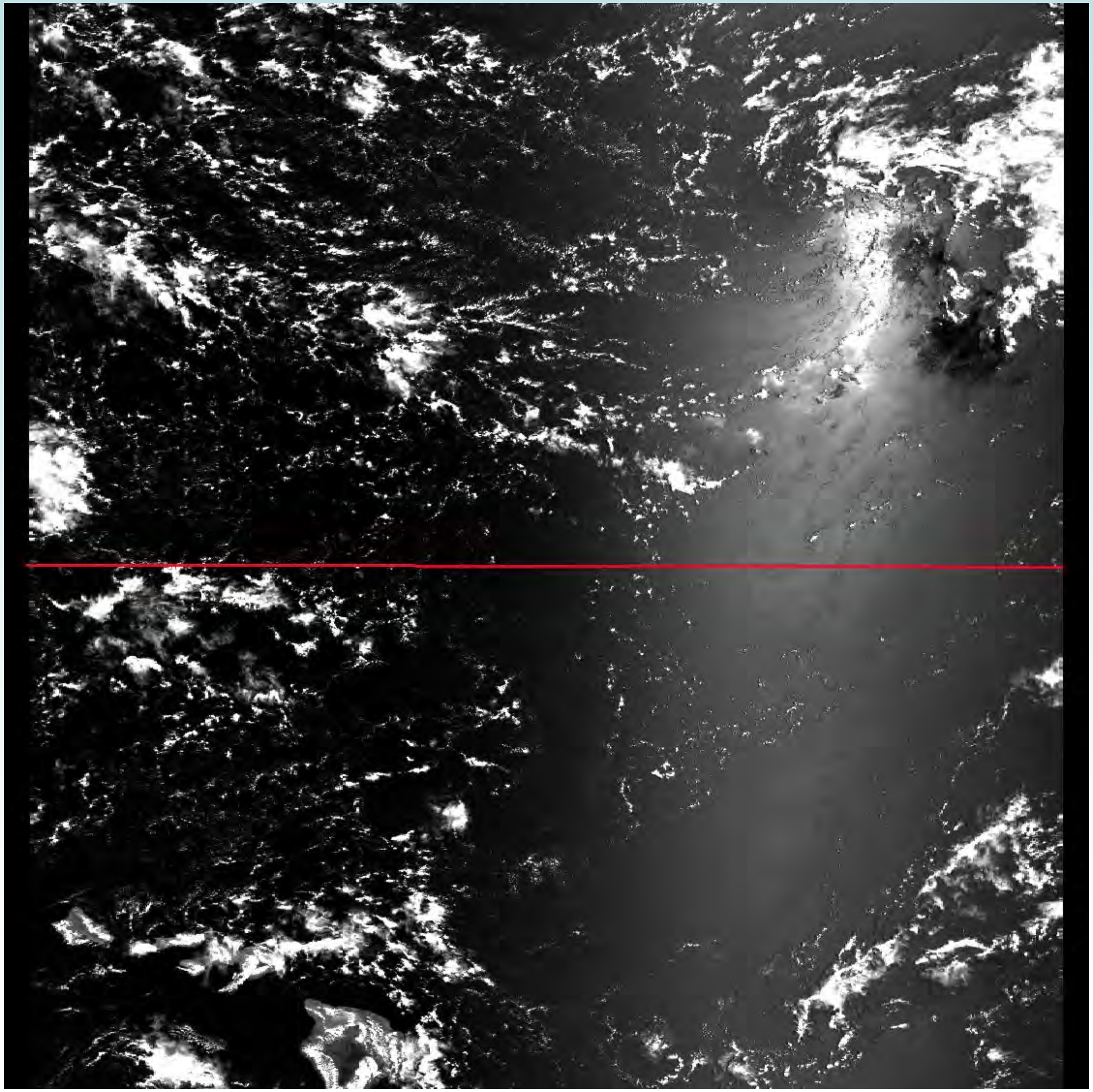

MERIS RR 20030422 pix 864 line 253 lat 54.477386 lon 7.5852623
foam 0.00
RL_toa
RL_tosa
RL_path
RLw_bread
RL [sr-1]
wavelength [nm]
0
0.01
0.02
0.03
0.04
0.05
0.06
400
450
500
550
600
650
700
750
800
850
900


MERIS RR 20030422 pix 864 line 253 lat 54.477386 lon 7.5852623
foam 0.10
RL_toa
RL_tosa
RL_path
RLw_bread
RL [sr-1]
wavelength [nm]
0
0.01
0.02
0.03
0.04
0.05
0.06
400
450
500
550
600
650
700
750
800
850
900

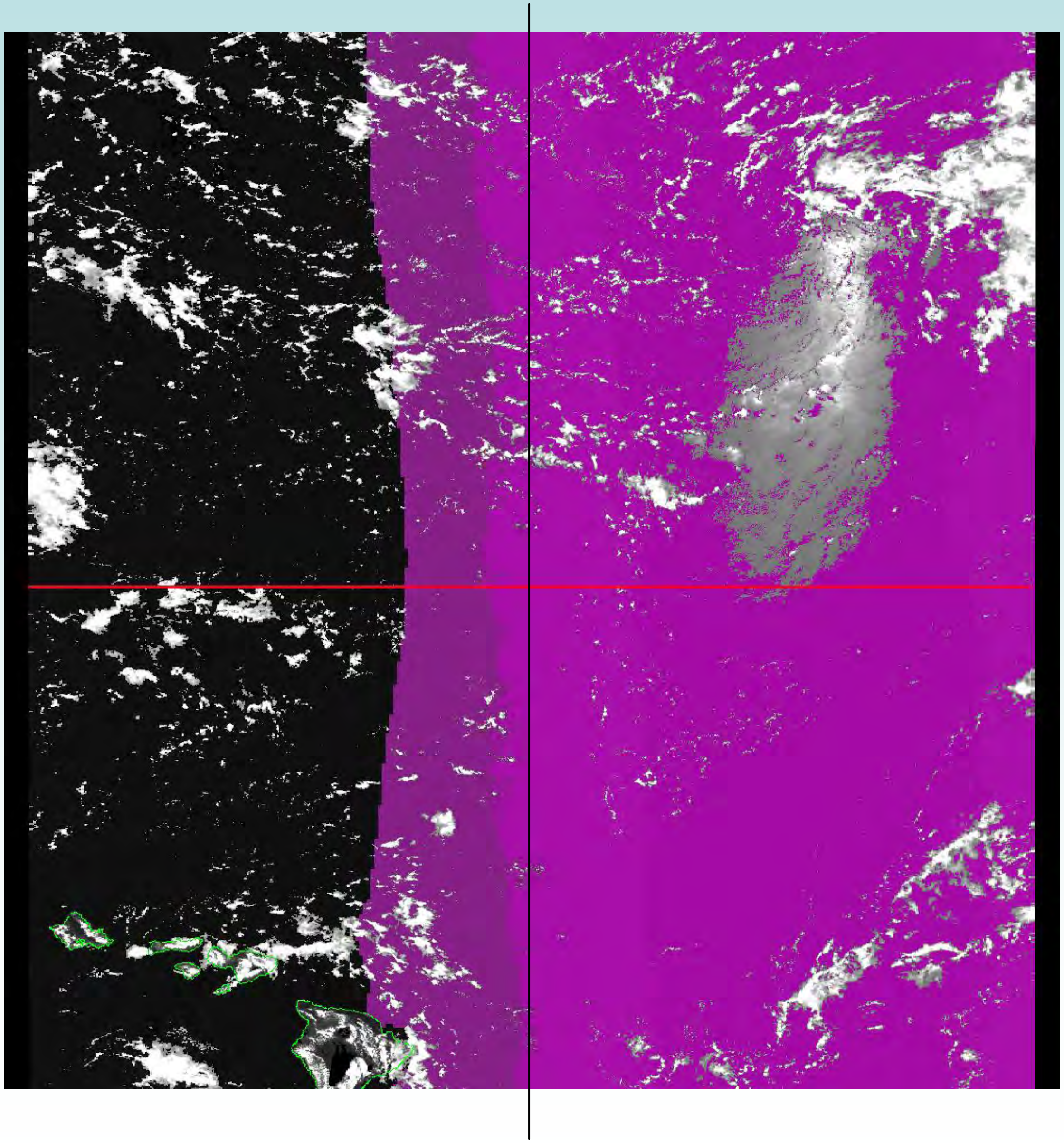

Comparison RLw
MERIS rlw_0.00
MERIS rlw_0.02
MERIS rlw_0.05
MERIS rlw_0.10
RLw [sr-1]
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
400
450
500
550
600
650
700
wavelength [nm]

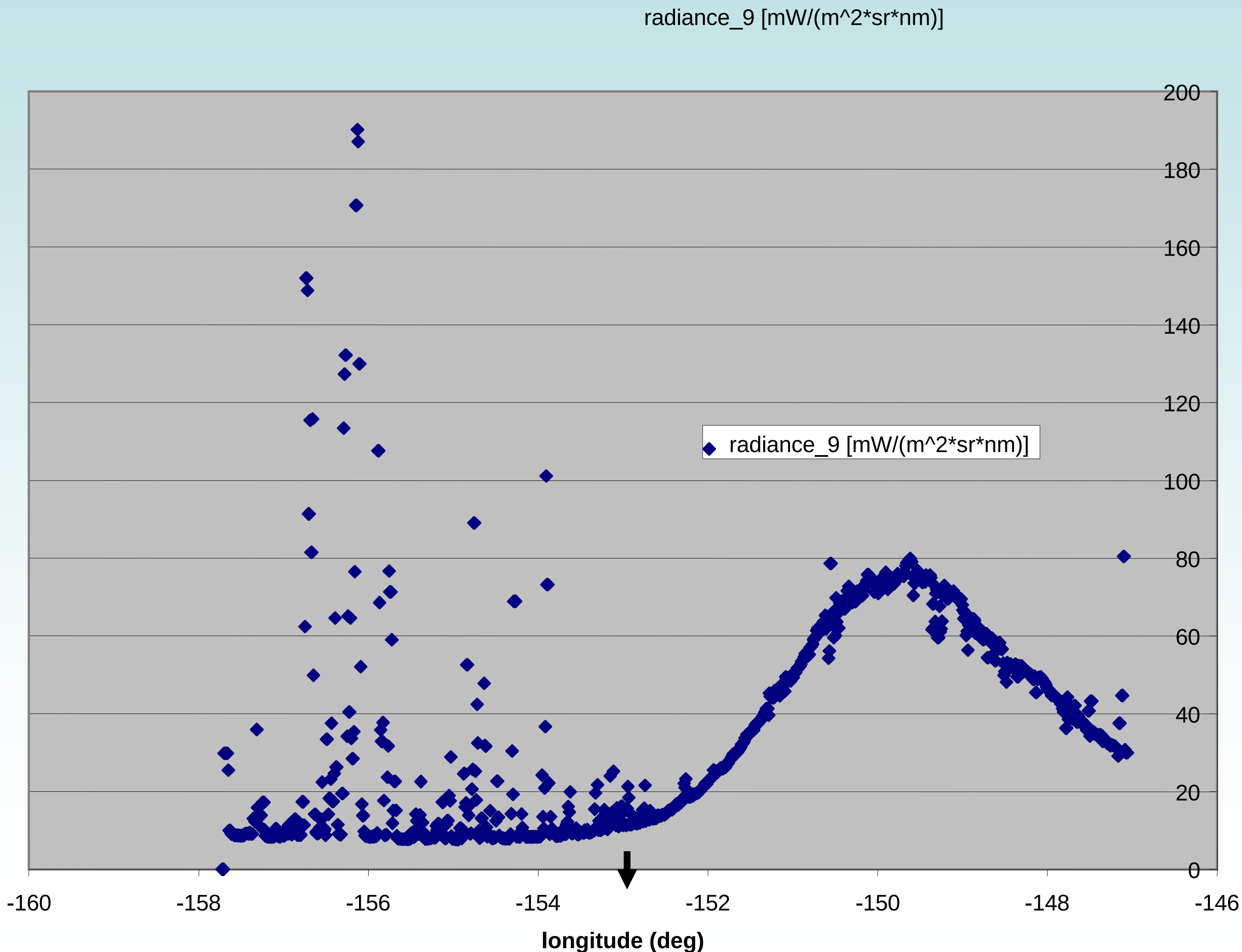
Sunglint

Hawai 20030705



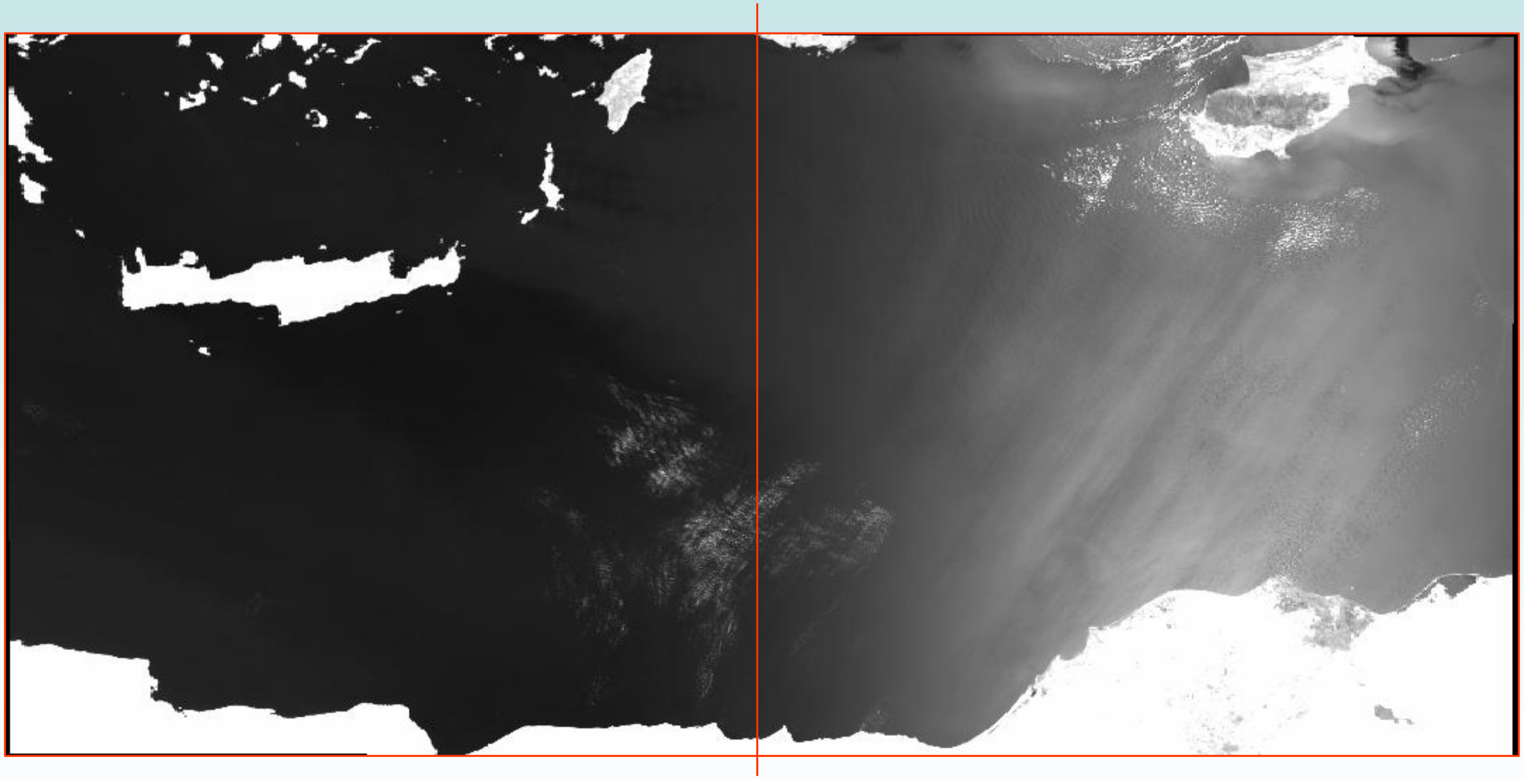
Sun glint mask for medium and high glint





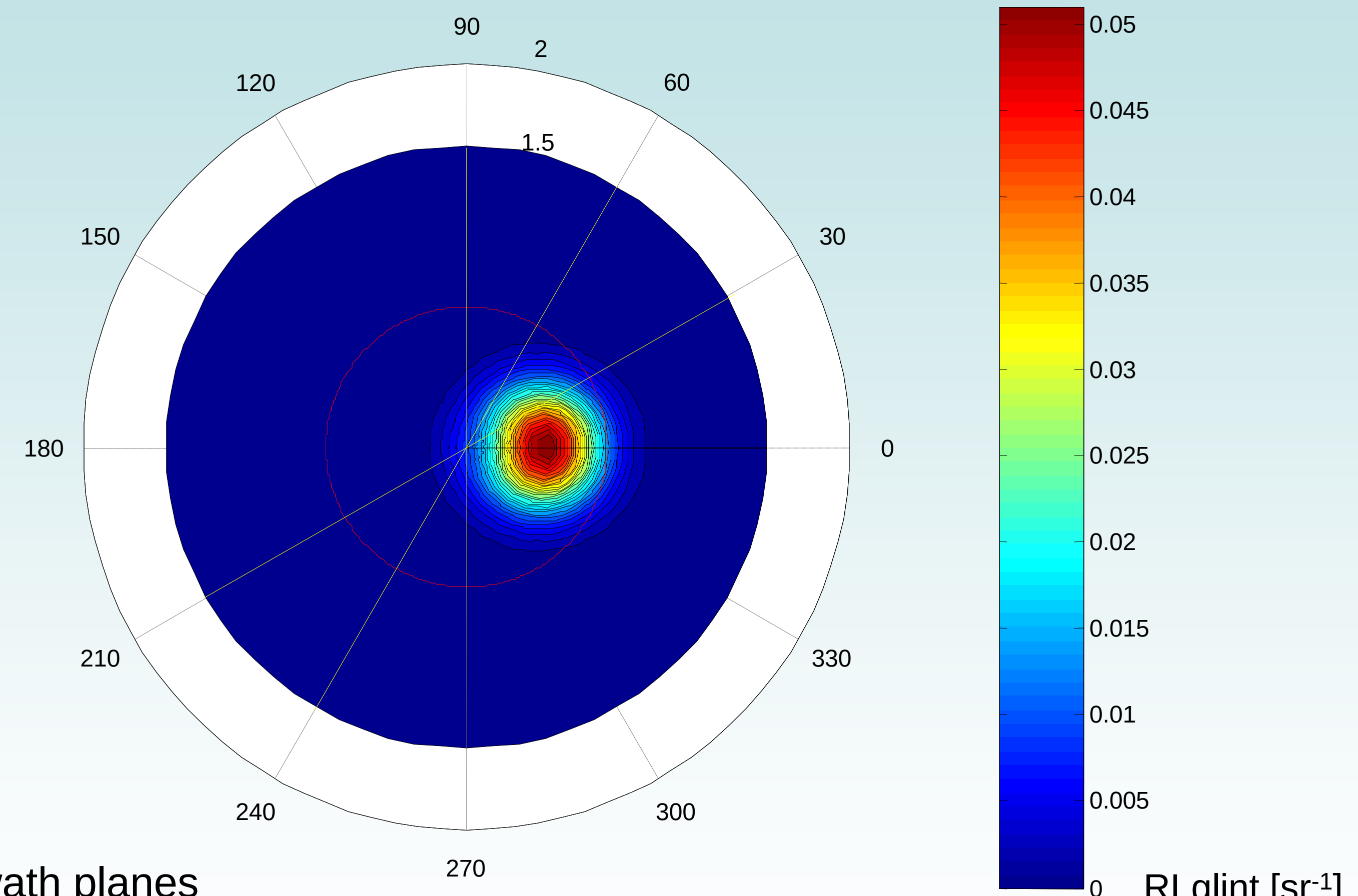
radiance_9 [mW/(m^2*sr*nm)]
200
180
160
140
120
100
80
60
40
20
0
radiance_9 [mW/(m^2*sr*nm)]
-160
-158
-156
-154
-152
-150
-148
-146
longitude (deg)

Sunglint MERIS RR 2.8.2002 band 8



Sun glint radiance reflectance

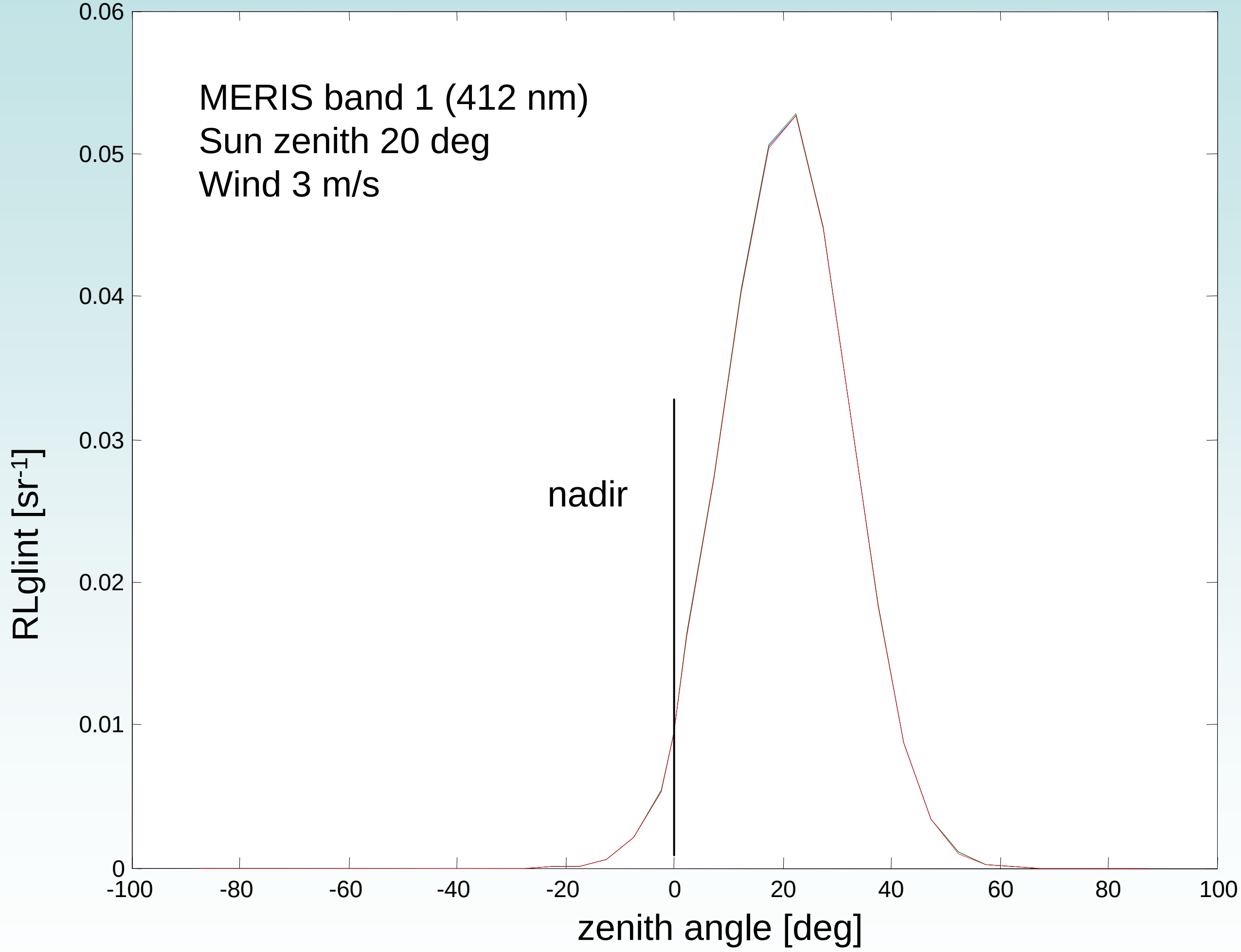
MERIS band 1 (412 nm), wind 3 m/s, sun zenith 20 deg



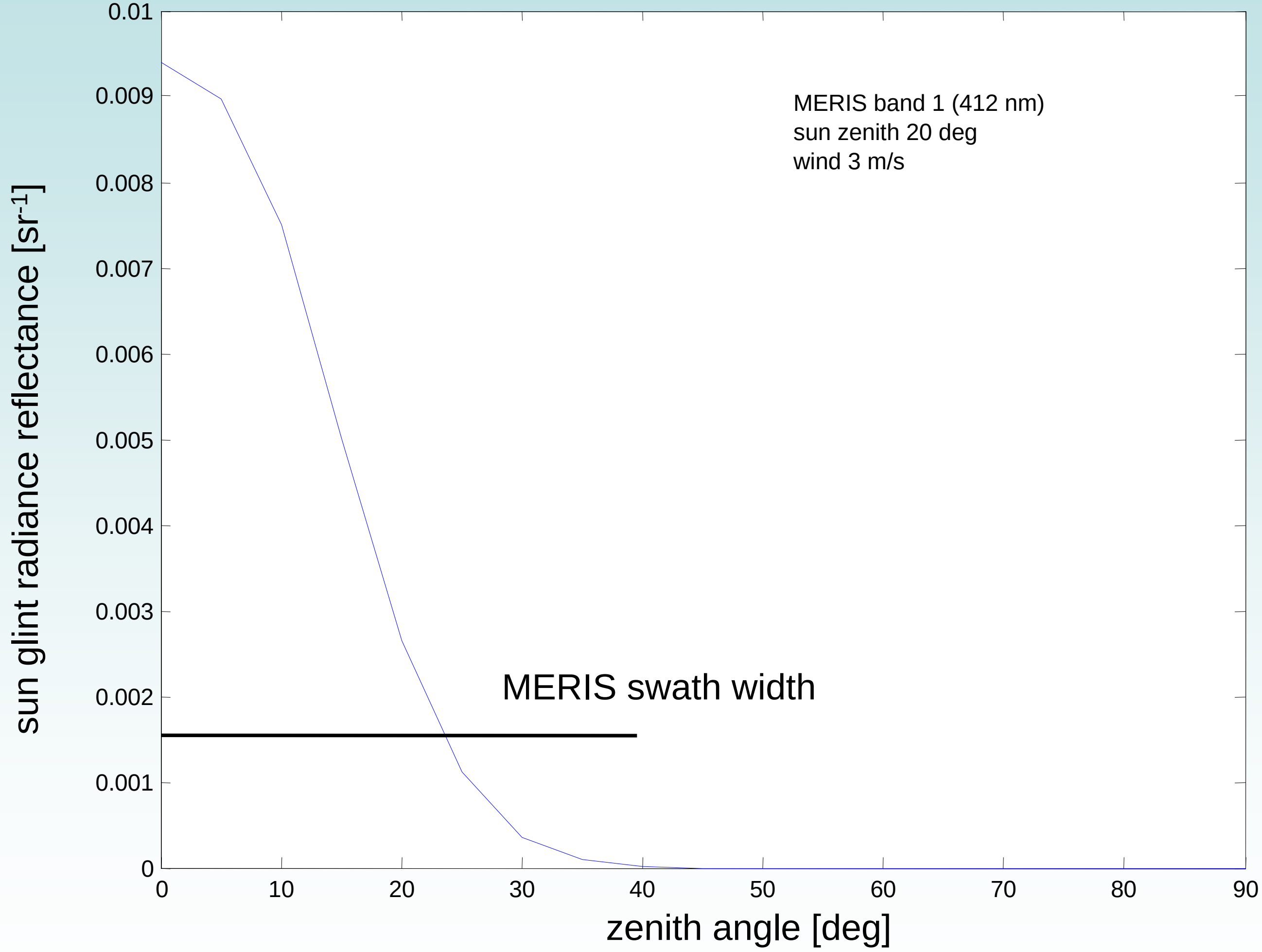
Red circle 42 deg
Yellow lines:
possible MERIS swath planes

azimuth angle [deg] / nadir angle [rad]

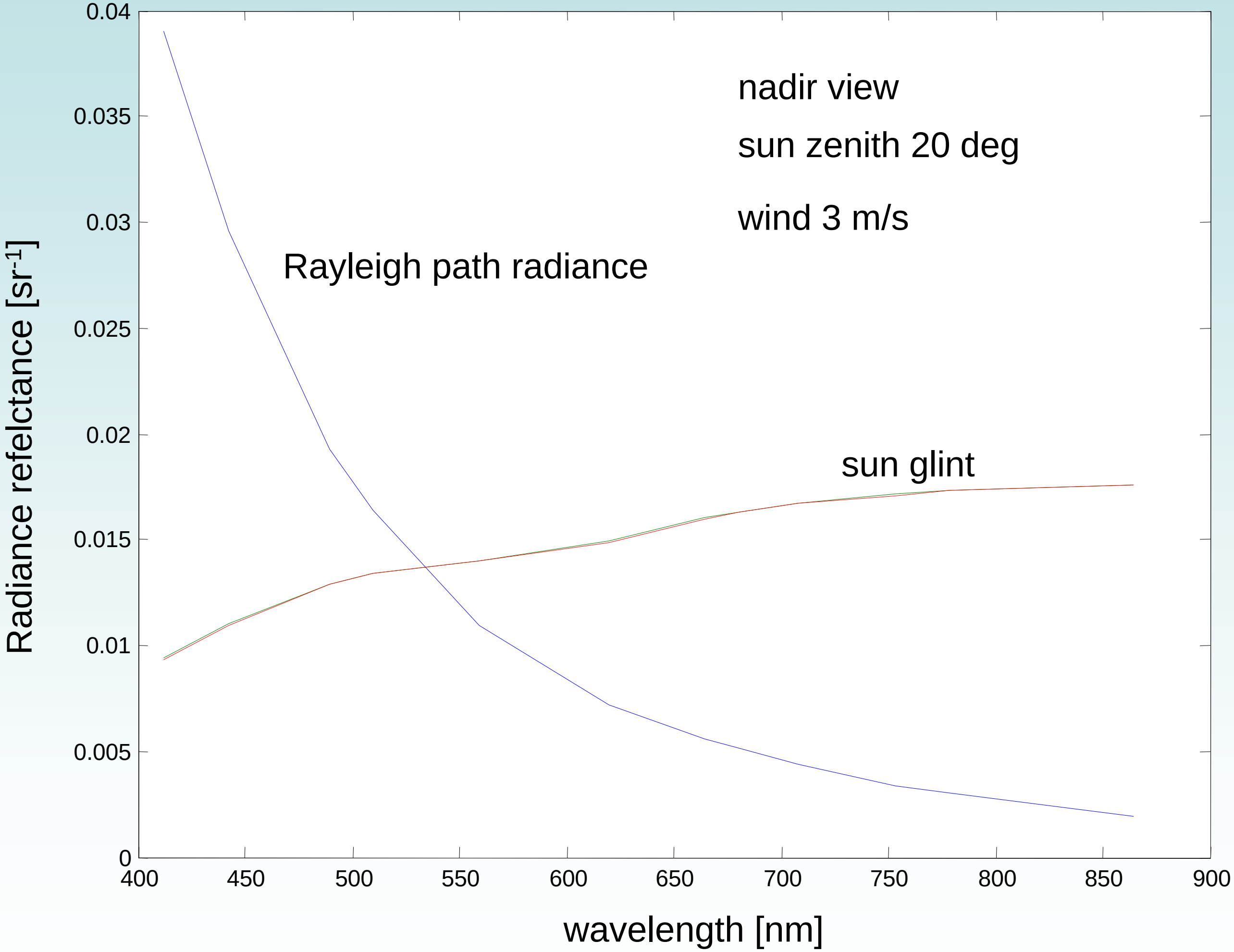
Sun glint radiance reflectance, principle plane



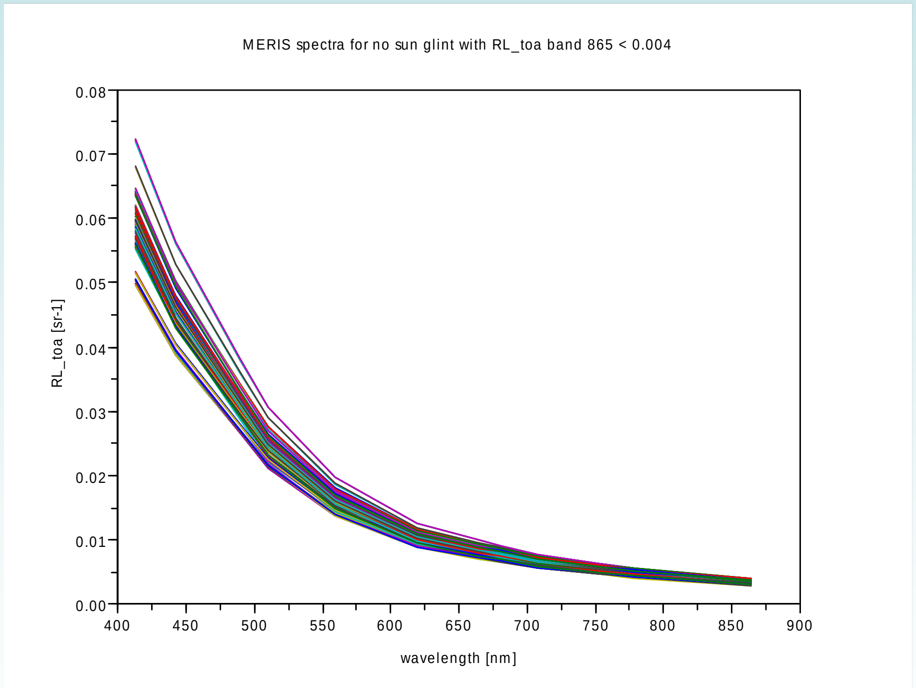
Sun glint radiance reflectance, cross plane

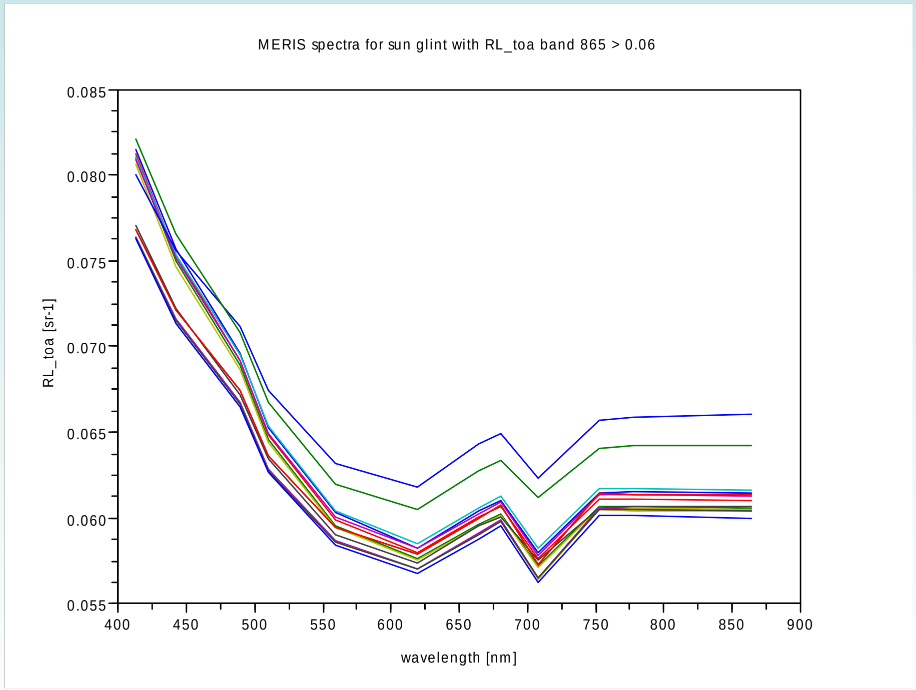


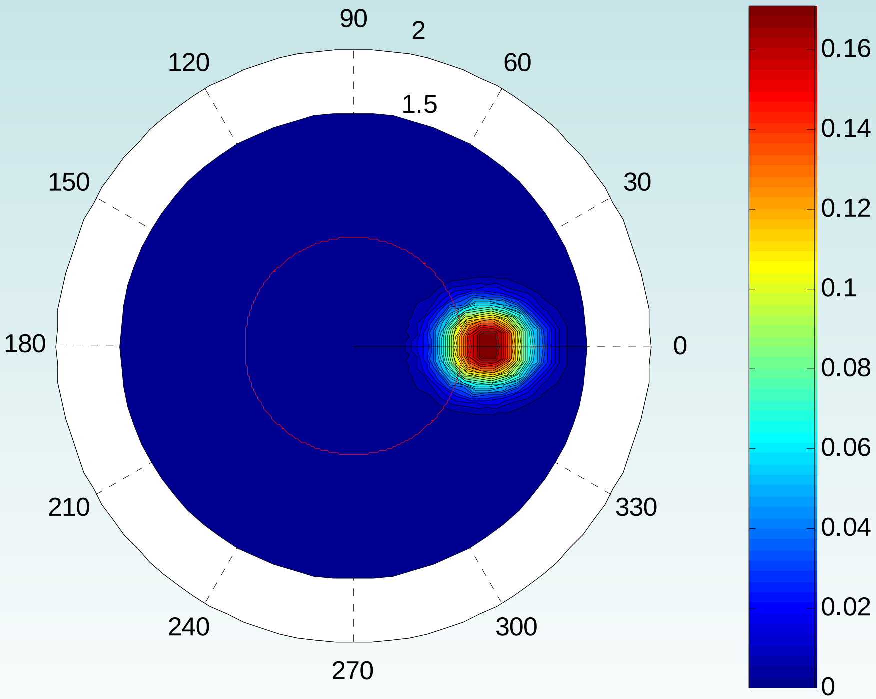
Simulated Rayleigh path radiance reflectance and sun glint radiance reflectance

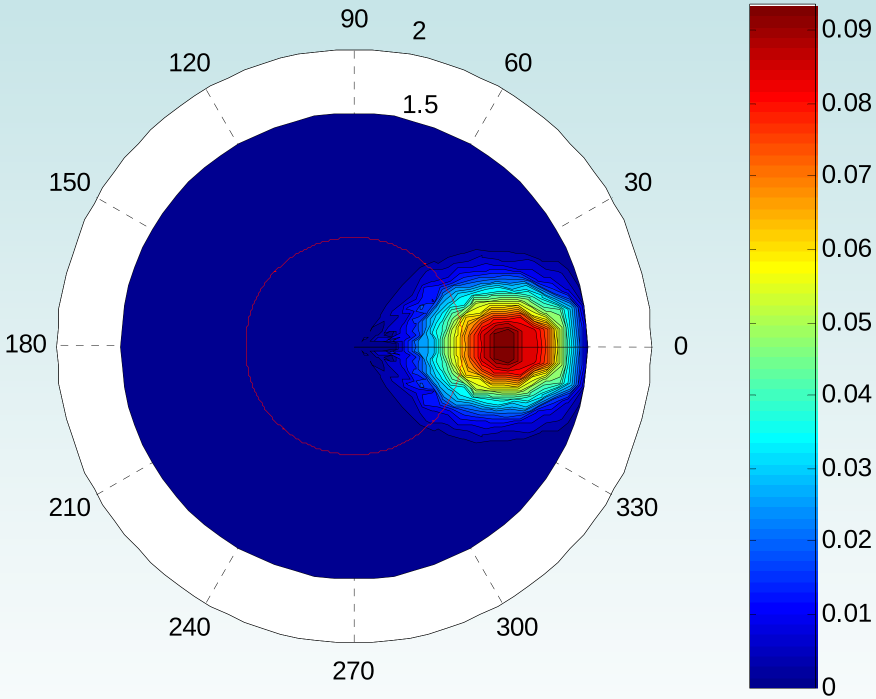


No glint and high glint TOA reflectance spectra





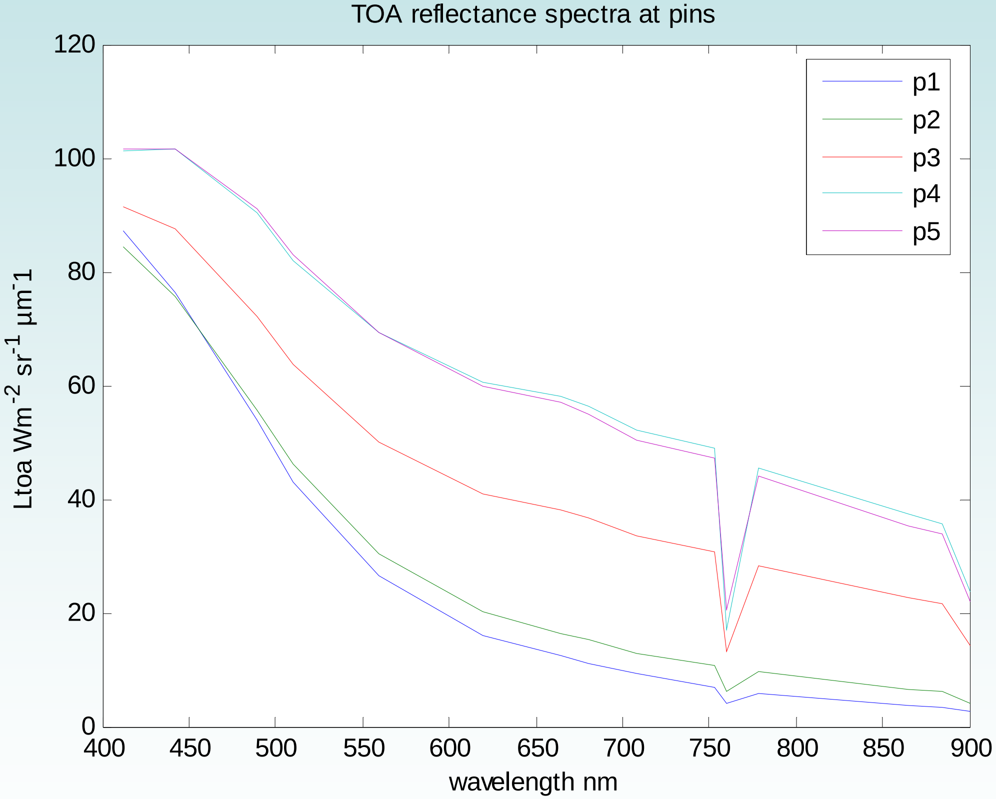




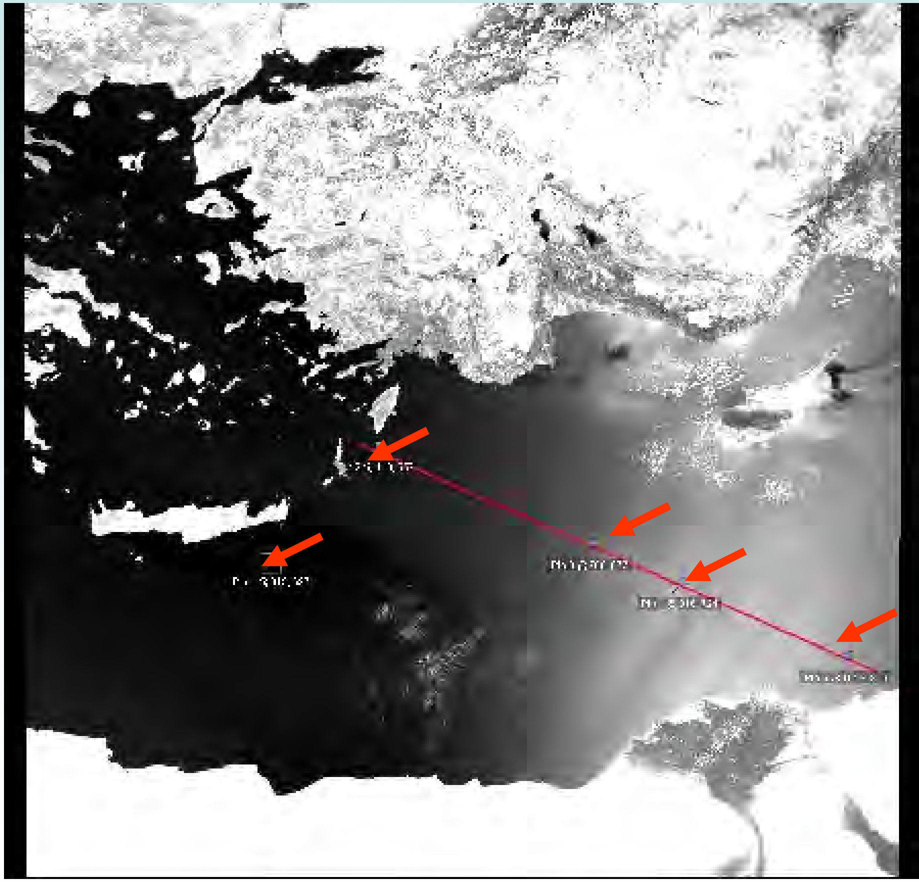
Sun 45 deg, wind 3 m/s

Sun 45 deg, wind 7 m/s

Sunglint



TOA reflectance spectra at pins
120
100
80
60
40
20
0
400
450
500
550
600
650
700
750
800
850
900
wavelength nm
Ltoa Wm-2 sr-1 µm-1
p1
p2
p3
p4
p5



Sun glint distribution

- Sun glint may appear in more than half of the image
- In many cases it is not homogeneously distributed with angles
- Lokal wind, surface material, wind shields etc.determine distribution
- Sunglint distriubtion may rapidly change due to wind variations
- Slick patches may be persistent for hours

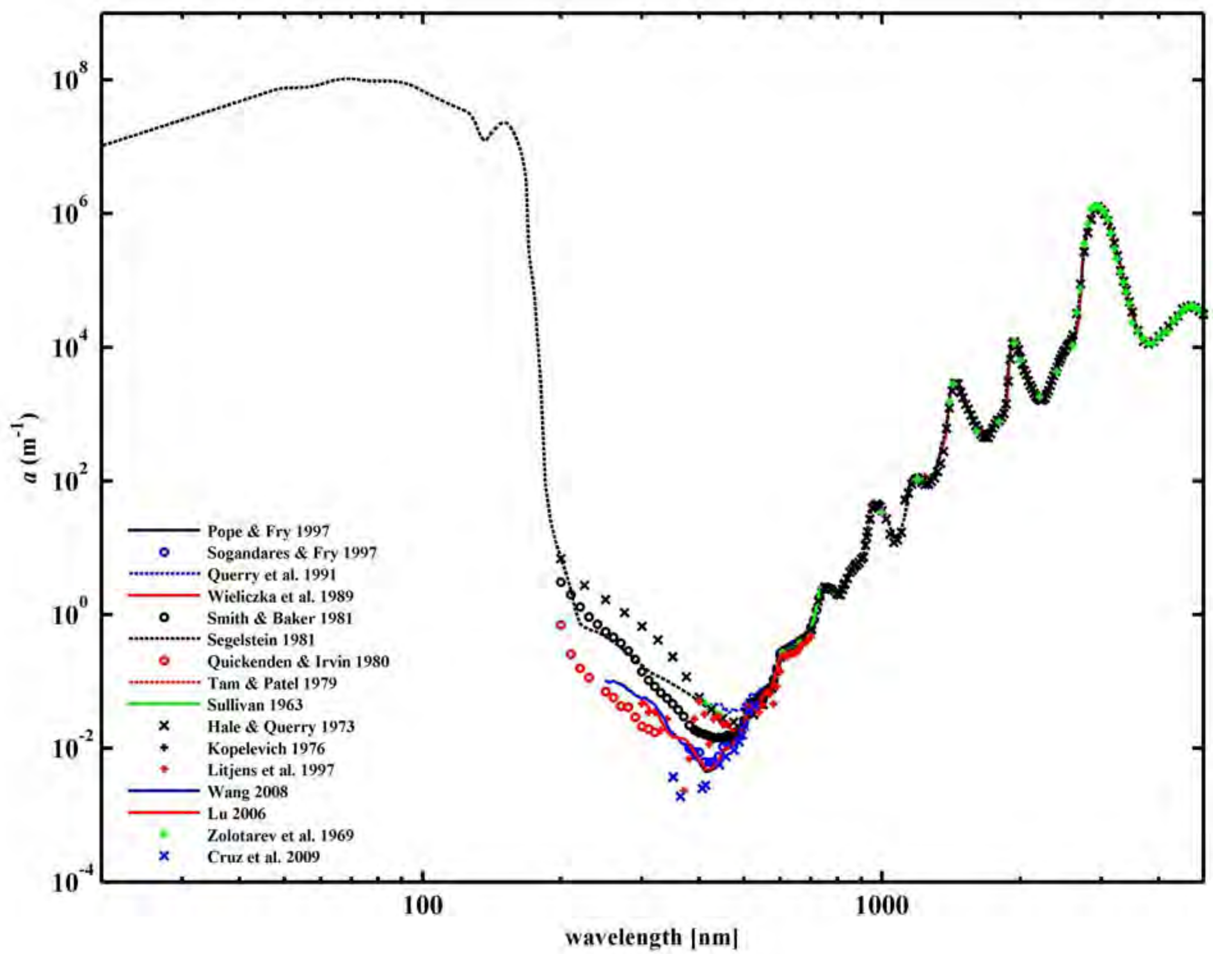
Consequence:

- Sun glint distribution cannot be predicted (and not corrected) from wind speed (as included in MERIS product) and angles

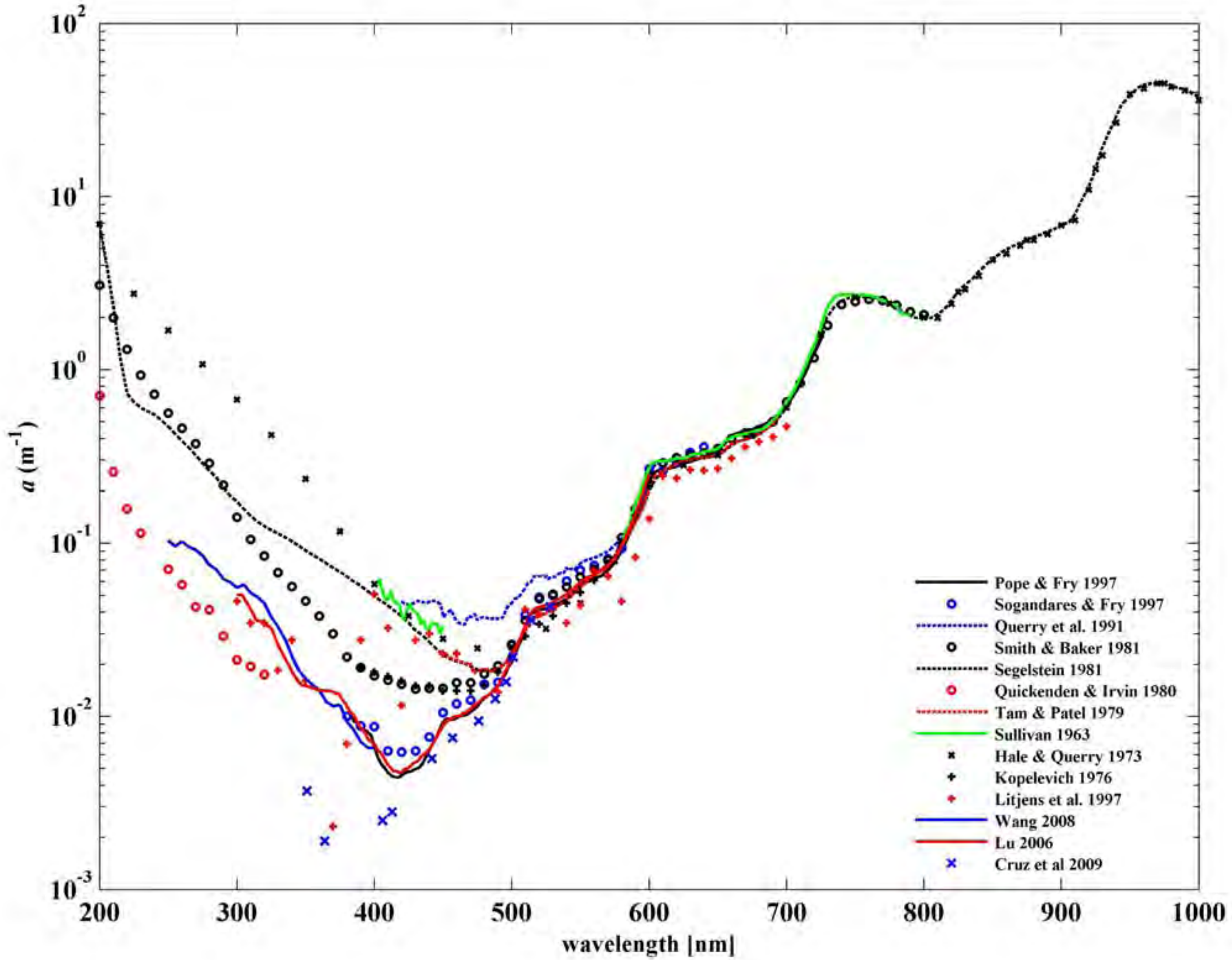
Water

- Nature of water
  - Pure water optical properties only partly known with required accuracy
  - Temperature and salinity effects
  - Many different water constituents with different and varying inherent optical properties
  - Vertical distribution not homogenous
  - Sub pixel patchiness
- Model of water
  - Definition of a bio-optical model
  - Optical components and their similarity and variability
  - Methods to separate different components

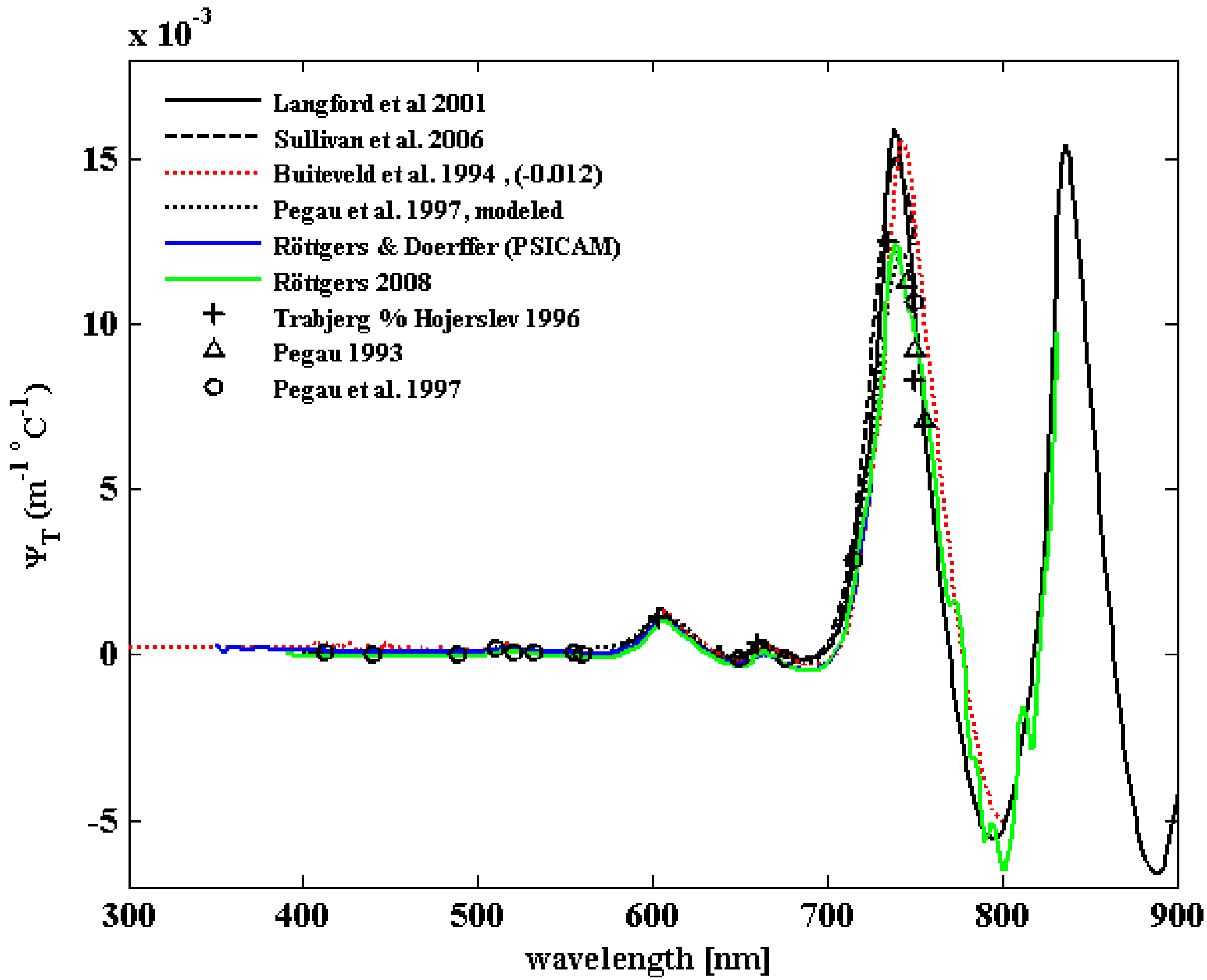
Pure Water Absorption



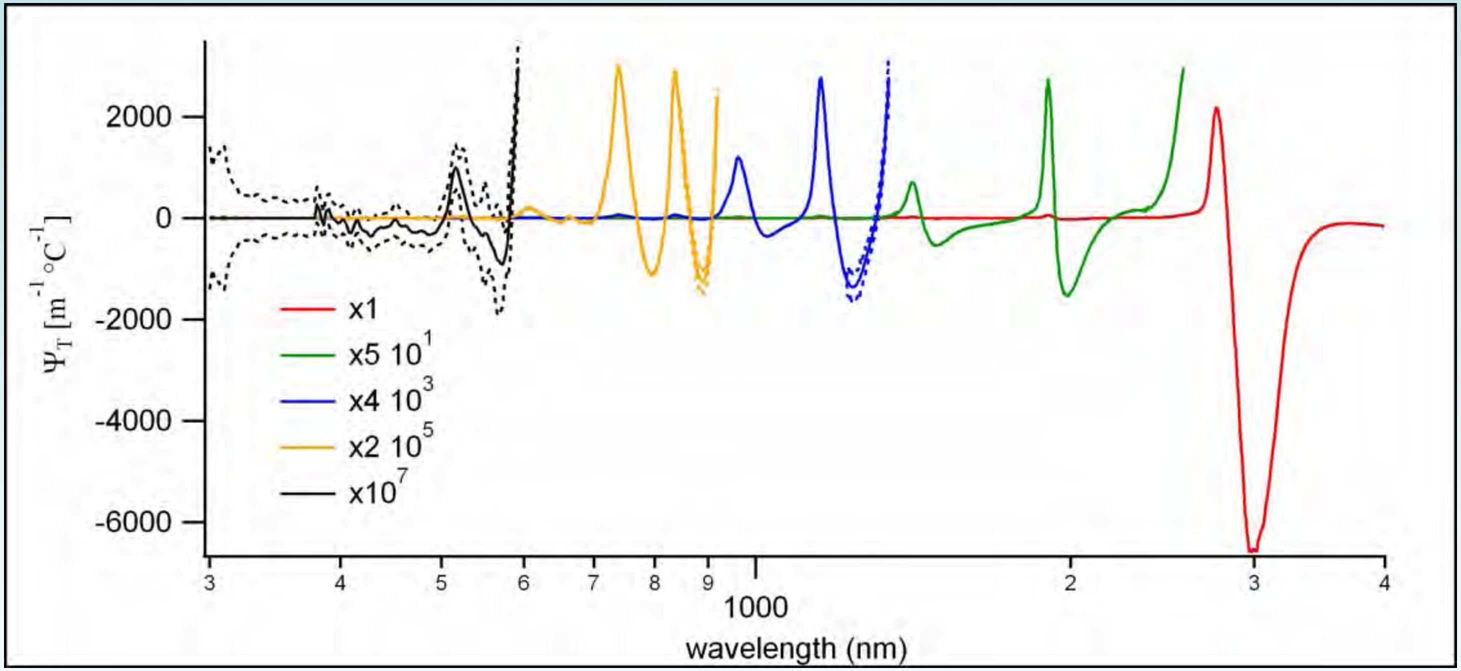
Pure water absorption II



Temperature and absorption of pure water

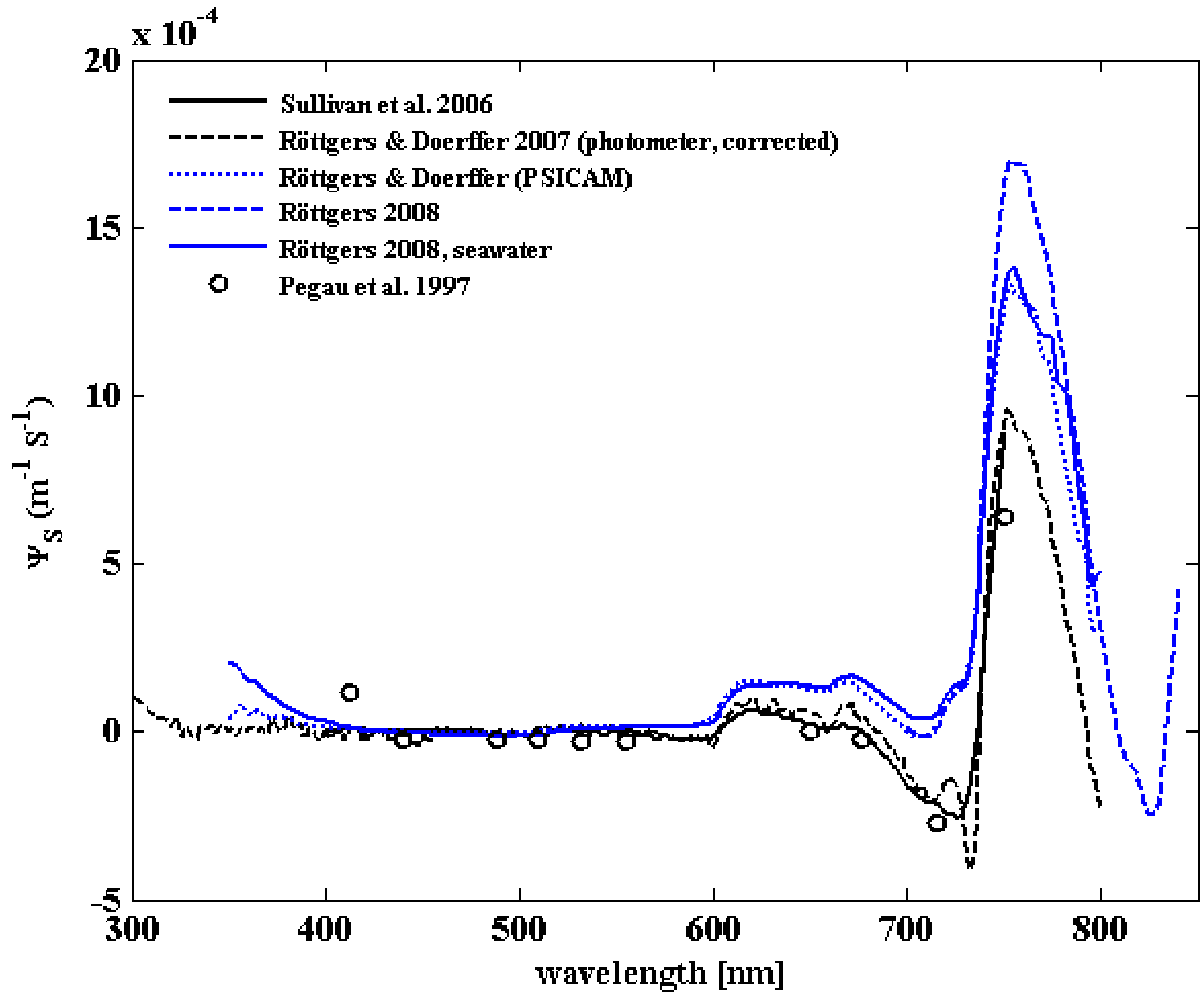


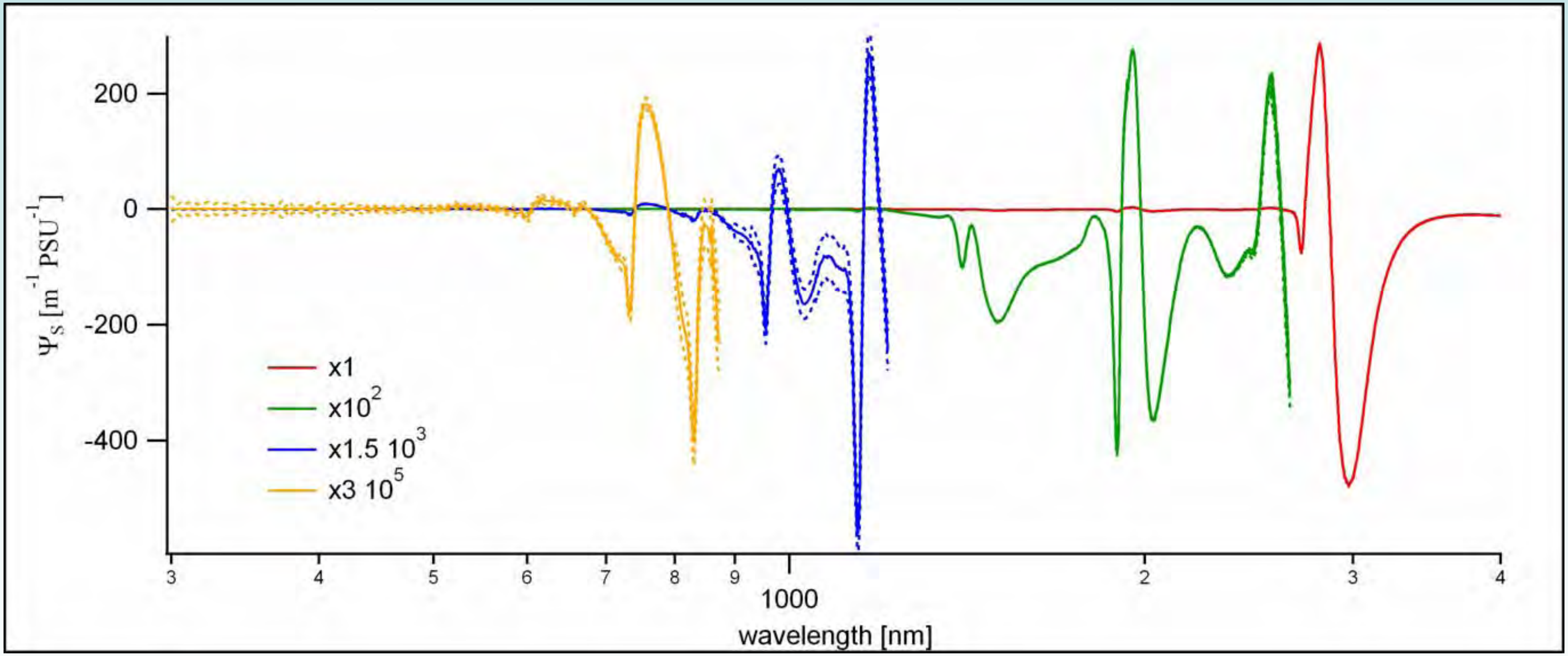
Uncertainties of temperature effect



The temperature coefficient of pure water absorption,YT (m-1 °C-1), as a function of wavelength. The original data are shown in red. In addition, for specific spectral ranges the spectral features were enlarged by multiplying the values with different factor as indicated in the legend. The errors are shown as 2s contour lines (dashed lines).

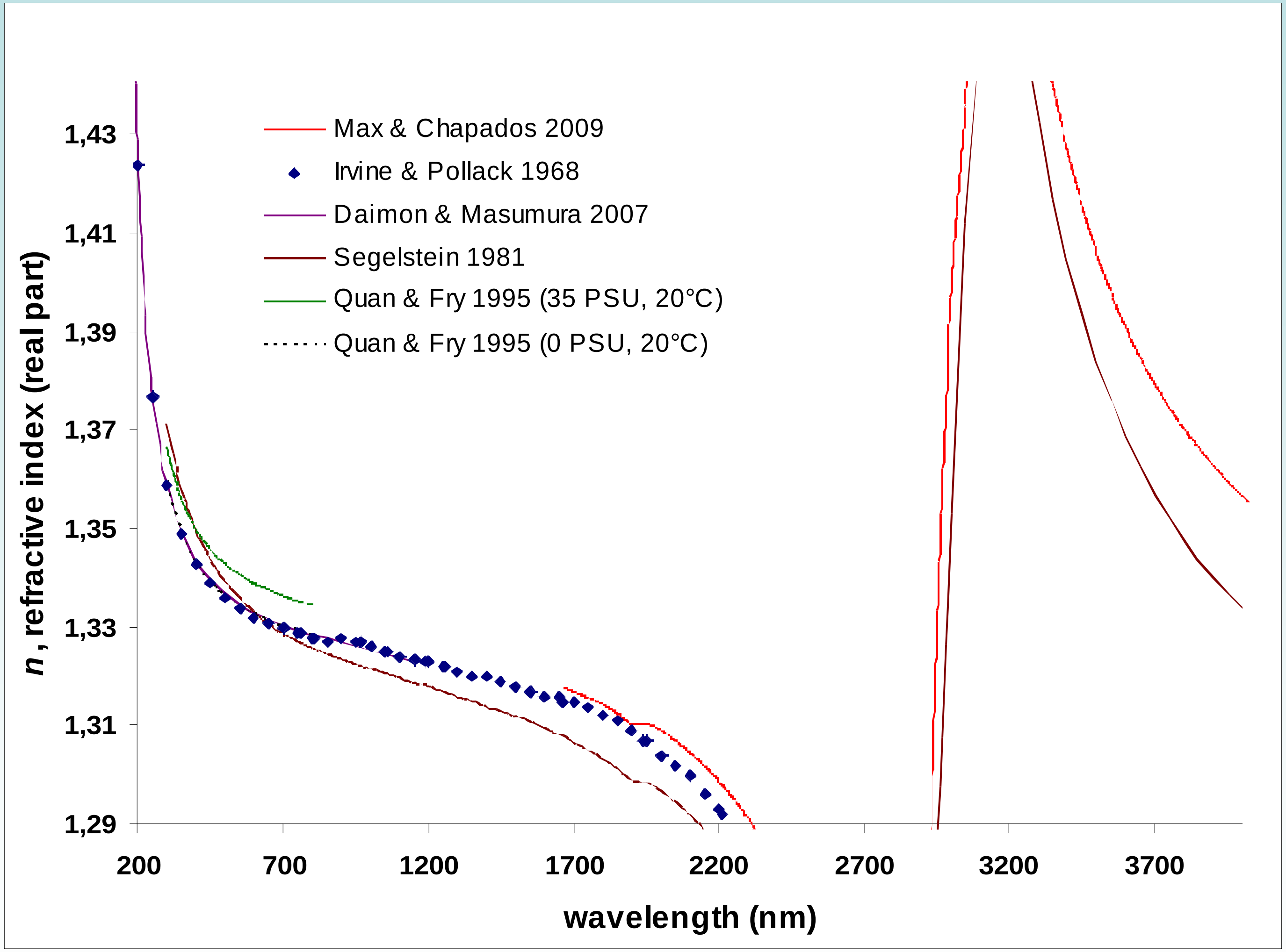
Salinity and absorption



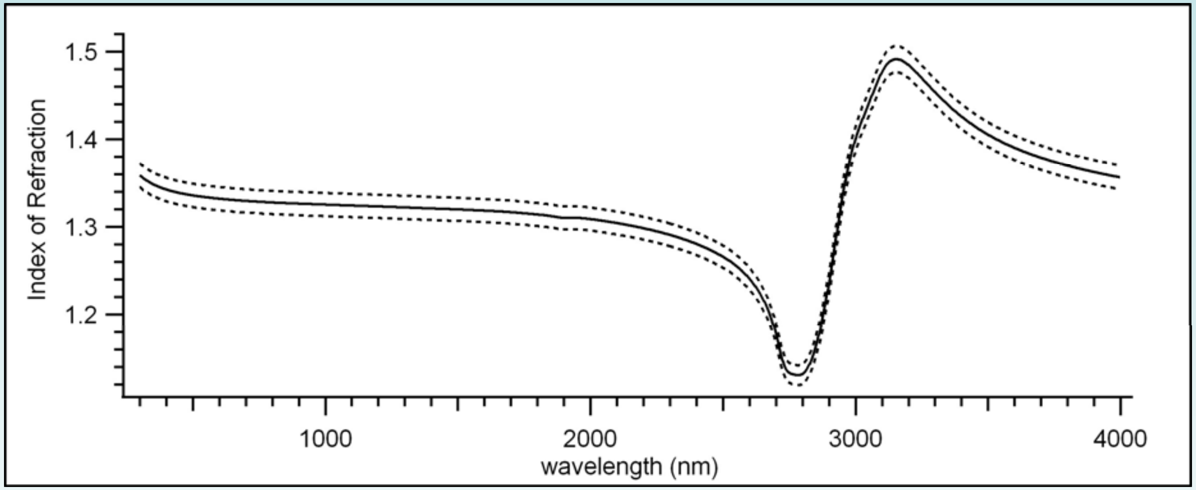


The salinity coefficient of pure water absorption,YS (m-1 PSU-1), as a function of wavelength. The errors are shown as 2s contour lines (dashed lines).

Refractive index

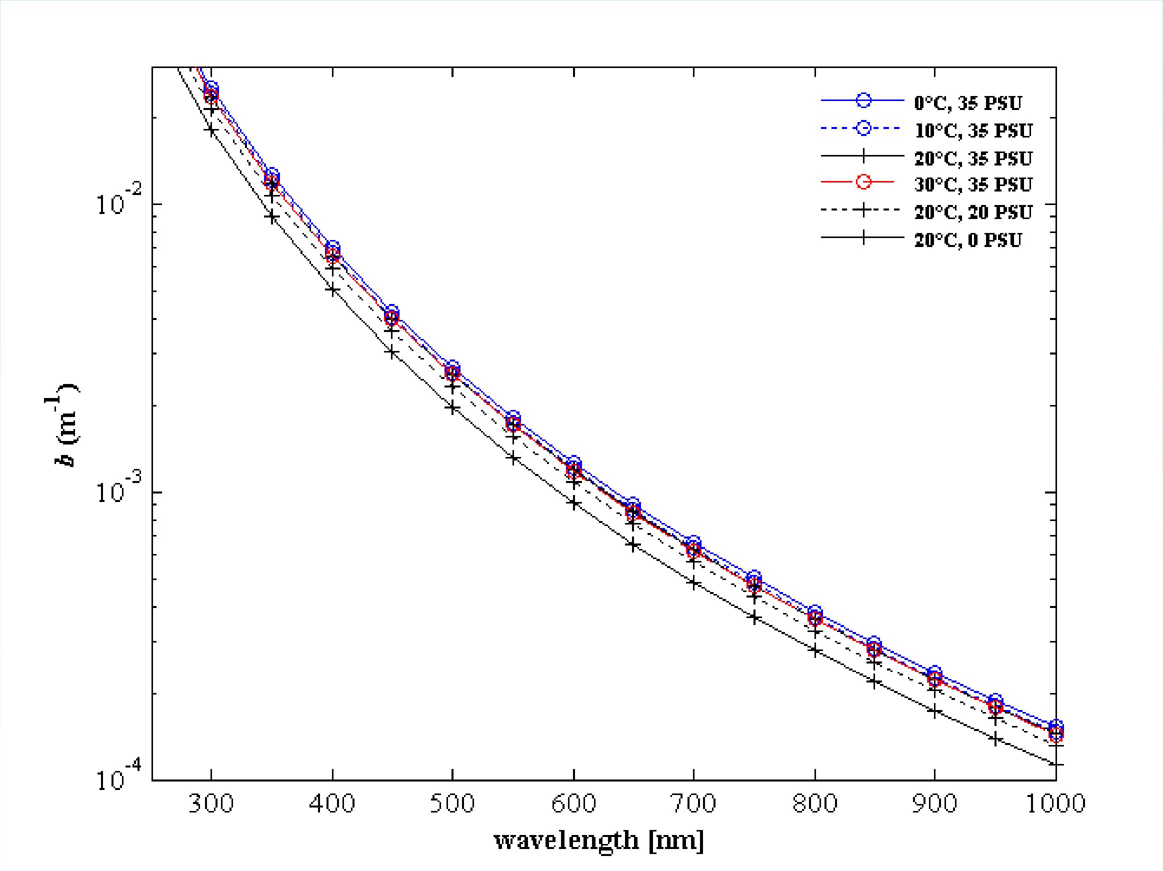


Uncertainties of refractive index

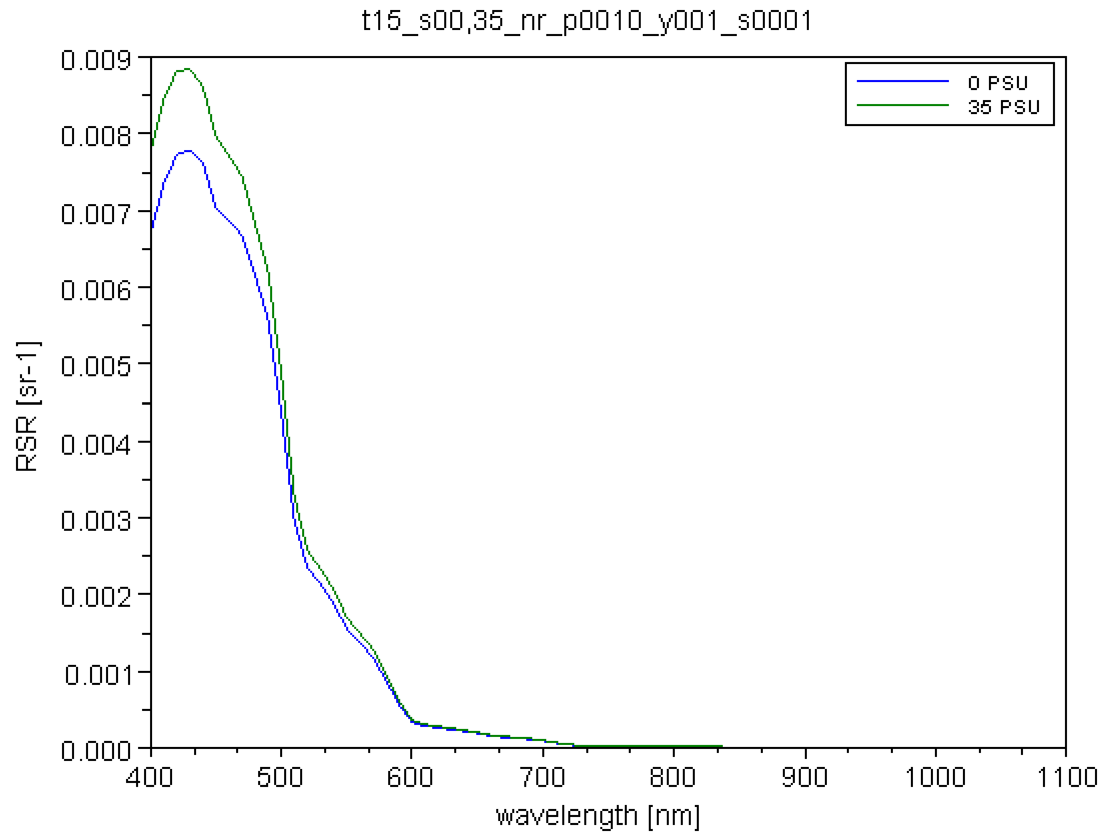


The real part of the index of refraction of pure water and seawater. Combined spectrum at 27 °C using formulation of Quan & Fry 1995 and data of Max & Chapados 2009, the error is indicated as contour lines (±2s, dashed lines).

Salinity and temperature effect on scattering of pure water

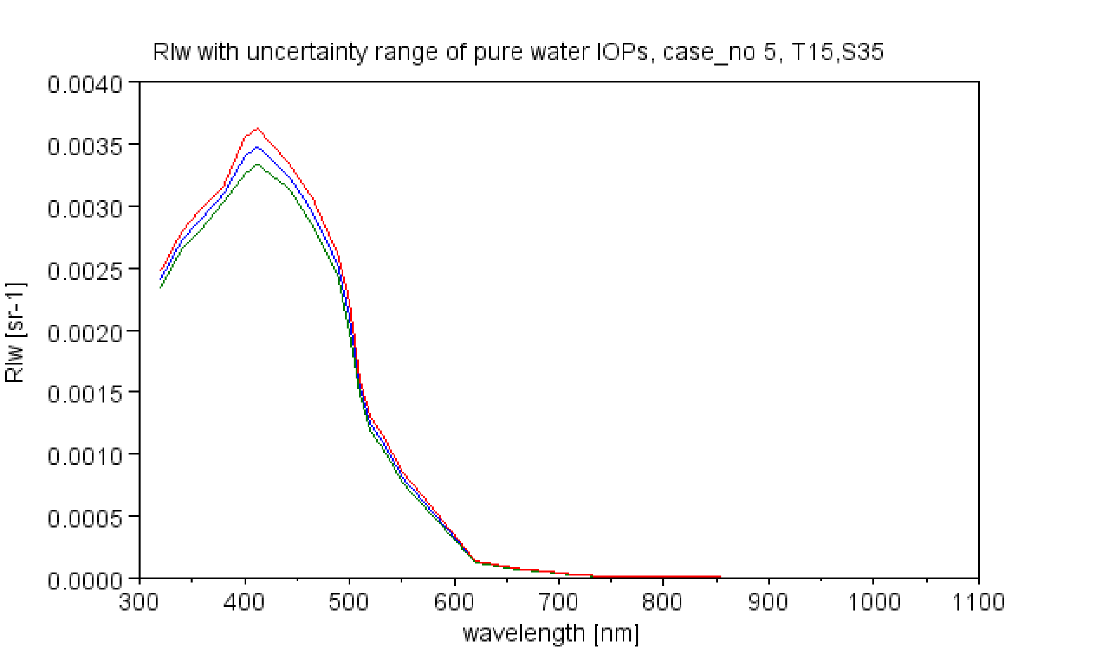


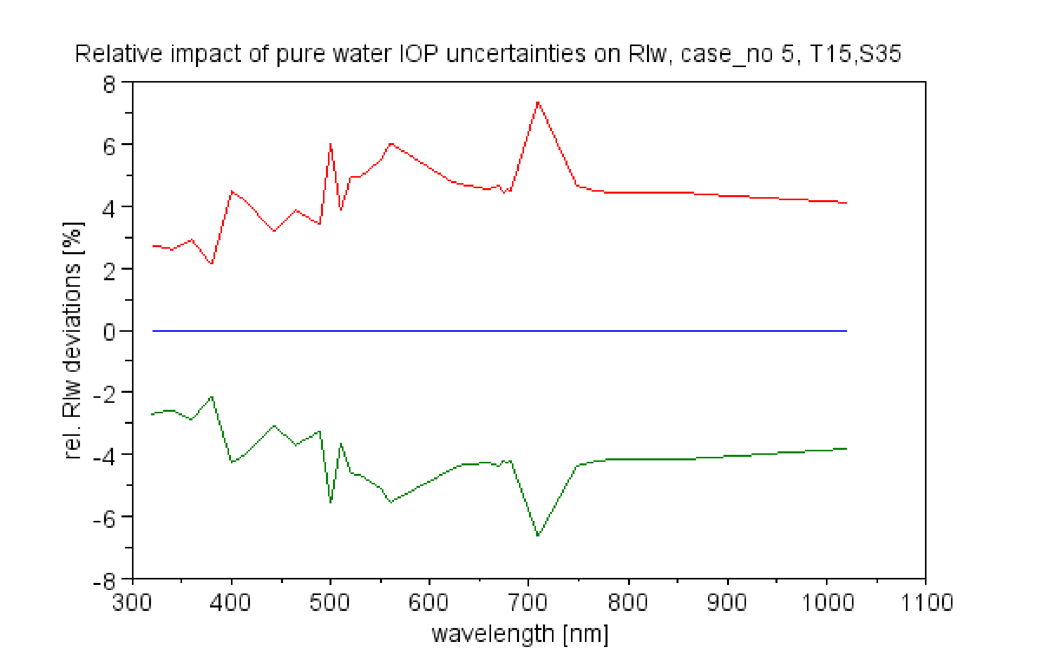
Impact of salinity on reflectance spectrum



Water leaving radiance reflectance of oligotrophic water for temperature 15 deg C, salinity 0 and 35, chl 0.1 mg m-3, ys(440 nm) 0.01, SPM 0.01 g m-3.

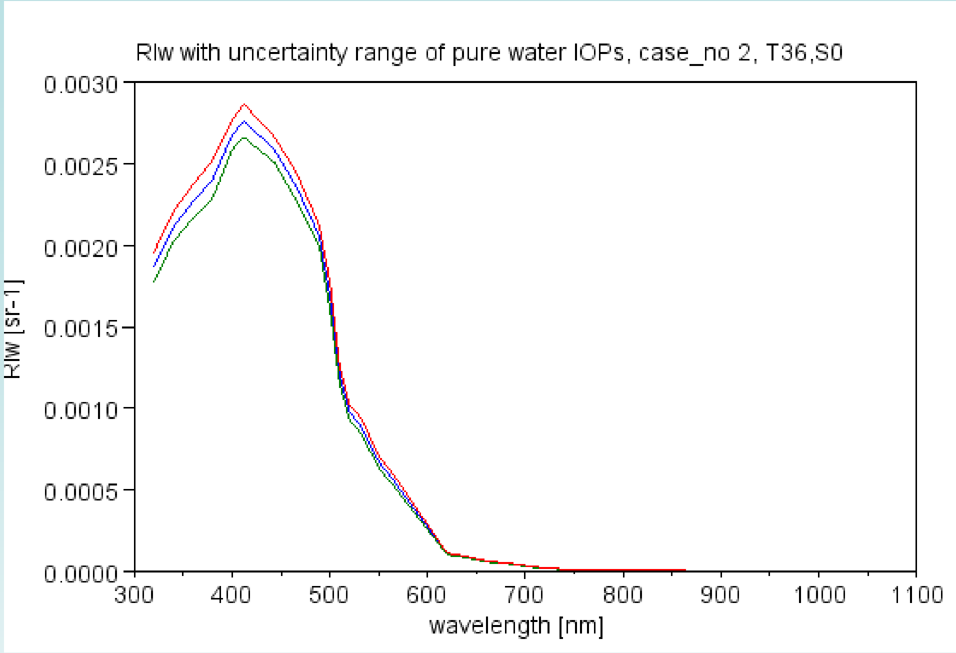
Effect of pure water IOPs uncertainties

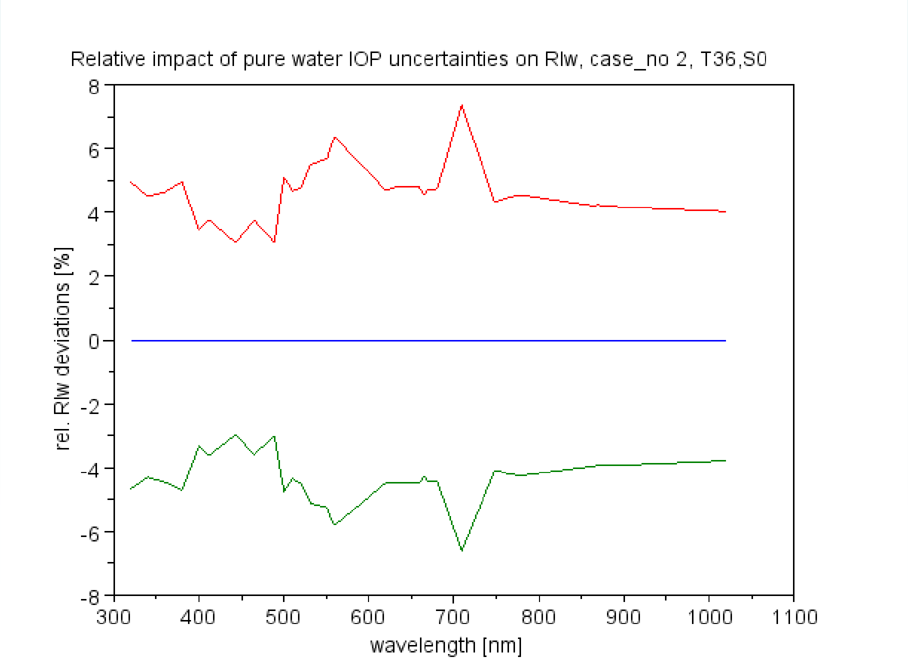




Relative deviations of Rlw due to lower and upper bounds of uncertainties of pure water absorption and scattering for S=35, T=15, apig=0.01, adet=0.01, ays=0.01, bpart=0.01, bwit=0.01

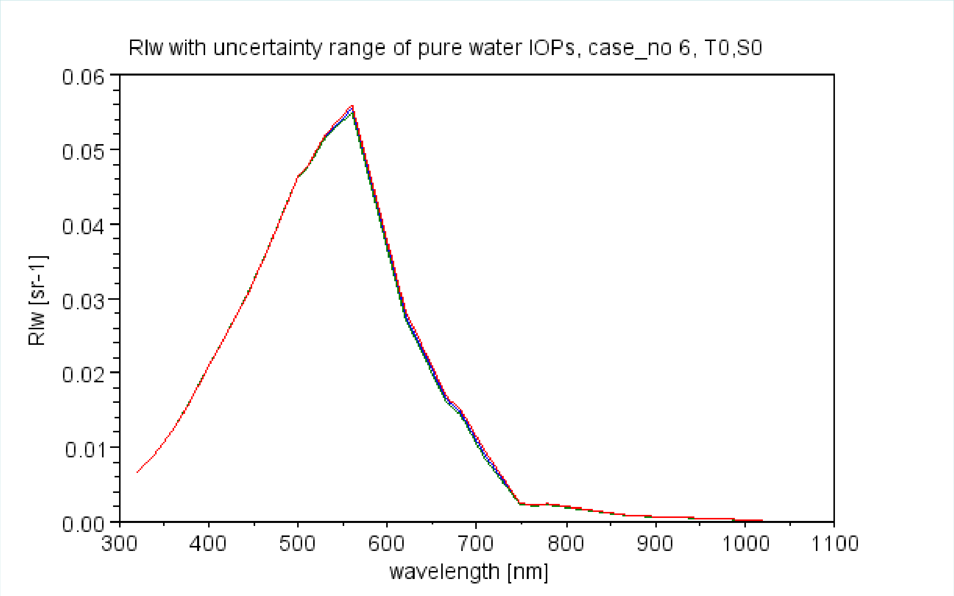
Effect of pure water IOPs uncertainties: warm water

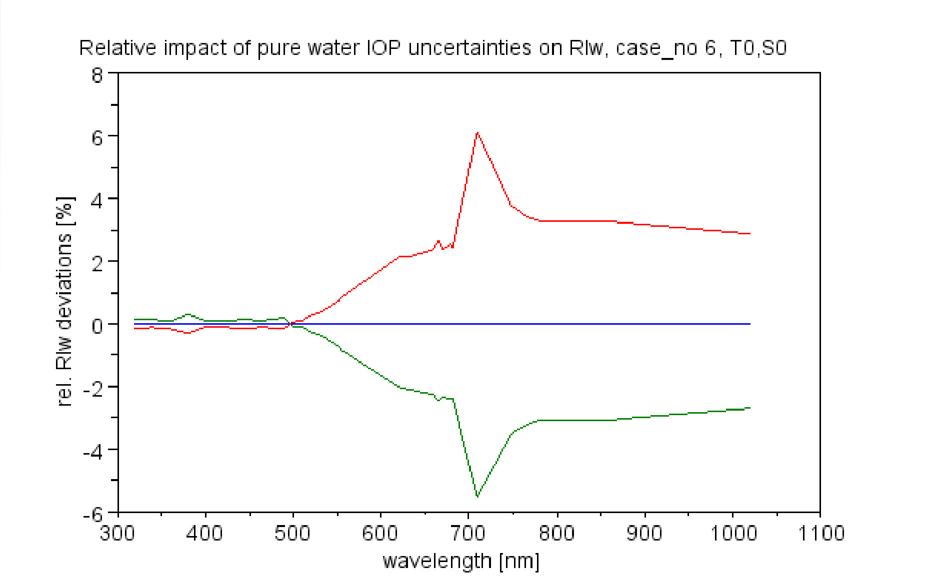




Relative deviations of Rlw due to lower and upper bounds of uncertainties of pure water absorption and scattering for S=0, T=36, apig=0.01, adet=0.01, ays=0.01, bpart=0.01, bwit=0.01

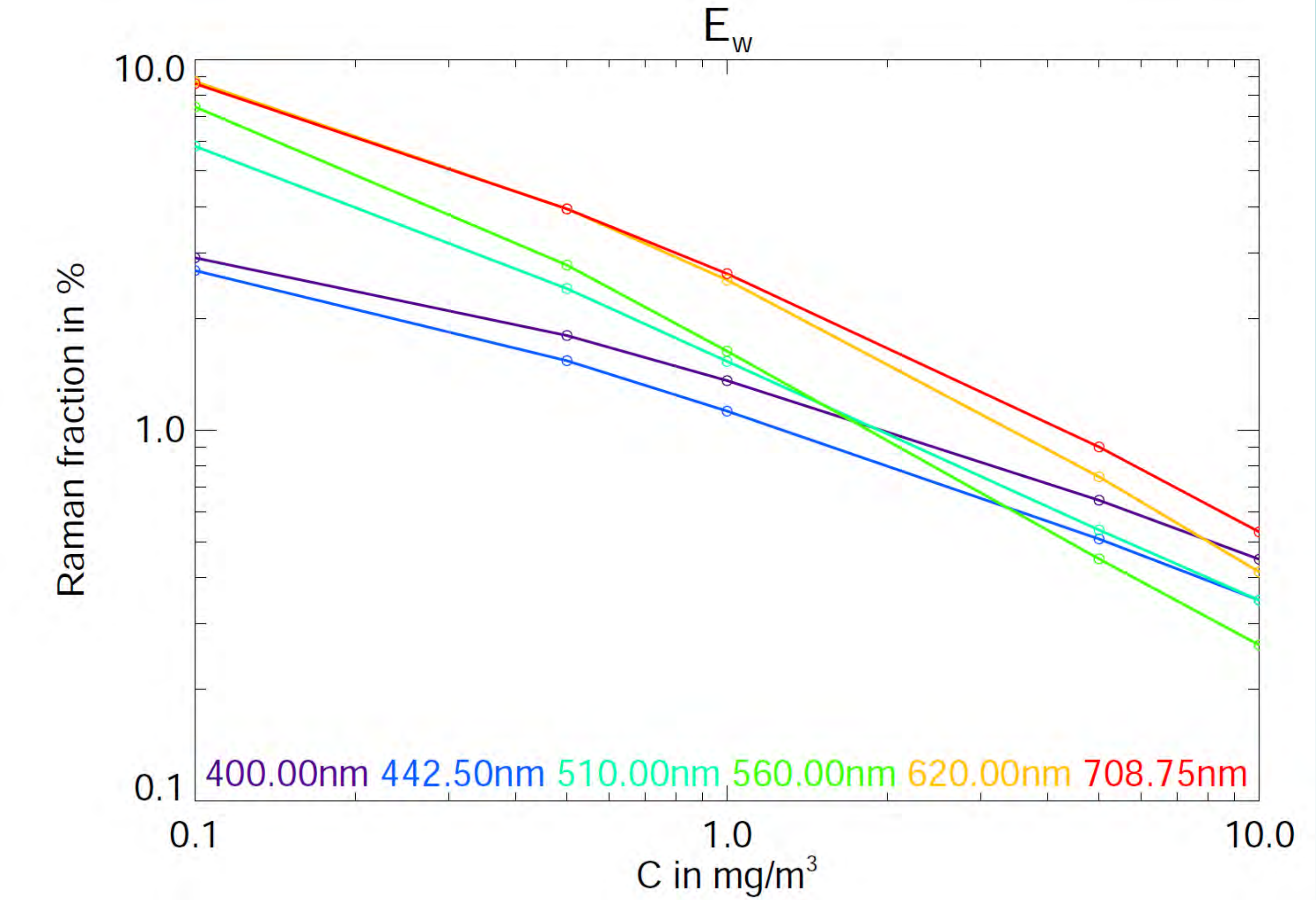
Effect of pure water IOPs uncertainties: turbid water





Relative deviations of Rlw due to lower and upper bounds of uncertainties of pure water absorption and scattering for S=0, T=0, apig=0.1, adet=0.15, ays=0.15, bpart=10.0, bwit=0.01

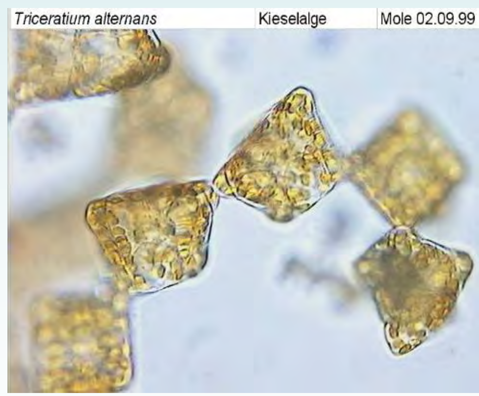
Effect of Raman scattering



The dependence of the water-leaving radiance on the chlorophyll concentration, for sea water with a temperature of 15°C and a salinity of 35 PSU. Results for six roughly equidistant OLCI channels were plotted representatively. The solar zenith angle is 41°.

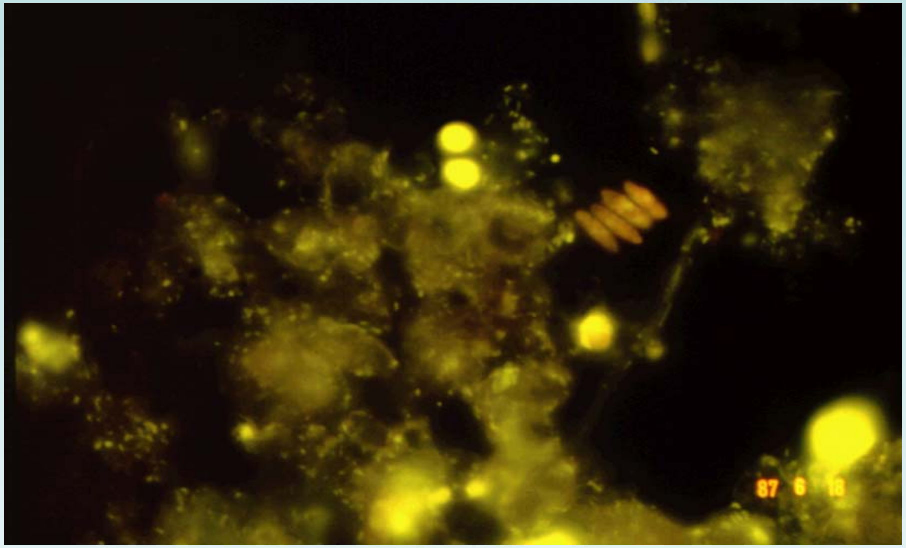
J v. Bismarck, water radiance project

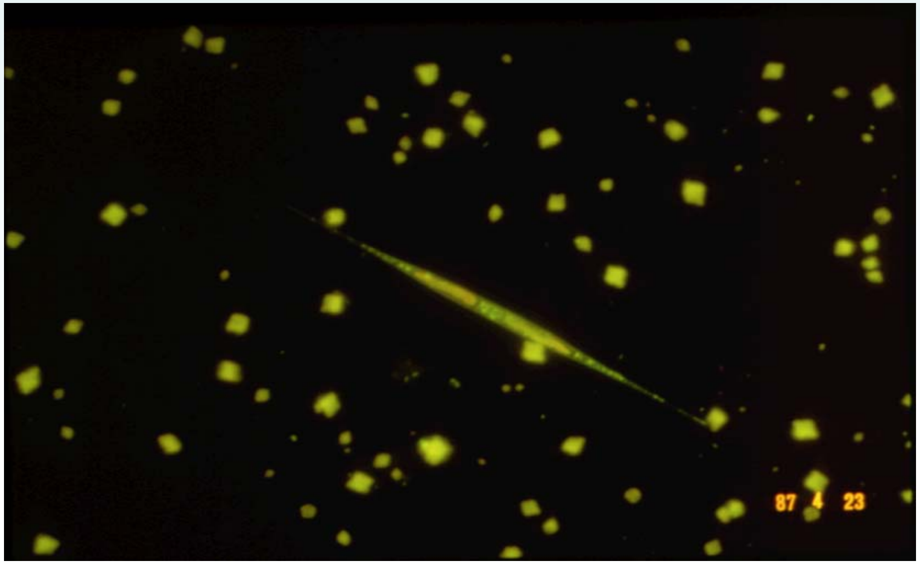
Phytoplankton



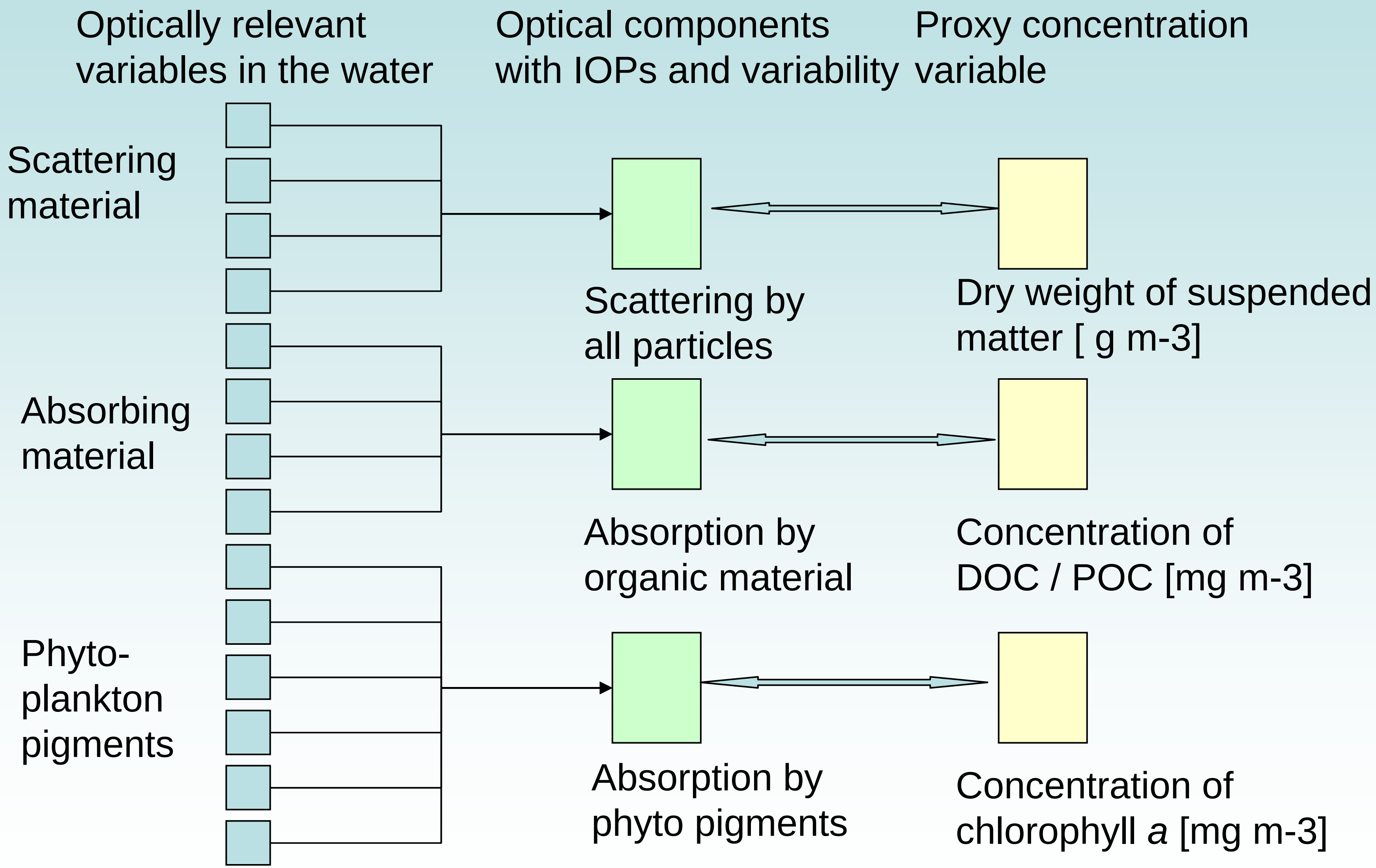
Photos by Marion Rademaker

Suspended Matter and Phytoplankton in Coastal Water

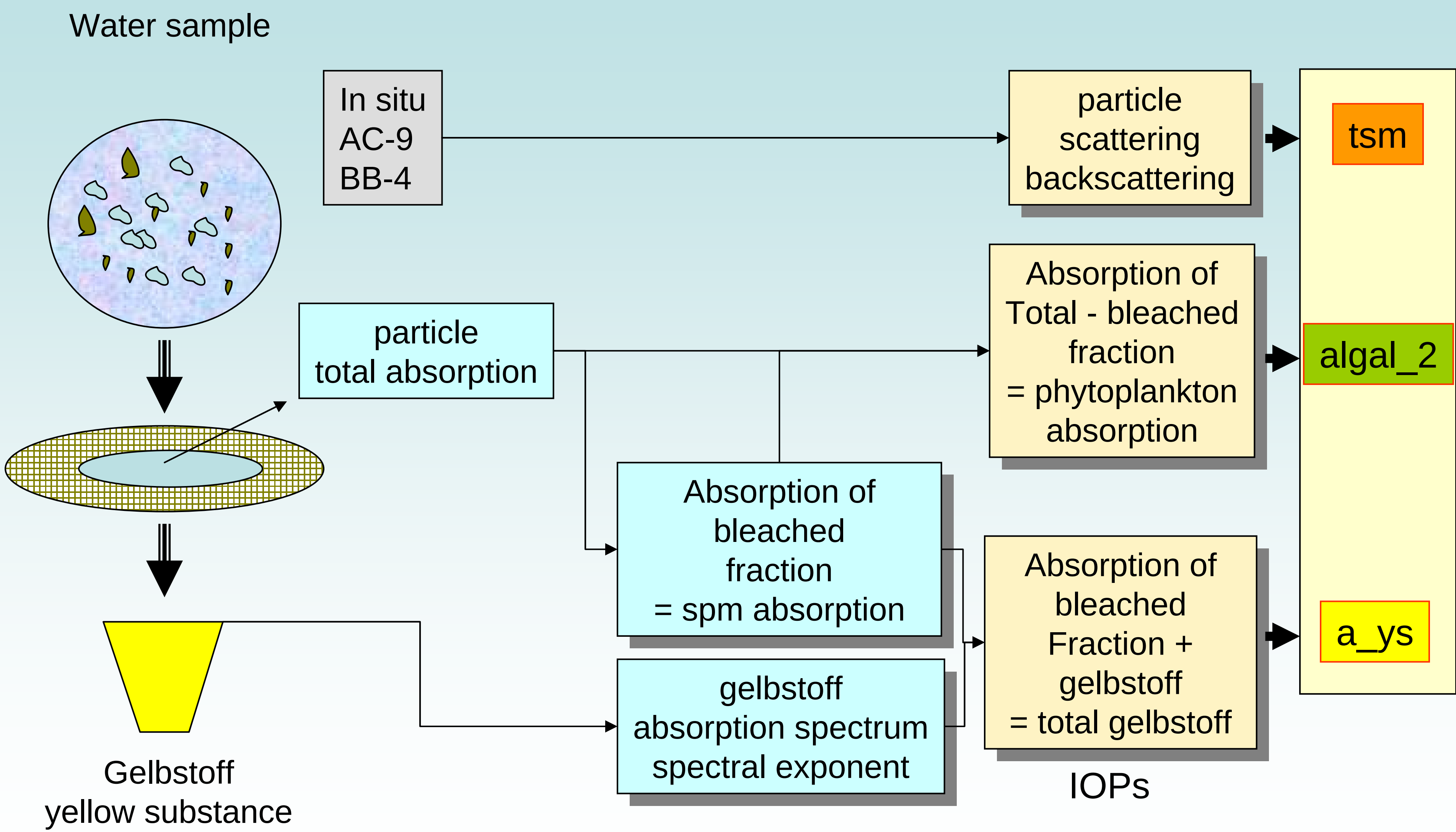




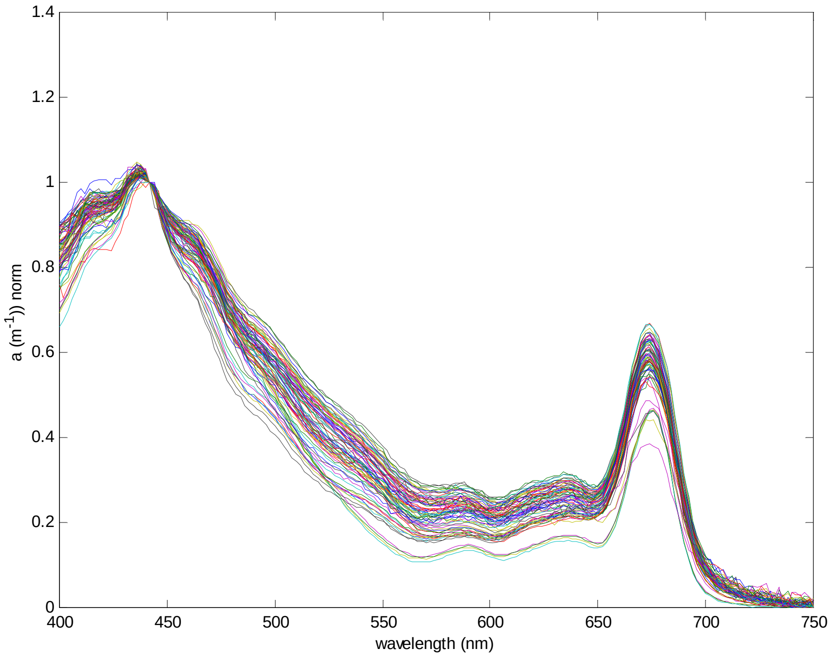
Uncertainties due to the bio-optical model

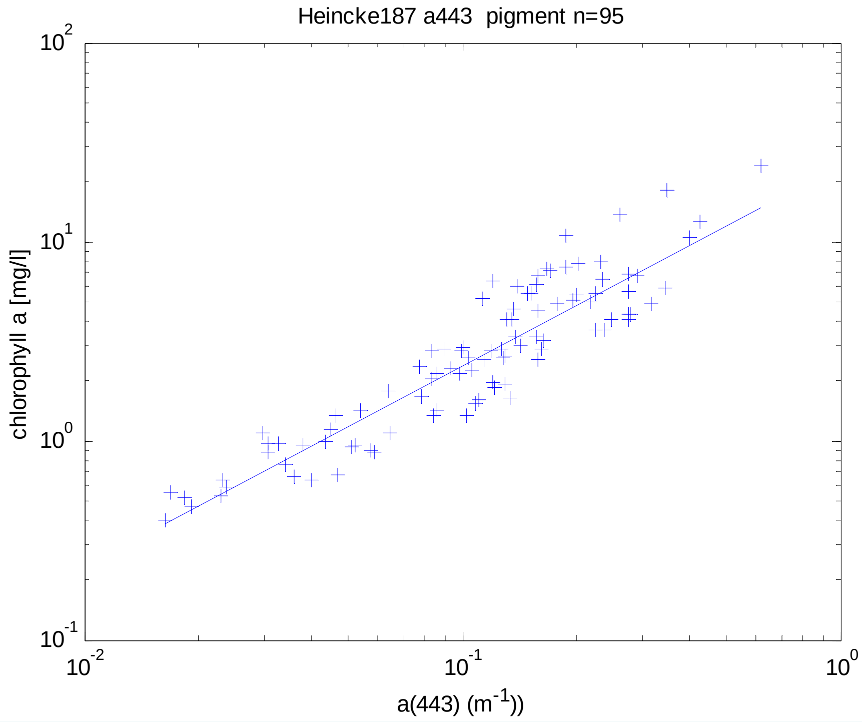


Scheme of a bio-optical model: optical components for MERIS



Uncertainties due to variability of optical properties

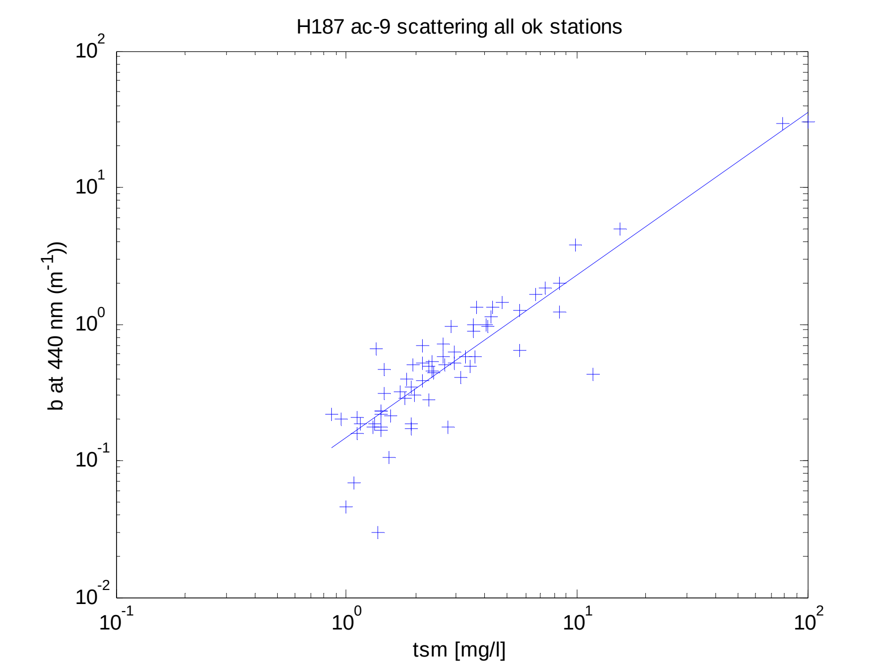




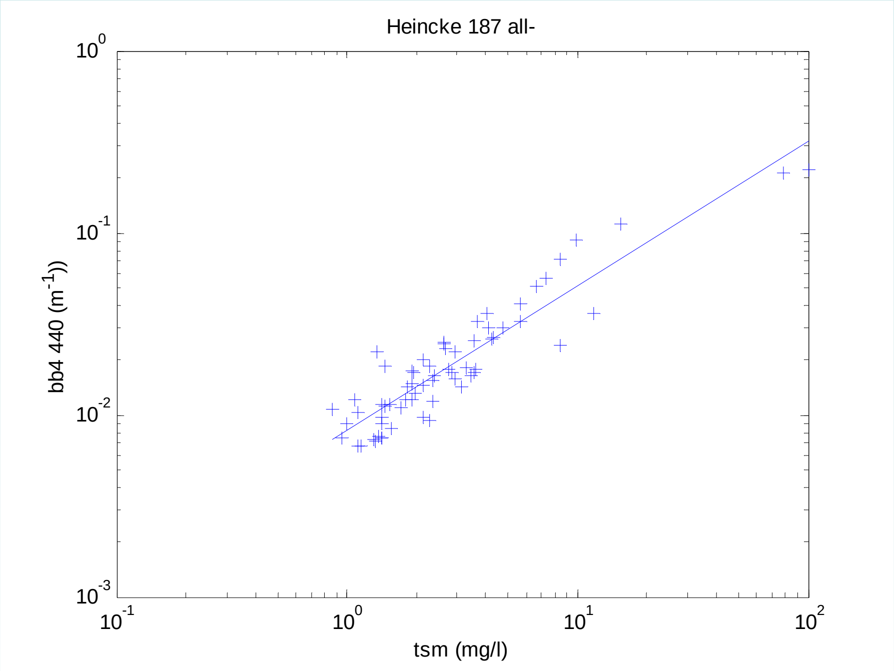
Normalized absorption spectra of North Sea phytoplankton
Summer period

Variability in the relationship between a_pig and chlorophyll concentration
Conversions:
Chl. a [mg m-3] = 21 * a_pig_442 ^1.04

TSM scattering, H187



AC-9

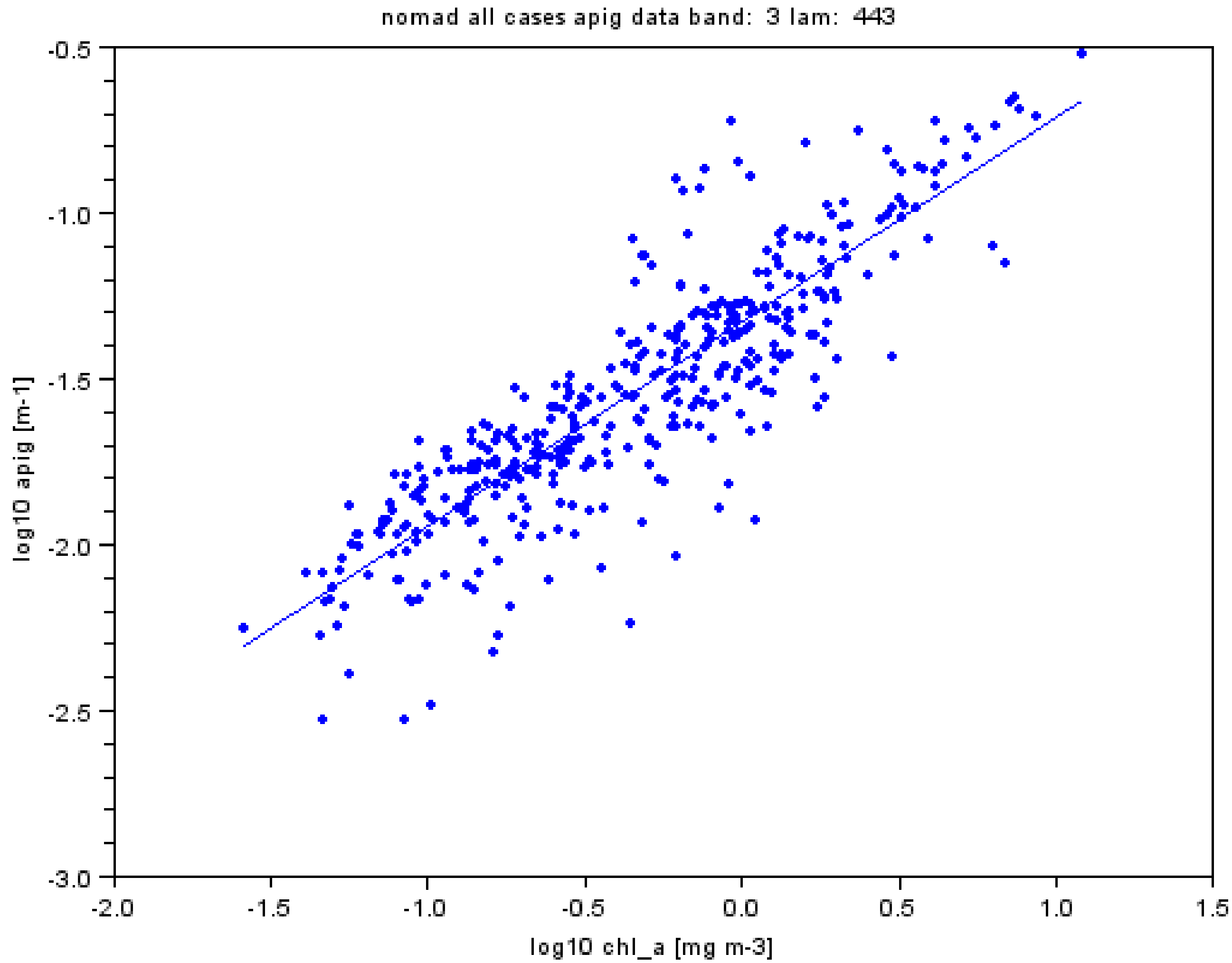


BB-4

Conversions:

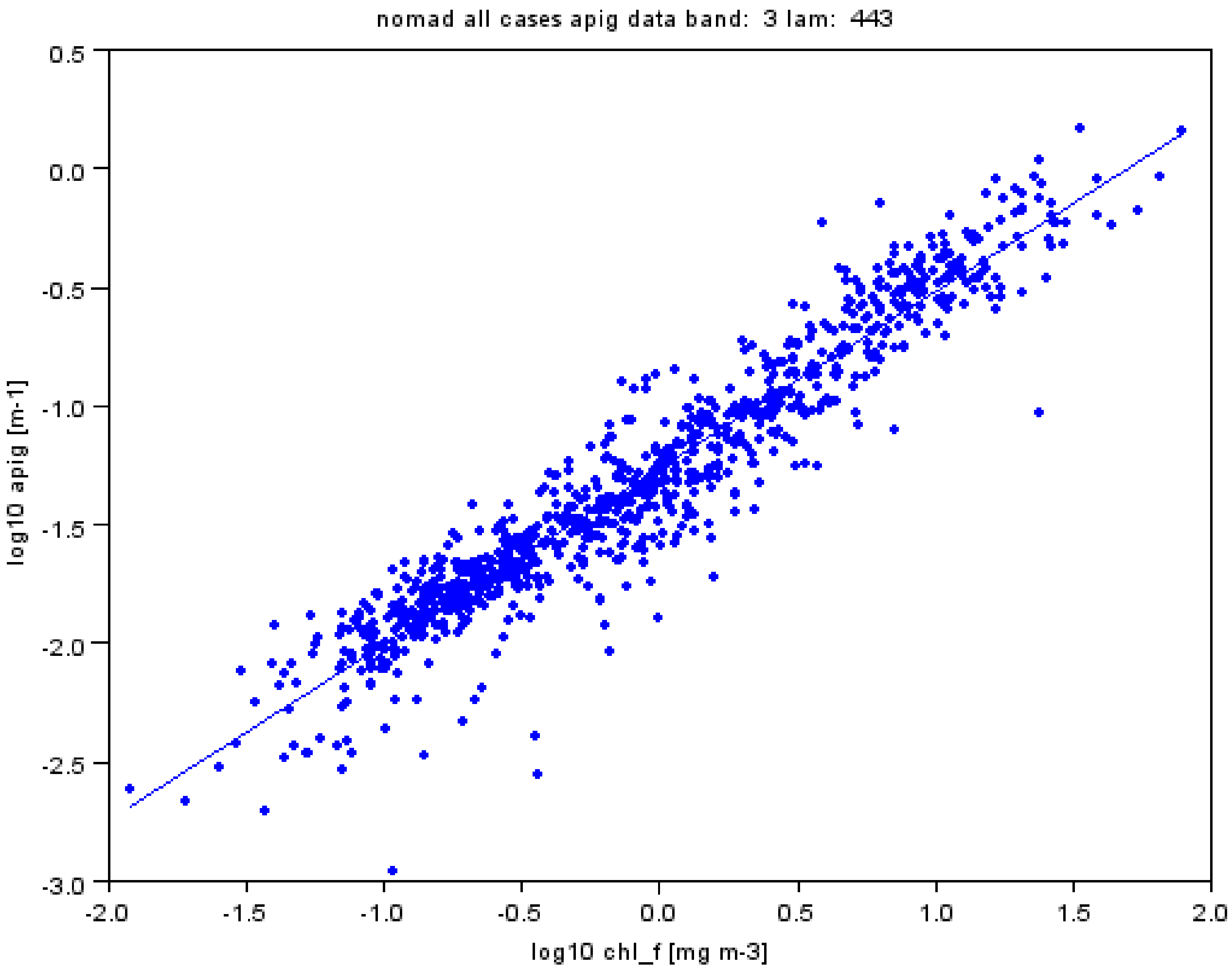
TSM [g m-3] = 1.72 * b_tsm_442

Bio-optical model: relationship between a_pig and chl_a (443 nm)



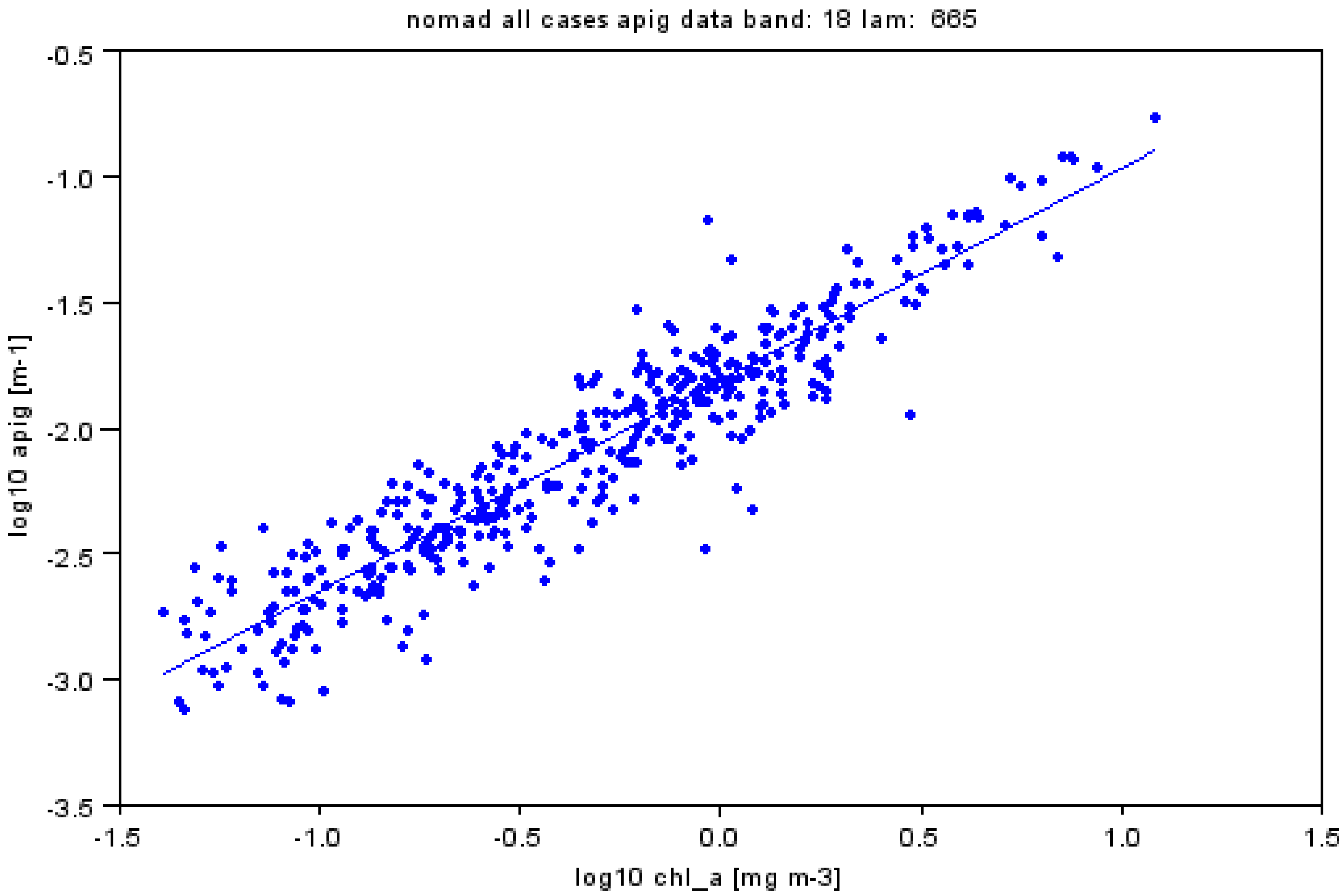
443 nm, log10 scale

Bio-optical model: relationship between a_pig and chl_f



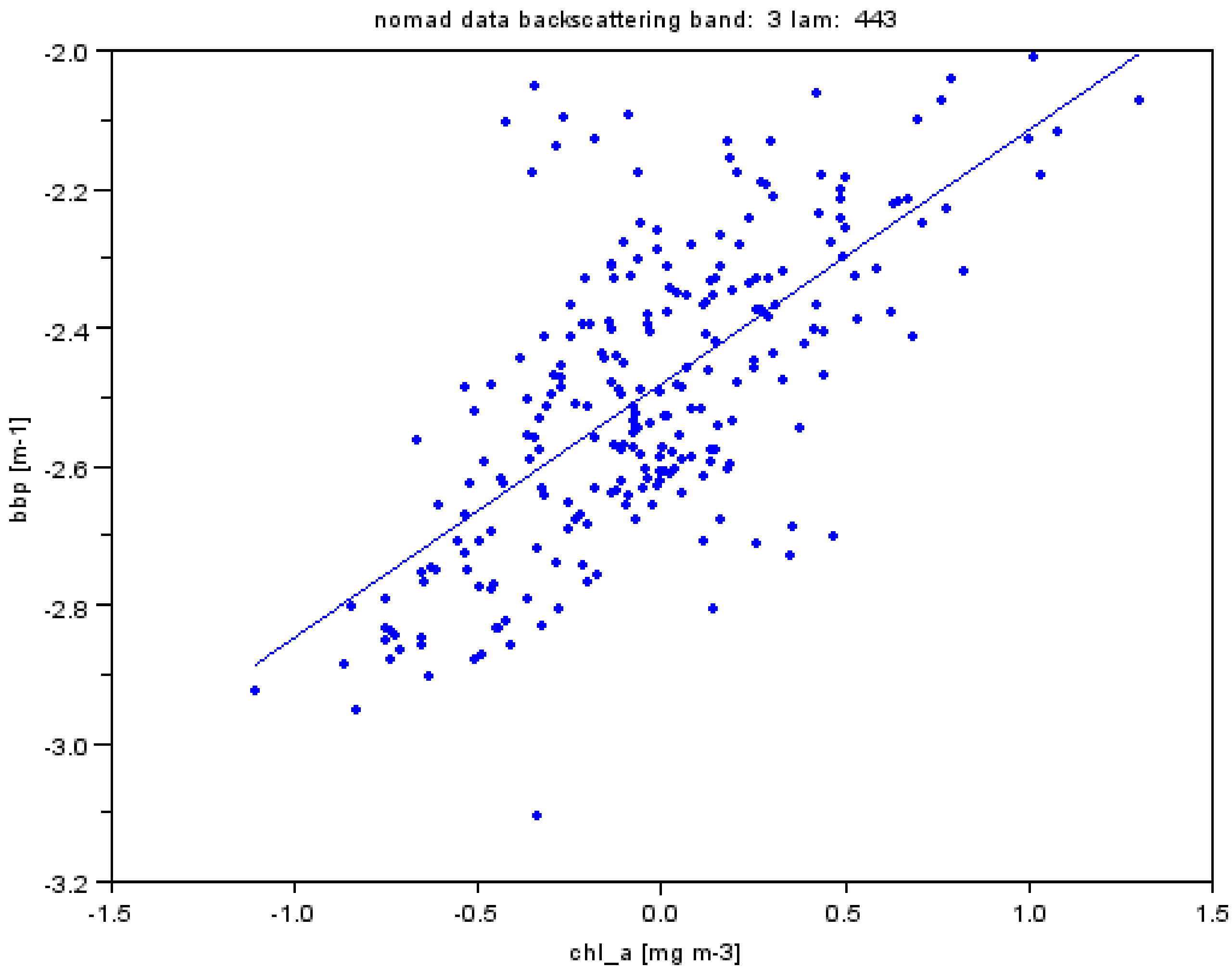
443 nm, log10 scale, 920-956 samples for chl_f

Bio-optical model: relationship between a_pig and chl_a (665 nm)



665 nm, log10 scale

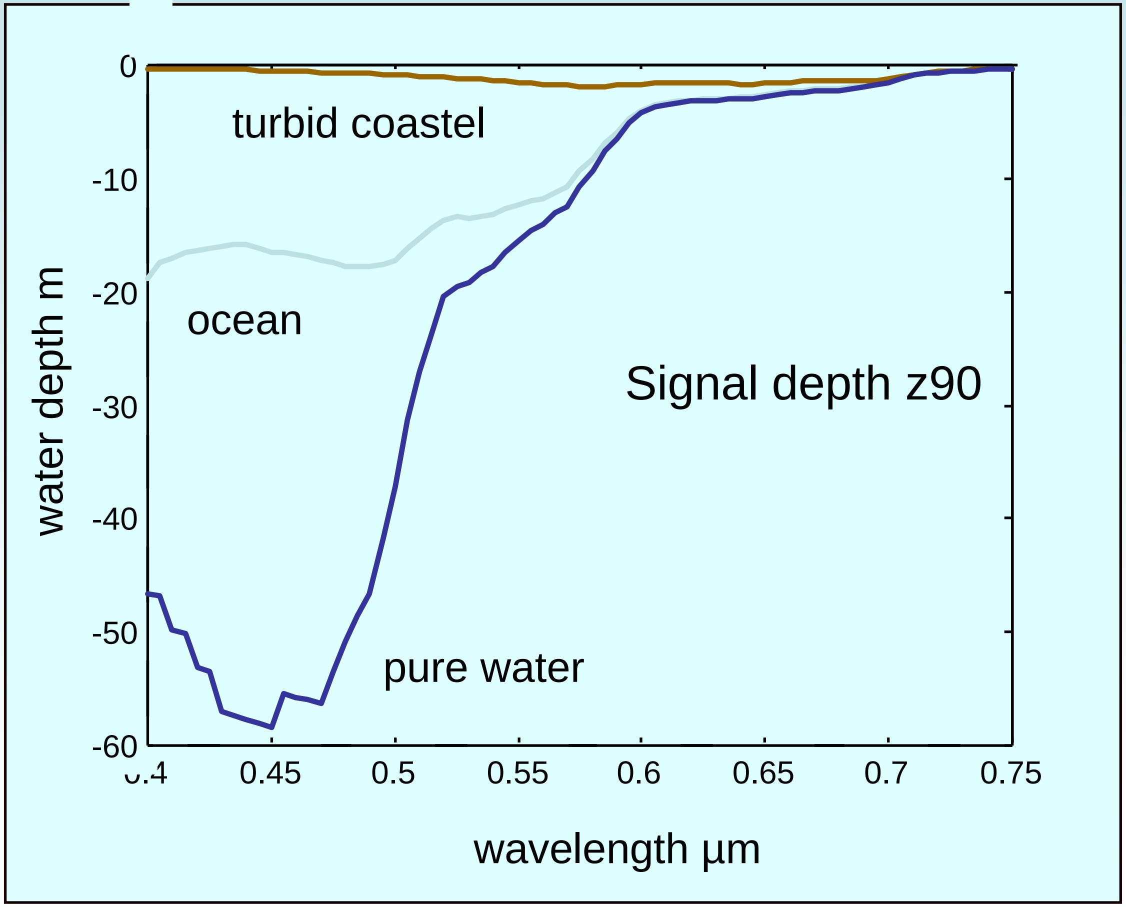
Relationship chl_f and backscattering coefficient



443 nm, 249 samples, log10 scale

Signal depth at different spectral bands

Multiband algorithms: the information for each band may come from a different water layer



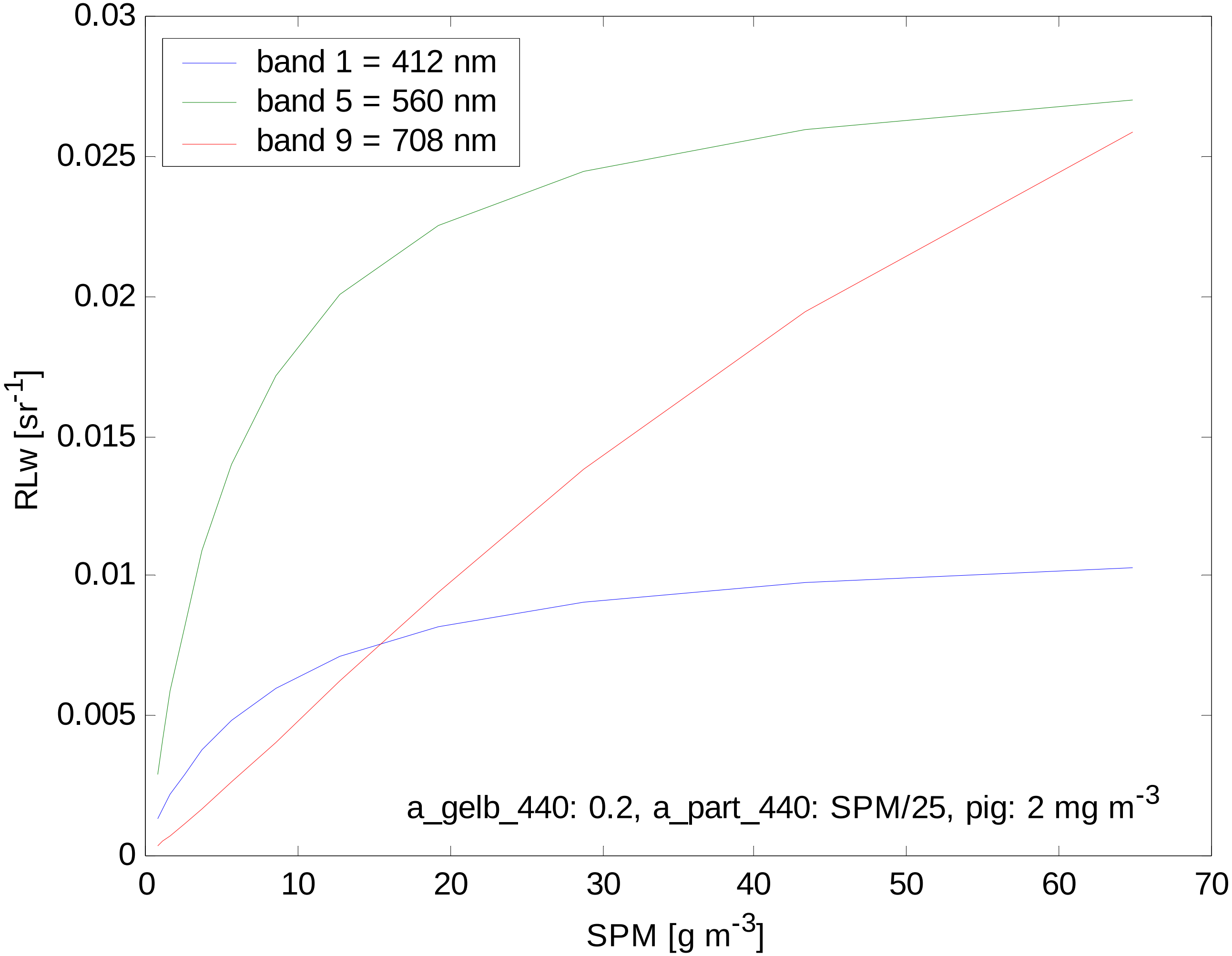
$z_{90} = 1/k$

coastal:
TSM=5 mg/l
Chlor.=5µg/l
Gelb=a_{380}=1m^{-1}

open ocean:
Chlor.=1µg/l

Sensitivity at different concentration ranges and spectral bands

RLw for MERIS bands 1 (412 nm), 6 (560 nm), 10 (708 nm)



Sensitivity of the reflectance at a spectral band depends on the concentration

To cover a large concentration range many bands from the blue to NIR range are necessary

Summary of uncertainty causes

- Sensor: calibration and stability
  - Must be monitored, remaining uncertainties should be < 1%
  - Vicarious adjustment or calibration necessary to improve accuracy of water reflectances
- Atmosphere is the dominant contributor to toa radiances
  - Any error in describing the atmosphere (atmospheric correction) produces a 10fold or even larger error in water reflectances
  - Improvements are still necessary
  - Small and thin clouds and cloud shadows still a problem
  - Adjacency effect
- Water surface contribute to reflectance by foam (white caps) and specularly reflected sky and sun light
  - T and S effect on refractive index for sun glint correction
- Pure water optics is variable and partly not sufficiently known
  - T, S and Raman scattering effects cause uncertainties in 5-10% range

Summary of uncertainty causes II

- Water constituents and their optical properties are variable
- Problem to define useful bio-optical component model
- Problem to separate different components and measure their IOPs indepently
- Variable relationship between concentrations and IOPs (50% range)
- Variable vertical distribution and sub-pixel patchiness: 50% range

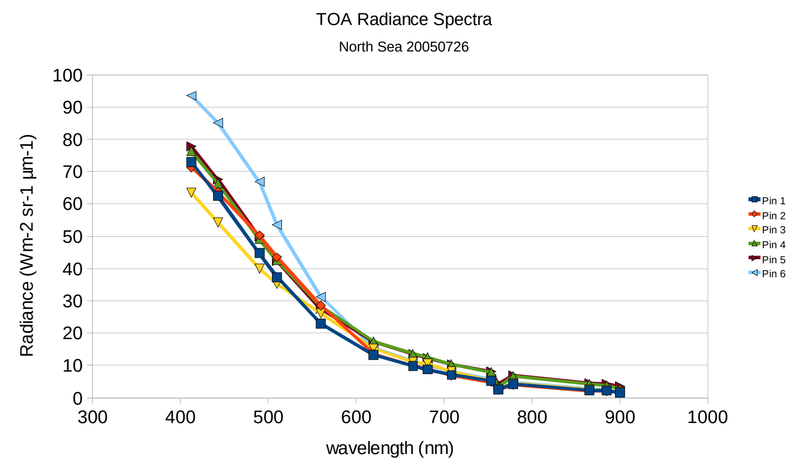
Next: Relationship between TOA reflectance spectra and water properties

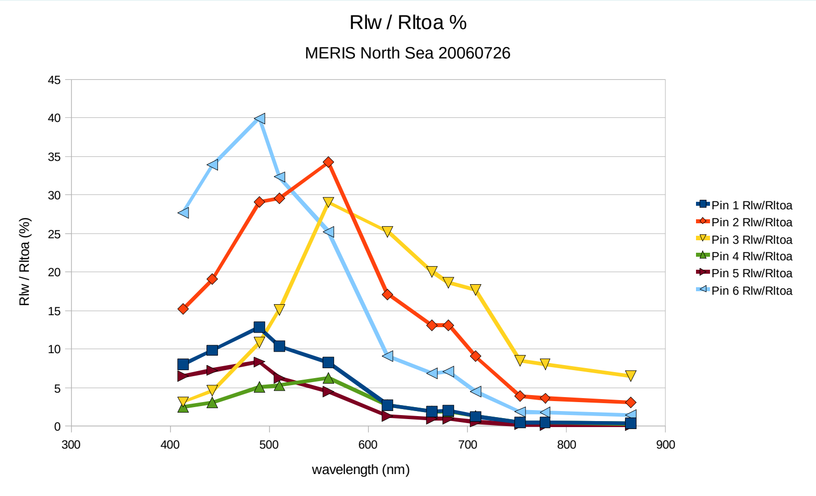
- Algorithms
- Validation
- Detection of failures
- Determination of uncertainties on a pixel-by-pixel bases
- How to reduce uncertainties

Exercises

- Use Scilab (similar to Matlab, but free): www.scilab.org
- Basic code of exercises will be distributed

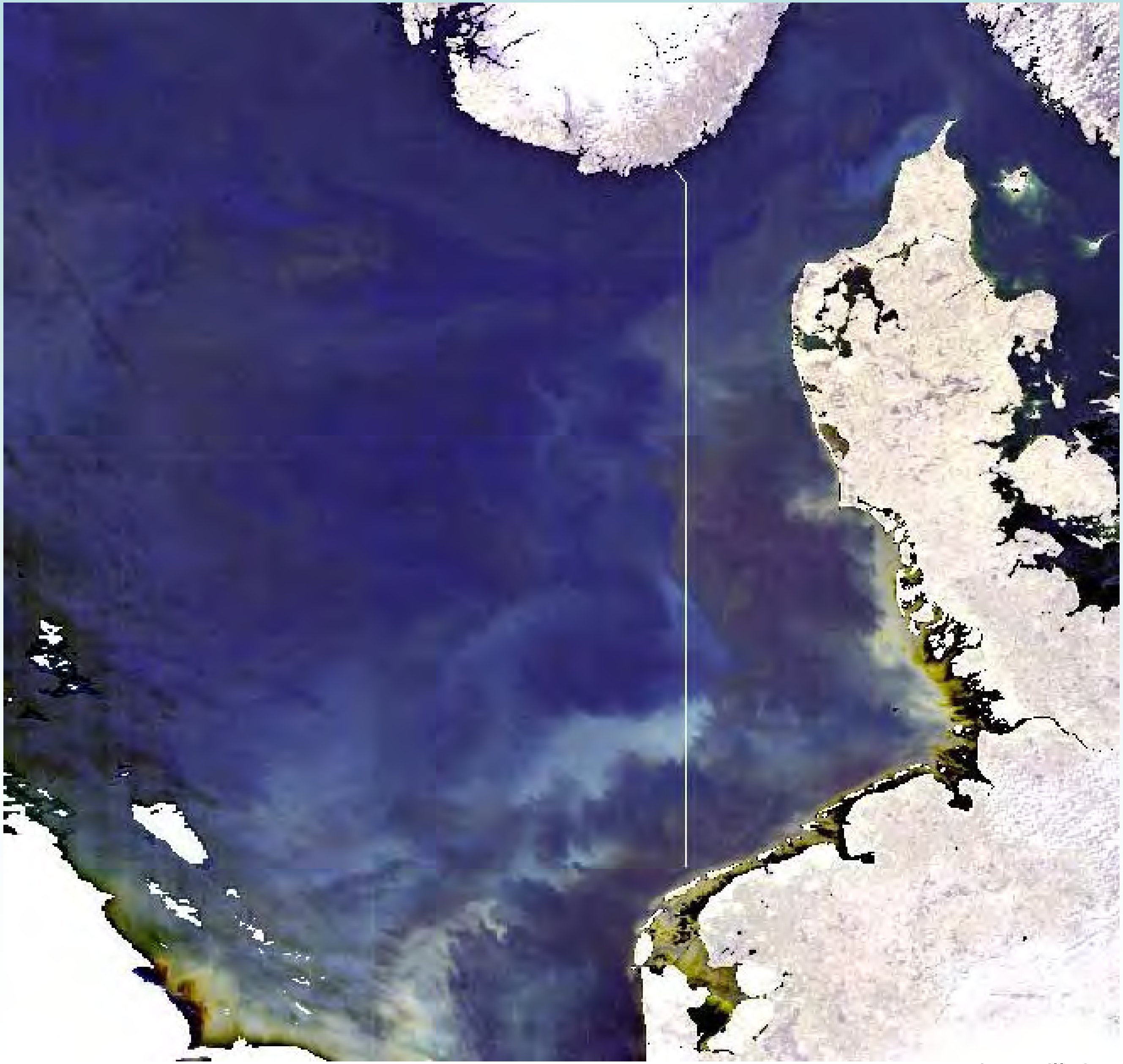
Exercise I: information content



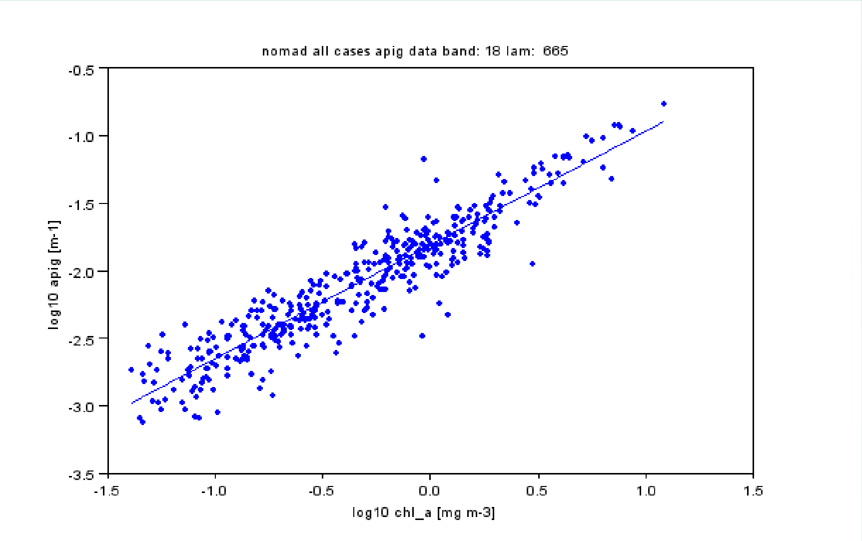


- TOA radiance spectra along transect
- Water reflectance spectra along transect
- Determine correlation matrix of spectral bands
- Perform principle component analysis
- How many independent variables can be derived?
- Repeat for different sections of the transect

Working transect MERIS 20080422 North Sea

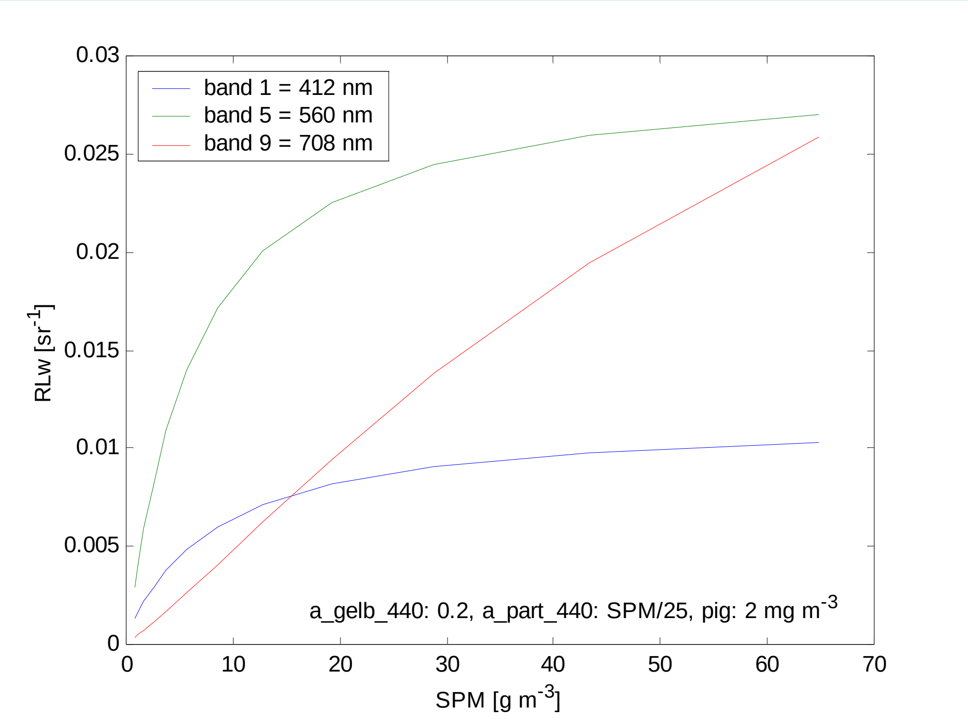


Exercise 2



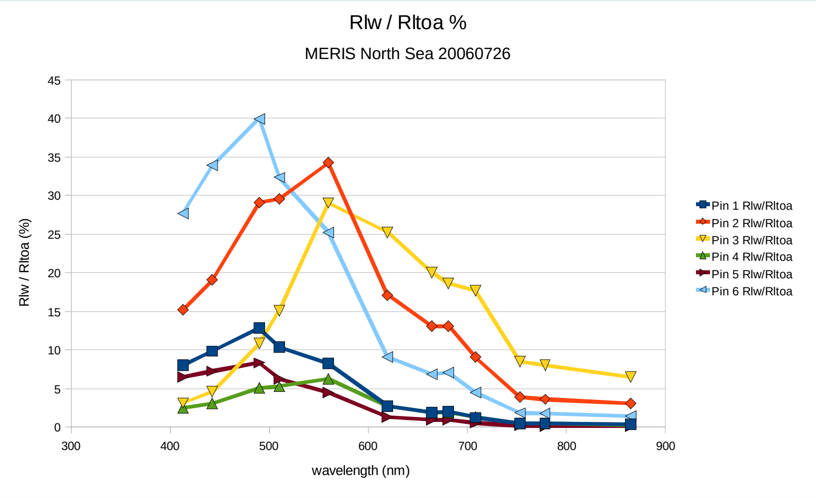
- Determine relationship between chlorophyll concentration and pigment absorption
- Use also bootstrapping method
- Determine uncertainty from standard deviation
- Try for different concentration ranges

Exercise 3: Saturation and masking effects



- Determine change in reflectance per concentration change
- Repeat for different ranges and mixtures
- Determine uncertainty of pigment retrieval in clear and turbid water

Exercise 4: retrieval error



- Simulate reflectance spectra
- Try to retrieve IOPs or concentrations from simulated using inverse modelling
- Try different mixtures
- Determine spectrum fit
- Determine retrieval error

Result exercise 1.1