Aerosol optical property retrieval from visible and infrared: sensitivity analysis.

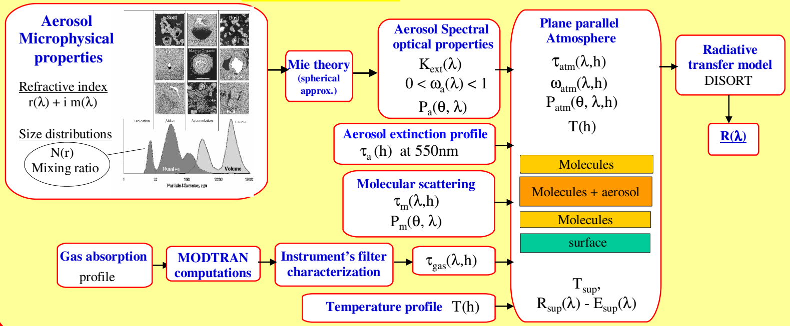
Carboni E. (1) , G.E. Thomas (1) , R.G. Grainger (1) , C.A. Poulsen (2) , R. Siddans (2)
(1) Oxford University, UK., (2) Rutherford Appleton Laboratories, UK.

ABSTRACT: A sensitivity analysis of a radiative transfer model for the retrieval of aerosol properties from satellite measurements will be presented. The model includes both visible and infrared components and will be used in conjunction with the SEVIRI (Spinning Enhanced Visible and Infra-red Imager) instrument on board of Meteosat Second Generation. This work is based on the ORAC aerosol retrieval algorithm, developed at Oxford University and Rutherford Appleton Laboratories for the visible and near infrared channels, with the extension to the two SEVIRI infrared channels centered at 10.8 and 12.1 micron. The forward model values of atmospheric scattering, absorption and emission are calculated by DISORT (DISCrete Ordinate Radiative Transfer) radiative transfer code. The forward model uses an aerosol database of macrophysical optical properties computed from published aerosol micophysical properties. The aerosol parameters we retrieve are: aerosol optical depth (at 550nm) and effective radius. We show that the IR channels are sensitive to the scattering and absorption of aerosol. This information is of particular interest when monitoring aerosol events, such as desert dust or a volcanic eruption. This application to SEVIRI is particularly interesting as it enables us to follow the aerosols evolution in time.

Oxford-RAL retrieval of Aerosol and Clouds (ORAC)

The Oxford-RAL retrieval of Aerosol and Clouds (ORAC) scheme was developed to determine aerosol properties from satellite borne radiometers such as SEVIRI and (A)ATSR instruments. The ORAC forward model is sensitive to aerosol size, chemical composition, and shape, as these characteristics determine aerosol radiative behavior. The addition of the 2 infrared channels add sensitivity to aerosol vertical distribution and surface temperature.

Forward model Computation scheme



SEVIRI

Spinning Enhanced Visible and Infra-Red Imager
On board of Meteosat Second Generation (MSG) geostationary satellite
Spatial resolution 3 Km. 15 min time resolution.
SEVIRI has 12 channels in the 0.6-14µm range. In this study we use 3 VIS-NIR + 2 IR channles centered at 0.640,0.809,1.64, 10.78, 11.94 [um]

Forward Model Details

- aerosol optical properties from OPAC or user defined components (updated for two IR channels)
- gas absorbing optical depth profile from MODTRAN computation .
- vertical profile of temperature (standard atm in 33 layer).
- radiative transfer solved calling DISORT for absorption, scattering and emission. vector of relative aerosol optical depth
- vector of spectral surface reflectances for SEVIRI VIS/IR channels
- geometric conditions (satellite zenith angle, solar zenith angle, relative azimuth angle)

OPTIMAL ESTMATION APPROACH (Rodger 2000)

FORWARD MODEL $y = F(x,b) + \varepsilon$

y is the measurement vector, x the state vector, F forward model, ε error measurement vector

LINEARISATION

For the purpose of assessing information content and to perform an error analysis it is necessary to linearize the forward model around some reference state vector x_0

$$y - F(x_0) = \frac{\partial F(x)}{\partial x}(x - x_0) + \varepsilon = K(x - x_0) + \varepsilon$$

y are the simulated SEVIRI reflectances and brightness temperatures

x are:
- AOD = aerosol optical depth at 550nm
- Reff = effective radius (between 0.01 and 10 um)
- Rs = surface reflectance at 550nm
- Ts = surface temperature [K]
- H = aerosol layer height

RETRIEVAL MODEL

State vector x is optimised to minimise the cost function:

$$J = (x-x_a)^T S_a^{-1}(x-x_a) + (F(x,b)-y)^T S_e^{-1} F(x,b)$$

This quantifies departure of modeled radiances (based on the state vector) from the observations and the departure of the state from prior knowledge:

Se = measurement covariance matrix
Sa = a priori covariance matrix

The solution state vector which minimises the cost function is

$$\hat{x} = x_a + A(x - x_a) + G_y \varepsilon_y = (I_n - A)x_a + Ax + G_y \varepsilon_y$$

G = gain matrix $G = \left(K^T S_e K + S_a^{-1}\right)^{-1} K^T S_e^{-1}$

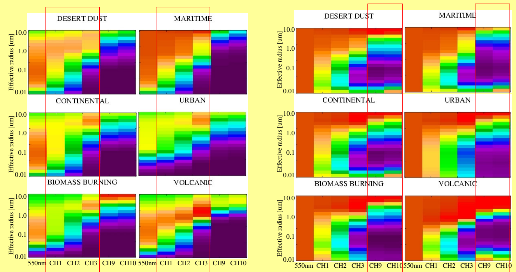
A = averaging kernel $A = GK$

Sx = solution covariance matrix $S_x = \left(K^T S_e^{-1} K + S_a^{-1}\right)^{-1}$

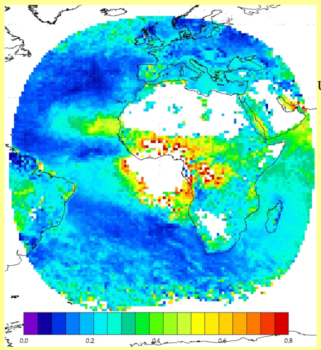
Errors in x can be estimated using these matrices e.g.:

$\hat{x} - x = (\mathbf{A} - \mathbf{I}_n)(x - x_a)$	Smoothing error
$+ \mathbf{G}_y \mathbf{K}_b (b - \hat{b})$	Model parameter error:
$+ \mathbf{G}_y \Delta f(x, b, b')$	Forward model error
$+ \mathbf{G}_y \varepsilon$	Error due to noise on measurements

AEROSOL OPTICAL PROPERTIES



Nadir satellite signals are influenced predominantly by scattering, in visible and near infrared spectral region (first 3 SEVIRI channels), and by total extinction in the infrared (ch 9 and 10)



SEVIRI AOD

(preliminary result)

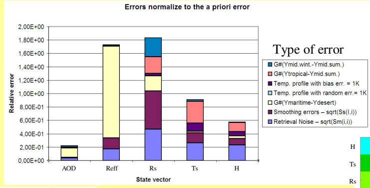
Monthly average AOD at 550nm from SEVIRI measurements at noon Using only first 3 Channel (VIS-NIR)
Case study: September 2004

Data obtained during ESA DUP/DUE GlobAerosol project study

ERROR ANALYSIS

Retrieval errors estimated for reference aerosol scenario:

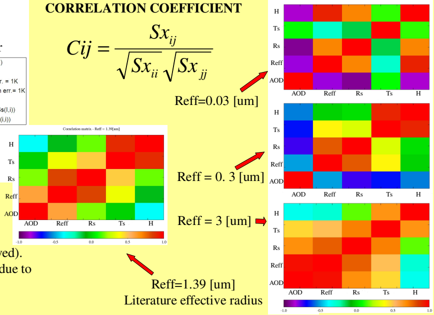
Desert dust over ocean
AOD=1
Reff=1.39 µm
Rs=0.045
H=3.5 km
Ts=290 K
Mid latitude summer gas absorption profile, standard atmosphere temperature profile



	AOD	Re [um]	Rs	Ts [K]	H [Km]
A priori state vector - Xa	1,00E+00	1,39E+00	4,50E-02	2,90E+02	3,50E+00
A priori variance – sqrt(Sa(i,i))	1,00E+00	2,00E+00	1,00E-02	1,00E+01	3,50E+00
Retrieval Noise – sqrt(Sm(i,i))	3,48E-02	3,45E-01	4,65E-03	2,61E+00	8,10E-01
Smoothing errors – sqrt(Ss(I,i))	8,23E-03	3,20E-01	5,71E-03	1,52E+00	3,34E-01
Solution errors - sqrt(Sx(i,i))	3,57E-02	4,71E-01	7,36E-03	3,03E+00	8,76E-01
G#(Ymaritime-Ydesert)	1,41E-01	2,75E+00	2,25E-03	1,85E-01	1,42E-01
Temp. profile with random err.= 1K	4,74E-05	8,57E-05	3,79E-06	1,43E-02	3,62E-03
Temp. profile with bias err. = 1K	2,20E-03	6,70E-03	3,72E-04	1,24E+00	2,12E-01
G#(Ytropical-Ymid.sum.)	-1,39E-02	-1,51E-02	2,48E-03	-3,23E+00	4,74E-01
G#(Ymid.wint.-Ymid.sum.)	2,11E-02	-2,00E-02	-2,84E-03	2,89E-01	3,60E-02
G#(Ysub.art.sum-Ymid.sum.)	6,59E-03	-1,96E-02	-1,14E-03	3,35E+00	-2,35E-01
G#(Ysub.art.wint.-Ymid.sum.)	3,36E-02	-9,59E-02	-5,29E-03	1,10E+01	-7,80E-01

CORRELATION COEFFICIENT

$$C_{ij} = \frac{Sx_{ij}}{\sqrt{Sx_{ii}}\sqrt{Sx_{jj}}}$$



Significant correlations exist between retrieved parameters (indicating not all parameters can be independently retrieved). Correlations vary with effective radius due to wavelength dependence of the optical properties.

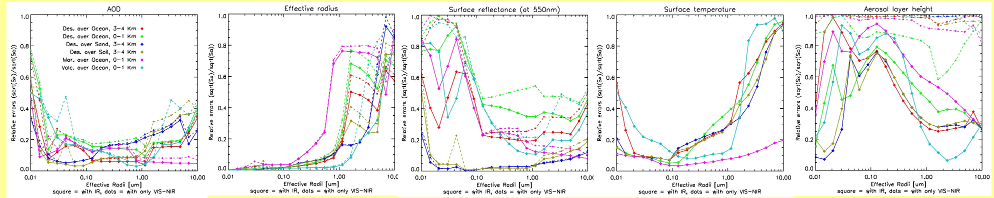
ERROR ANALYSIS

(i) Effect of changing aerosol & surface scenario
(ii) Effect of adding ir channels

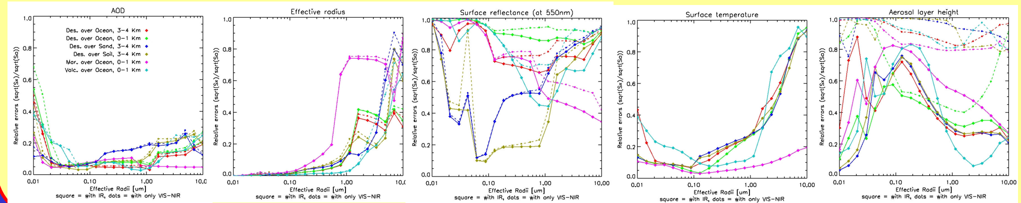
Random retrieval errors for different scenarios as a function of effective radius considering all the 5 channels (VIS-NIR-IR) and only the 3 VIS-NIR channels

Sx = errors on the state vector after adding measurements to the a priori → Sqrt(Sx(i,i))/sqrt(Sa(i,i)) as measurement of how much the measurements have reduced the uncertainties on each elements of x

CASE (A) *A priori*: AOD=1 exception for maritime case in which AOD=0.5, Ts = 290 K
Rs = 0.045 (Ocean), 0.220 (Sand), 0.107 (Soil) ΔRs a priori error = 100% Other *a priori* error value defined as in previous case study



CASE (B) As above but *a priori* error on surface reflectance = 0.01 for every surface



INFORMATION CONTENT

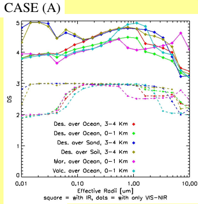
The information contend is described by the degrees of freedom of signal (DFS), which is a measure of the number of parameter that can be independently retrieved. It is given by the trace of the averaging kernel.

$$\mathrm{DFS} = \sum_{i=1}^{m} \frac{\lambda_i^2}{1 + \lambda_i} = tr(\mathrm{A})$$

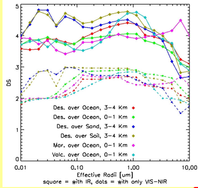
DFS typically less than 5 so not all state vector parameters can be independently retrieved (though DFS approaches 5 for some effective radii).

Adding the 2 IR channels increases the degrees of freedom by 1.2 to 2

CASE (A)



CASE (B)



CONCLUSION

In this work we present the an analysis of the errors pertaining to the retrieval of aerosol optical properties from the MSG SEVIRI vis-nir-ir imager. Here the analysis is focused on retrieval of desert dust events, for which it is expected that the ir channels can add useful information to vis-nir channels which are strongly affected by surface reflectance which is difficult to characterise.

The error analysis shows that the retrieval of AOD and effective radius is very sensitive to the assumed aerosol class. The errors in surface reflectance (Rs) and temperature (Ts) are dominated by retrieval noise and smoothing error, while aerosol height (H) is dominated by retrieval noise. Errors in the assumed gas absorption profile have little influence on Rs,Ts and H, while errors due to temperature profile are smaller that retrieval noise.
In the different scenarios considered, AOD is the retrieved parameter with smallest errors, aerosol effective radius is affected by more uncertainty especially for when the true Reff is larger than 1µm.

H and Ts are affected by relatively large errors, in particular we can have errors of around 2-3km for aerosol height and 2K in surface temperature in the central aerosol effective radius range (0.1-1um). When the particle size increases (more than 1um) the error on aerosol effective layer height can be less than 1km but in this situation information on effective radius and surface temperature is very limited. Nevertheless this study confirms that in certain circumstance the addition of the 2 IR SEVIRI channels adds new information of aerosol height, as well as surface temperature.

FUTURE WORK AND ANALISIS IMPROVMENTS

Estimate the further errors e.g:
- aerosol refractive index
- spectral shape of surface reflectance
- aerosol vertical profile shape

Implement the IR channels in ORAC (for application to real data), using:
- ECMWF data for gas and temperature profile
- RTTOV for fast computation of gas absorption

- Extend analysis to include other SEVIRI channels
- Transfer scheme to (A)ATSR instruments & exploit dual view capability of this class of instrument
- Investigate potential to gain information by considering SEVIRI observations at multiple times of day simultaneously (and thereby reduce ambiguity of surface BRDF/aerosol phase function).

REFERENCE:
Rodgers C.D. (2000), "Inverse methods for atmospheric sounding" Word Scientific Pubblishing.
Hess M. et al. (1998) "Optical Properties of Aerosol and Clouds: the Softwar Pakage OPAC", p831-844, Bull. Amer.Meteo.Society.
Dubovick O. et al (2002), J.Atm.Sci., 59, 590-608.
Marsh S.H. et al. (2004) "An Optimal Estimation Aerosol Retrieval Scheme For ATSR-2", AOPP Technical Memorandum.
Watts P.D. et al. (1998)" Study on Cloud Properties derived from METEOSAT second generation observations", EUMETSAT ITT,97/181,Final Report.

A special thanks to EODG group for support, suggestions and comments.
This work has been supported by NERC (Sahara dust project).

Author info:
E-mail: **elisa@atm.ox.ac.uk** (Elisa Carboni)
Tel: +44/0 1865 272 915
Fax: +44/0 1865 272 923

Physics Department:
Atmospheric, Oceanic & Planetary Physics,
Clarendon Laboratory,Parks Road
Oxford OX1 3PU
UK