THE IMAGING SPECTROMETER EXPERIMENT MOS ON IRS-P3

- Three Years of Experiences -

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ABSTRACT

The Modular Optoelectronic Scanner MOS is a spaceborne imaging spectrometer for the visible and near infrared range of optical spectra with an additional CCD line camera for the short-wave infrared at 1.6 µm. MOS is especially designed for remote sensing of the atmosphere-ocean system. The spectral high resolution of the instrument are used to test and validate new algorithms for derivation of water constituents and aerosol optical thickness over Case-2 waters of European, US and Indian coastal zones.

INTRODUCTION

Imaging spectrometers in the visible/near-infrared (VIS/NIR) region are instruments of increasing importance in the investigation of the ocean-atmosphere system (OAS). They can provide many narrow spectral channels at medium spatial resolution as well as best co-registration of all spectral channels. The acquired spectral high resolution data give new and improved potentials to transfer measured data into the spectral characteristics of the ocean and allow better quantitative retrieval of the geo-/bio-physical properties of the water, especially for the more turbid Case-2 water.

The Institute of Space Sensor Technology of the German Aerospace Center (DLR) has developed a VIS/NIR imaging spectrometer named MOS (Modular Optoelectronic Scanner) for ocean remote sensing. It was launched on March 21st 1996 by the Indian rocket PSLV-D3 on board the Indian Remote Sensing Satellite IRS-P3 into a sun-synchronous polar orbit at 817 km height.

BASIC GOALS OF THE MOS EXPERIMENT

The MOS experiment had some preceding activities (on satellites and MIR-Station) with non-imaging spectrometers /1/ of nearly the same spectral parameters. The objective was to test a new methodical idea for remote sensing of the Ocean-Atmosphere System. The experiences made during these experiments led at the beginning of the MOS study phase (1988) to the formulation of the following basic conditions:

- To have a chance for case-2 water remote sensing, or more general for coastal waters, one must be able to measure the spectral characteristic or signature with better spectral resolution than usually is possible with operational sensors (MS-Scanners).
- To get a promising chance to retrieve quantitative values about the coexisting and covarying water constituents (Chlorophyll, Sediments and Gelbstoff) one should acquire spectral data in a large number of channels with small bandwidth and by using a broad spectral range.
- The instrument channels must be carefully selected with respect to the target signature and the unavoidable absorption bands of atmospheric gases like Ozone (Chappuis-Band), Oxygen (A- and

B-Band) and the number of Water vapour bands (cp. Fig. 3). The last one are influencing the multispectral images because of high regional and time variability of atmospheric humidity. It hardly can be corrected.

- If possible – separate satellite measurements should be made of the amount of atmospheric scattering (degree of turbitidy), to get an estimate value for the atmospheric correction procedure.
- The data of the spectral high dimensional (hyperspectral) data cube must be of high quality concerning spectral purity, radiometric resolution and calibration and also long term stability of this parameters.

The deduced goals have been:

- To design and build a spectral imaging instrument, dedicated for Ocean Colour Remote Sensing with many (> 10) narrow spectral channels in the VIS-NIR range (400-1000 nm).
- To separate the problem of object signature and atmospheric disturbance by independent measurements in different spectral regions and with special designed optical means.
- To make experiments to prove the instrument concept and to get experiences in high spectral data handling and image processing.
- To develop algorithms and test the methodical concept with emphasis on Case-2 coastal water.
- To make measurements at different ocean/coastal regions, by satellite and synchronous ground truth to verify the algorithm or carry out its "regional tuning", if necessary.

THE MOS-PAYLOAD

The payload parameters were selected and designed for the conditions of remote sensing of the Ocean-Atmosphere-System (OAS). Because of the large amount of atmospheric scattering and its effect on top-of-atmosphere radiance (TOAR) we realised a separate measurement of atmospheric turbidity. This concept has been tested on previous missions (on Russian satellites and space stations Salyut 7 and MIR) with non-imaging spectrometers /2/. Following this concept, the MOS-complex consist of two imaging spectrometers (MOS-A, -B) for the VIS/NIR range and an additional CCD-line camera (MOS-C) to have one channel in the SWIR at 1.6 µm (Fig. 1). MOS-A is designed for measurements of atmospheric stray light (turbidity) in one window and 3 absorption channels of $\Delta\lambda$ = 1.4 nm in the O_2A-band near 760 nm. MOS-B is the main block for measuring the target features in 13 spectral VIS/NIR-images between 400-1010 nm, with a halfwidth of $\Delta\lambda$ = 10 nm (Table 1).

To meet the basic conditions concerning spectral data, the imaging spectrometer was selected as instrument concept. With this sensor principle it is easy possible to combine, on the one hand, a linear dispersion with high spectral resolution over the full VIS-NIR range for selection of a larger number of narrow channels with, on the other hand, the imaging of a ground swath into the focal plane with a high degree of geometrical congruence of the used spectral channels.

The imaging spectrometer concept is limited to small angles by fundamental optical imaging reasons. We have extended the FoV to ±7° by compensating the resulting non-flat focal curve and chromatic aberration over the wide spectrum of MOS-B by means of an staircase formed focal plane hybrid. At each stair of the hybrid is mounted a CCD-line of 512 elements of 23 x 480 μm^2 (not all elements are used, cp. Tab. 1). The hybrid is temperature stabilised at +5 ±0.1°C. The resulting swath width at ground for an orbit height of 817 km is ~ 200 km and nearly equal for all three blocks (Tab. 1). The pixel size is 520 m for MOS-B and –C, which is reasonable for Ocean Remote Sensing. For MOS-A we designed a larger pixel size, because of the low available radiance in the narrow absorber channels. This is permissible, because the atmospheric turbitidy does not change so rapidly in small scales.

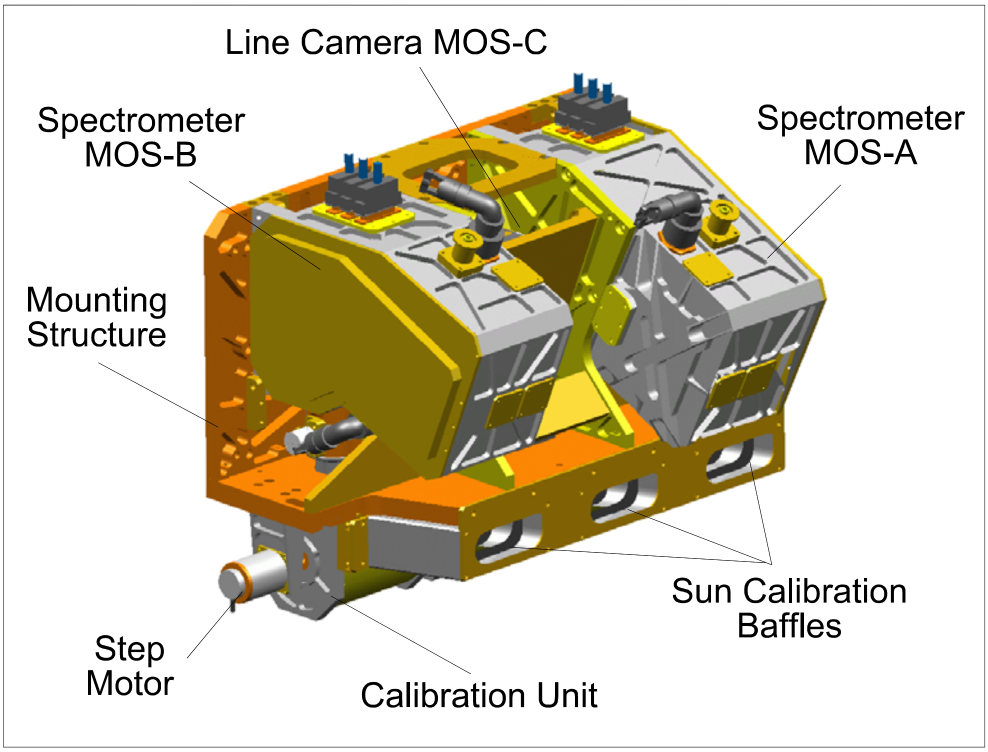

Fig. 1: Modular Optoelectronic Scanner MOS-IRS

Parameter	**MOS-A**	**MOS-B**	**MOS-C**
Spectral- Range (nm)	755 - 768	408- 1010	SWIR
No. of Channels	4	13	1
Wavelengths [nm]	756.7; 760.6; 763.5; 766.4 O_2A-band	408; 443; 485; 520; 570; 615; 650; 685; 750; 870; 1010 815; 945 (H_2O-vapor)	1600
spectral halfwidth [nm]	1.4	10	100
FOV along track x [deg] across track y [deg]	0.344 13.6	0.094 14.0	0.14 13.4
Swath Width [km]	195	200	192
No. of Pixels	140	384	299
Sampled pixel x*y [km^2]	1.57x1.4	0.52x0.52	0.52x0.64
Measuring Range L_{min} ...L_{max} [$\mu W cm^{-2} nm^{-1} sr^{-1}$]	0.1 .. 40	0.2 ... 65	0.5 ... 18

Tab. 1: MOS IRS – Technical Parameters

The hardware design and instrument realisation based on available technology. To reduce the costs and construction time all optical parts (refractive optics, grating) are commercial components modified by space proofed coatings (Fig. 2). The spectrometers are developed after the principle – faster, cheaper, better. Higher technical refinement and redundancy has been applied only to crucial parts which have decisive influence on data quality.

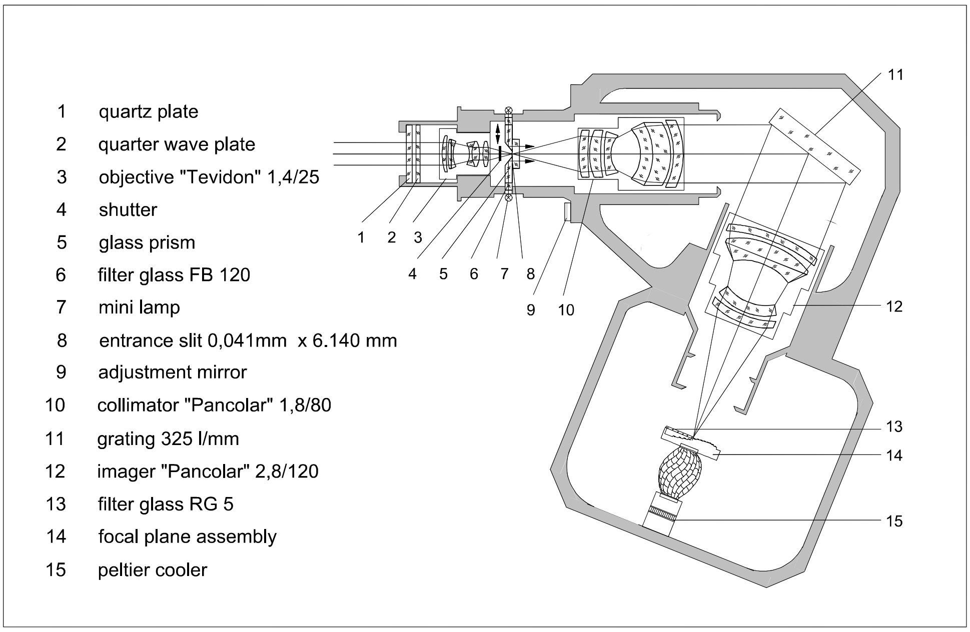

Fig. 2: Opto-mechanical Design Scheme of Block MOS-B

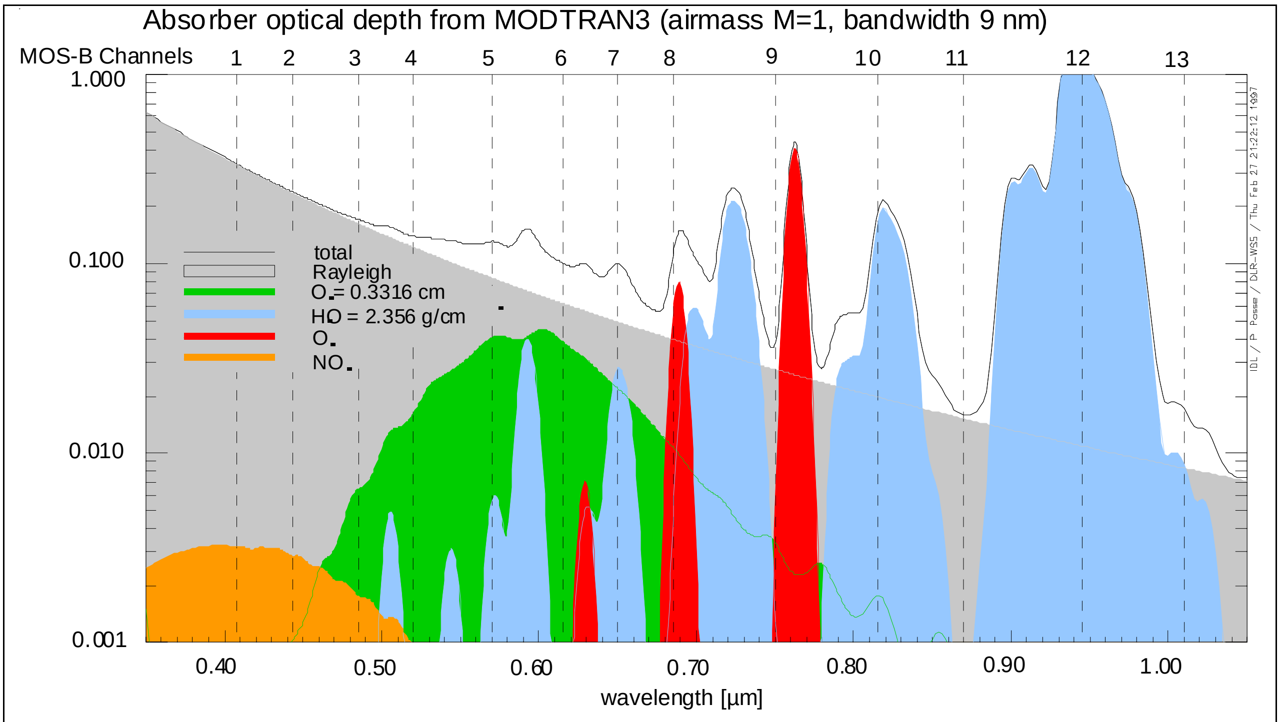

Fig. 3: Atmospheric Transmission and Absorber Bands

The wavelength of the channels were selected for case-2 water signatures as given in Tab. 1 and with respect to atmospheric absorbers as shown in Fig. 3. The totally used spectral range reaches from 0.4 to 1.6 µm, so we have channels with high (Rayleigh-dominated) and very low (only aerosol influenced) atmospheric scattering. To realise an optimal compromise between spectral range, number of channels and spectral purity a spectral halfwidth of $\Delta\lambda$ = 10 nm has been chosen in the MOS-B block for the target channels. For atmospheric turbidity measurements in the O_2-A band are only permissible halfwidths of $\Delta\lambda \leq 1.5$ nm. For the SWIR-channel line camera is used a spectral filter of $\Delta\lambda$ = 95 nm. This channel gives very profitable information even on atmospheric straylight or roughness of sea surface and glitter and has no water leaving signal, because the water is totally black in this spectral range due to its high absorption. This SWIR-data are very helpful for the assessment of the parameter retrieval algorithm and the state of the atmosphere (see colour image 1).
To meet the radiometric requirements a 16 bit quantisation was chosen. The reached S/N ratio guarantees an usable signal of better than 14 bit.

We took a lot of care of the signal handling in the video channel, including A/D converter. We compared the usual "correlated double sampling" (CDS) principle with the less spread "dual slope integration" (DSI) and decided to use the DSI and developed a dedicated small hybrid circuit, which up to now works in orbit since three years without restrictions.

SENSOR CALIBRATION

To guarantee the demanded radiometric data quality two on-board calibration concepts are realised in hardware – an internal sensitivity check and an external calibration to the Sun (SUNCAL). The internal check is made in each block with two small filament lamps mounted besides the entrance slit. Via the auxiliary slits the lamps are illuminating the collimator optic and after dispersion at the grating are illuminated the CCD-lines in the focal plane (Fig. 4). By powering the lamps in 4 high stabilised current levels and superposition of both lamps we have 16 levels of different illumination intensities for each channel in MOS-A and –B. In MOS-C the CCD is direct illuminated by the lamps.

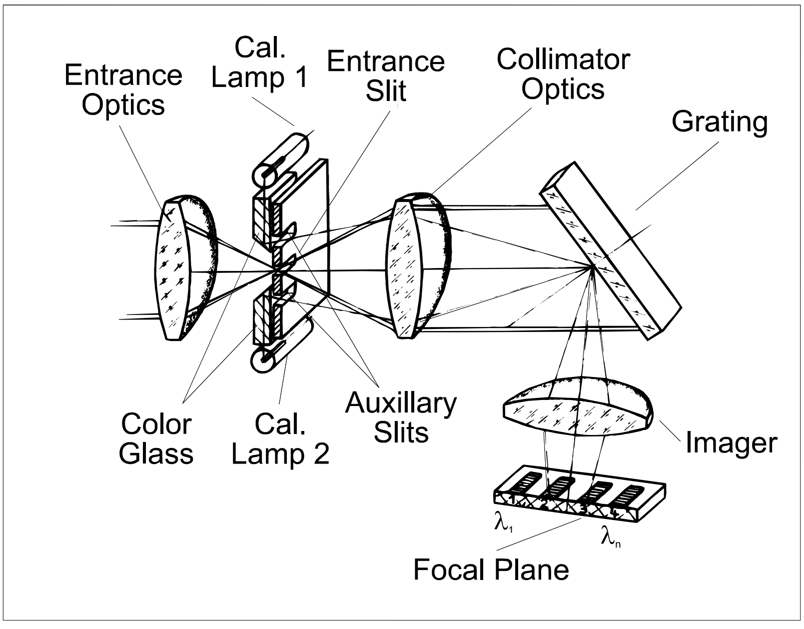

Fig. 4: Principle of the Imaging Spectrometer – Internal Calibration

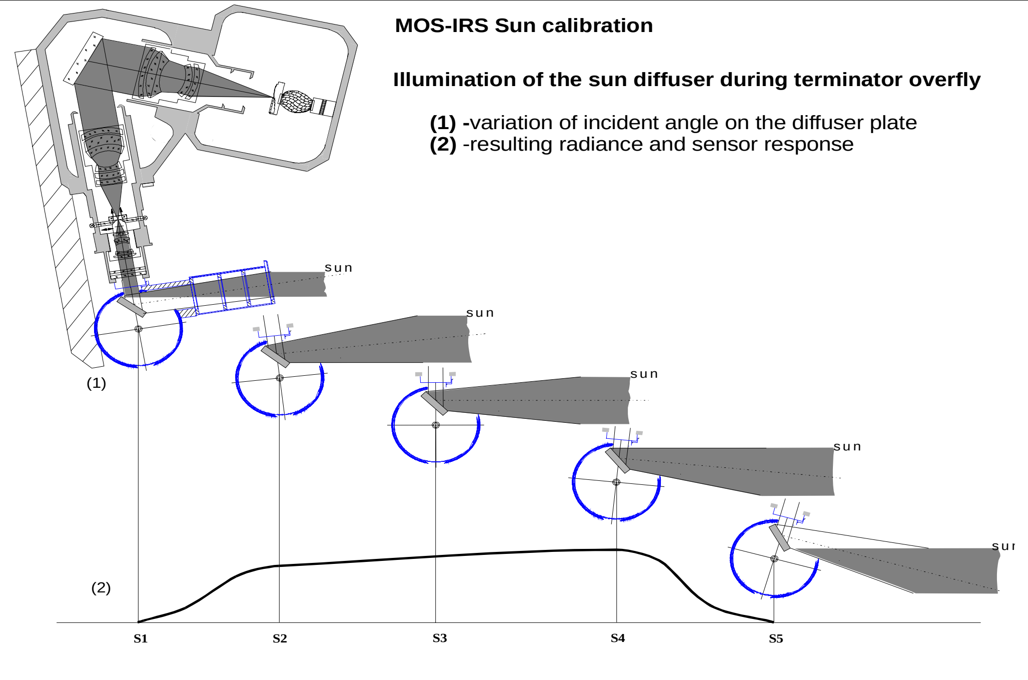

Fig. 5: MOS-IRS Sun Calibration

The SUNCAL is carried out during terminator crossing (at North Pole). During tangential illumination inside the CAL-Unit is rotated a white diffusor plate (SPECTRALON) into the Sun-rays and the brightness of the diffusor is measured by the spectrometers (Fig. 5). This data are used for absolute calibration of measured radiances in reference to the tables of Neckl & Labs /3/. During three years in orbit MOS showed a high stability of optical and electronical performance. All CCD-lines in MOS-A and –B (Si-arrays) as well as MOS-C (InGaAs-Array TH 7421 A) are working without any element defect. All arrays shows an increasing dark current which is changing in the mean since launch time at MOS-A from 500 to 2800 DN, at MOS-B from 150 to 350 DN and at MOS-C from 100 to 200 DN (DN= digital number or counts). This values gives no remarkable decrease of the dynamic range.

The internal lamp control and the SUN calibration show the same trend of sensitivity change, but with some difference for the three instruments. Unaccountably is up to now a slight rising sensitivity of up to +7%. Fig. 6 is shown the long term behaviour for SUN_CAL data of MOS-A, -B in comparison to the seasonal changing SUN-orbit plane angel. For MOS-B the difference of internal to SUN-calibration is ~ -3% for the short blue/green wavelength, becomes ~ 0 % up to channel 5 and reach +3 % for long wavelength at Channel 13. It shows a slight degradation in the blue/green region. Fig. 7 shows this change between first SUN-CAL of 16.5.96 and 25.3.99. For more details see /4/.

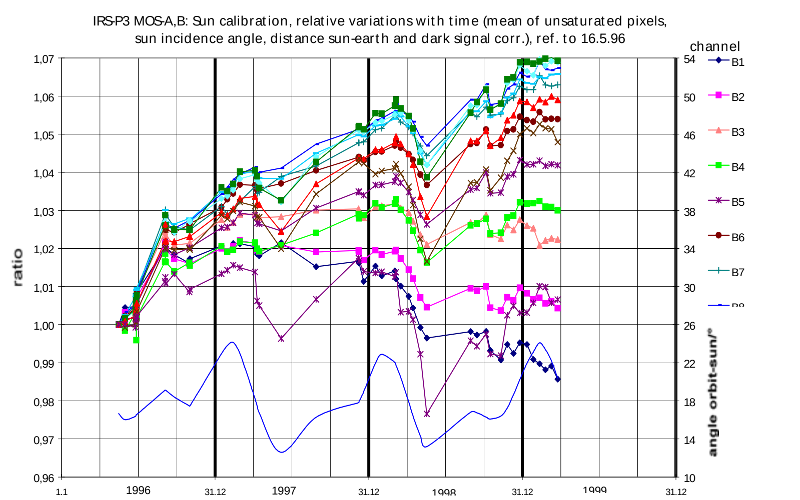

Fig. 6: Sun Calibration, Sensitivity Change MOS-A, -B

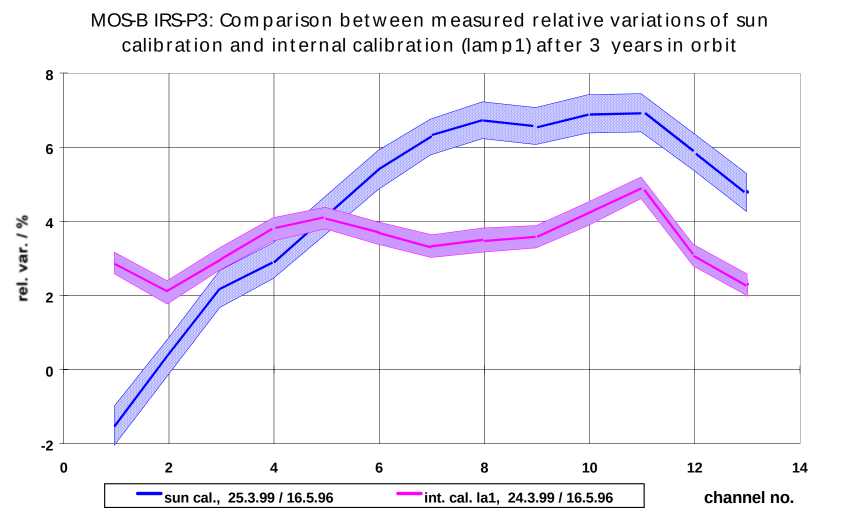

Fig. 7: Comparison Lamp-sun Calibration after 3 Years

DATA RECEPTION AND UTILISATION

At the beginning of the mission the data were received at the Indian Station Shadnagar near Hyderabad and at DLR-ground station Neustrelitz (150 km North of Berlin). Both stations are covering very interesting coastal regions around India and Europe. Because of the large scientific interests in the MOS data meanwhile an ESA-station at Maspalomas/Gran Canaria (since August 1997) and a NASA-station at Wallops Island (US-East Coast, since February 1999) are running for regular reception of 2-3 pathes each day. Unfortunately the satellite each year is working two times in the stellar mode for 2-3 month. During this time no nadir measurements are possible for earth observation. Fig. 8 shows the current distribution of receiving stations. All data of the different stations are archived in the central MOS-data archive at Neustrelitz. The processed level 1 data (calibrated and georeferenced) can be used for scientific purposes free of charge via the DLR data bank system ISIS. Nearly 30 groups of the international scientific community are using the data. Our own interest is the test and validation of the retrieval algorithm at different coastal regions.

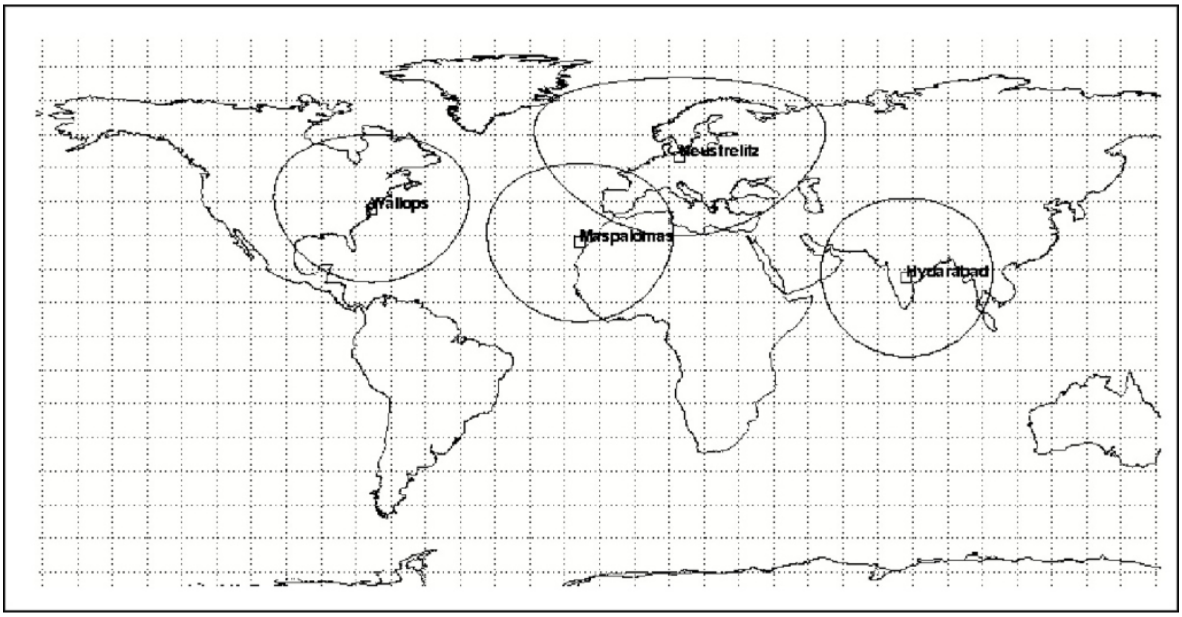

Fig. 8: MOS-IRS Receiving Stations

THE MOS PCI-ALGORITHM

The usual approach for interpretation of ocean RS-data is: After atmospheric correction (AC) of measured top-of-atmosphere (TOA) radiance is determined the bottom-of-atmosphere (BOA) or water leaving radiance L_w. The water constituents are than retrieved with different channel-ratio-algorithms. For AC is used the fact, that water is black for $\lambda > 700$ nm (black water condition) but this does not hold for turbid coastal Case-2 water. On the other hand atmospheric correction does not enhance the resolution or accuracy with respect to water constituents. AC removes atmospheric component from the measurement and realises a contrast enhancement with respect to water colour. The basic philosophy of the MOS algorithm development is therefore:

Features which are not radiometrically resolved in the TOA values, also cannot be seen after atmospheric correction in the BOA values!

Therefore a TOA approach must be possible and is attempted. The developed principle component inversion (PCI) algorithm dedicated for Case-2 water retrieves from MOS-TOA radiances at the same time 4 parameters: three water constituents – Chlorophyll C, Sediment S and Yellow substances (DOM) Y and the aerosol optical thickness τ_A of the atmosphere. This algorithm uses principal component analysis of modelled top-of-atmosphere radiance data to derive weightening coefficients for each measurement channel. These coefficients represent the contribution of information of the corresponding wavelength to the estimate of a given parameter. Based on modelling and inversion for different geophysical situations (i.e. types of atmosphere, different dominant factors in the water, regional specific models for the inherent water-optical properties etc.) are derived look-up-tables of coefficients from where suitable sets are selected for the interpretation of an actual scene by a linear estimator. The selection process of the coefficients needs a classification scheme that uses a priori knowledge as well as parameters derived from the actual scene. Fig. 9 shows the schematic approach. Theoretical basics and the detailed approach used for this algorithm are described in /5/, /6/.

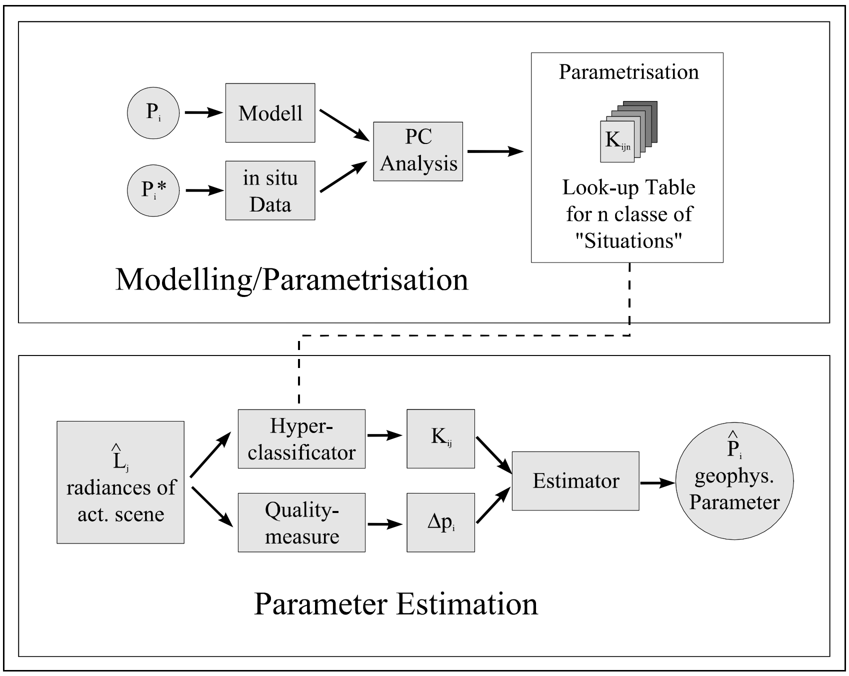

Fig. 9: Scheme of PCI Algorithm

TEST OF PCI-ALGORITHM

The complete validation of a retrieval algorithm like the PCI which works with TOA radiances can be done (for each channel) in three steps:

- ground measurements of water leaving L_w and of aerosol optical thickness τ_A and computation of TOAR by radiative transfer calculations and comparison with measured TOAR
- ground measurements of in-water inherent (absorption, scattering coefficients) and apparent (reflectance R_V, attenuation K_d) parameters for regional tuning of the bio-optical model, used for calculating the look-up tables of the PCI. Retrieve the water constituents (C, S, Y) and τ_A and compare it with in-situ values by water sample analysis
- atmospheric correction of measured TOAR and derivation of BOAR-values (e.g. L_w) and compare the calculated τ_A with the ground truth τ_A and also the calculated L_w with in-situ measured (e.g. from ship).

This is an extensive work and requires knowledge on the accuracy of the used calculations (e.g. radiative transfer model, bio-optical model, constituent retrieval algorithm etc.) and of the measured ground truth data. This work is not yet finished. Here will be shown examples giving an impression, that the MOS-PCI-Algorithm is well separating the information of the hyperspectral data set in that parts originated by absorbing and scattering Chlorophyll C, scattering Sediment (TSM), absorbing Gelbstoff Y (DOM) and the atmospheric scattering τ_A.

EXAMPLES OF DATA APPLICATIONS

IMAGE 1

PCI Algorithm Performance – "Separation of components"
Looking at the ocean from space one always sees a mixture of different phenomena: Rayleigh-scattering and scattering by aerosols in the atmosphere, and scattering and absorption by different water constituents. Because these phenomena have different spectral behaviour and main features are appearing in different ranges of the spectrum it is possible to separate the single components using the spectral high resolution data. In the SWIR region at 1.6 µm the water is black, also at high concentration of constituents. The features are of atmospheric origin.
The two scenes of the Strait of Gibraltar were processed using Principal Component Inversion technique. It demonstrates impressively that the decomposition is possible, even under extreme atmospheric conditions. The huge variation in the atmosphere does not affect the results obtained for the water constituents, what proofs the quality and stability of the PCI algorithm. The 1.6 µm image shows the evidence of the derived τ_A (750 nm) features.

IMAGE 2

PCI-Algorithm Performance -„Coccolithophoride blooms“
Coccolithophorides are a special type of Phytoplankton that is characterised by having an external shell composed of calcareous plates. Although it is Phytoplankton and performs photosynthesis it does not appear green but white because of high scattering. In some areas of the ocean blooms of Coccolithophorides happen regularly causing a milky colour of the water. The image shows an example of the bloom in the Skagerrak between Norway and Denmark. By the PCIA the Coco-patches are identified as "Sediments" but also Chlorophyll is found in and around the patches. The derived τ_A-pattern is similar to 1.6 µ image (like in Image 1)

IMAGE 3

„River Discharges and Coastal Pollution“
The images illustrates the importance of coastal monitoring. Rivers bring fresh water and nutrients to the sea, causing areas of increased bioproductivity. On the other hand rivers discharge also huge amounts of suspended matter (e.g. sediments) into the sea. The related currents also transport dangerous or toxic matter either suspended or bound to the sediments. For this reason it is necessary to understand transportation and sedimentation processes to prepare measures of coastal management.

WHAT WE LEARNED

Concerning the instrument and the mission we learned that:

- It has been demonstrated, that the needed sensor parameters (high spectral dimension, small non-overlapping channels, high radiometric resolution, long term stability of performance and calibration) can be realised with relative simple and inexpensive hardware. The pixel size difference in the channels is only ~ 2 % and the shift of the central wavelength between the center of swath and the corners is ~ 1 nm. This are essential reasons for the data quality in the 13 spectral channels of MOS-B.
- The spectral design concept is successful but low level linearity and the radiometric sensitivity should be improved, especially in the NIR-window channels, which give the main information on atmospheric turbidity and water surface signal (sea state, roughness, glitter).
- The spectral extension into the SWIR-region at 1.6 µm with MOS-C is very helpful for the atmospheric part in the TOA signal (cp. Colour image 1) and for ice, snow, cloud and water discrimination.
- The calibration concept – with periodically external SUN-CAL and internal LAMP-CAL procedures – was successful verified. In conclusion we have a good long term stability of the MOS-blocks and the ability of regular updating of the CAL-values.
- The degradation of the CCD-lines in the non-hermetised MOS-B focal plane is up to now (after 3 years) surprisingly less than commonly expected. The highest degration is found at the InGaAs line (THOMSON TH 7421A) for the 1.6 µm channel in MOS-C with regard of a rising dark current level and sensitivity change of individual line elements.

Concerning remote sensing methodology and retrieval algorithm we can emphasise that:

- The interpretation of TOA radiances can be done successful. The parameter retrieval from spectral high-dimensional TOA data is working well and has been experimentally confirmed, even without atmospheric correction.
- The PCI algorithm has demonstrated the separation of the atmospheric and water part in the TOA-signal. The water constituents (C, S, Y) can be separated and quantified in Case-2 water (colour image 1 and 2).
- The PCIA is working very fast and stable. It takes on a workstation (SUN) less than 1 min. to process a MOS-scene (200x200 km^2) from level 1 to the four parameter images (C, S, Y, τ_A).
- The application of the PCIA gives useful level 2 parameter images for monitoring coastal state and management decisions (colour image 3).
- The goal of retrieving the aerosol optical thickness τ_A as one in-situ value for the atmospheric correction from the MOS-A data in the O_2-A-Band at 760 nm and the adjacent window (757 nm) could not reached. The method has been not precise enough. Therefore and because the PCIA also gives the τ_A-values we decided to use the MOS-A-data only for determination of cloud heights and the existence and density of stratospheric aerosol layers, like after vulcano eruptions. It is under development a so called "Angstroem Estimator" for the α-exponent to characterise the atmospheric turbidity for the PCIA and to support separate atmospheric correction algorithm.
- It should be improved the theoretical back up of the PCIA. It is basing on the bio-optical model of Sathyendranath et.al /7/. By means of inherent optical parameters of absorption (a_i) and back-scattering (b_{bi}) for the different water constituents is calculated the water reflectance. This makes difficult the validation and needs water sampling for independent determination of a_i and b_{bi}. The thereby reachable accuracy is not satisfactory. The direct validation via in-water measured radiation parameters (E_d L_u, R, k_d), which are influenced/changed by the constituents, should be preferred in the future.

CHALLENGES FOR THE FUTURE

The experiences made with different data utilisations and retrieval of geophysical parameters showed that the basic TOAR-philosophy and the methodical background are encouraging for further application. In a follow-on mission basing on this results a more operational scenario for regional coastal monitoring can be realised. In this sense some performance parameters must be improved:

- a wider swath of not less than 400 km
- a shorter repetition rate of ~ 3 days

- a pointing capability (sensor or satellite) for daily mapping of selected regions (e. g. ecological events, hazards)
- no smaller spectral range should be used, extension to thermal IR is desirable
- some what better spatial resolution (down to ~ 100 m) is preferable
- programmable number and wavelength of spectral channels should be realised
- including the adjacent coastal land in the mission scenario.

LITERATURE

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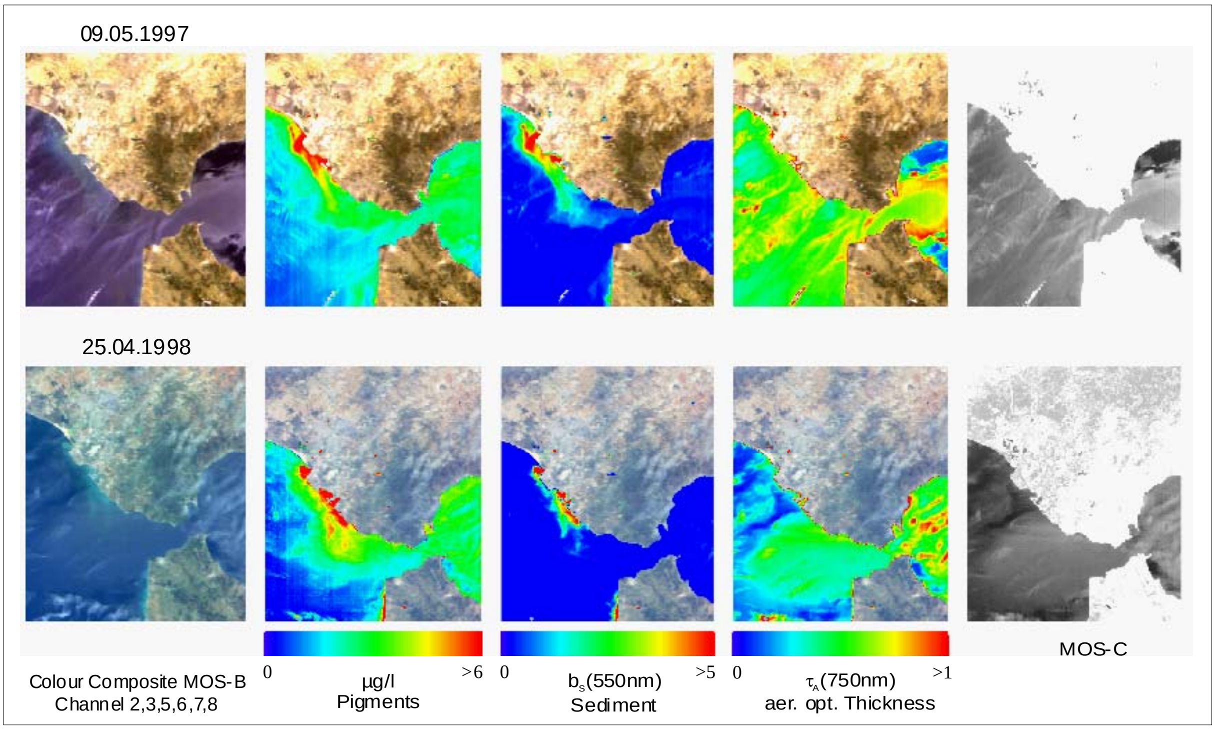

Image No. 1: MOS-IRS, Path 15, Strait of Gibraltar – derivation of water constituents for two typical situations with high atmospheric turbidity

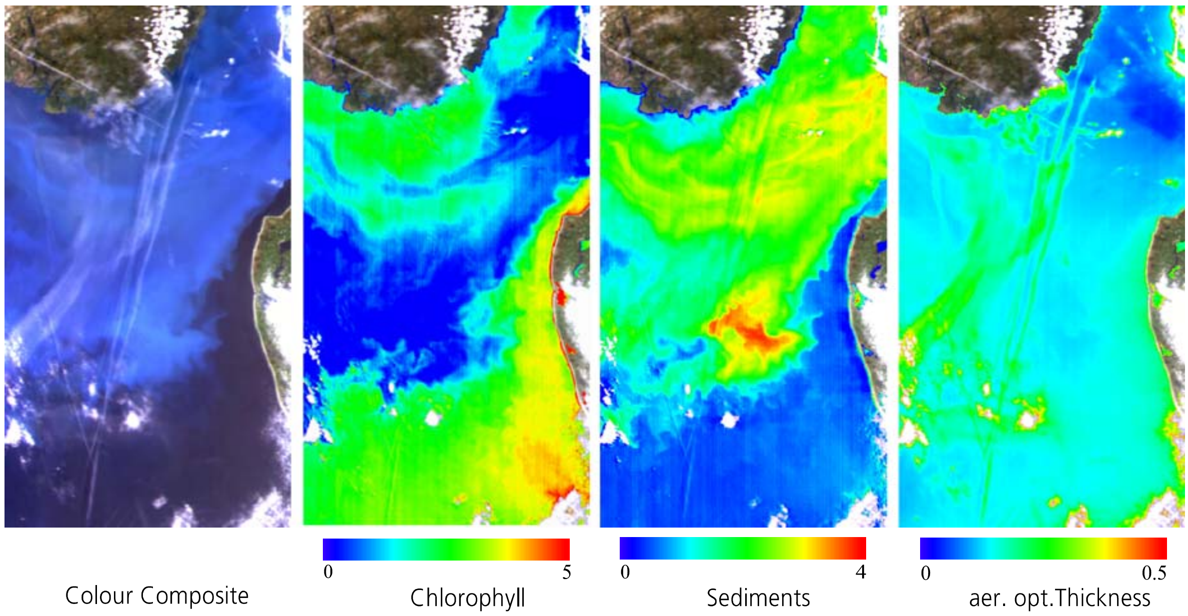

Image No. 2: Bloom of Coccolithophorides, Skagerrak, June 27, 1996

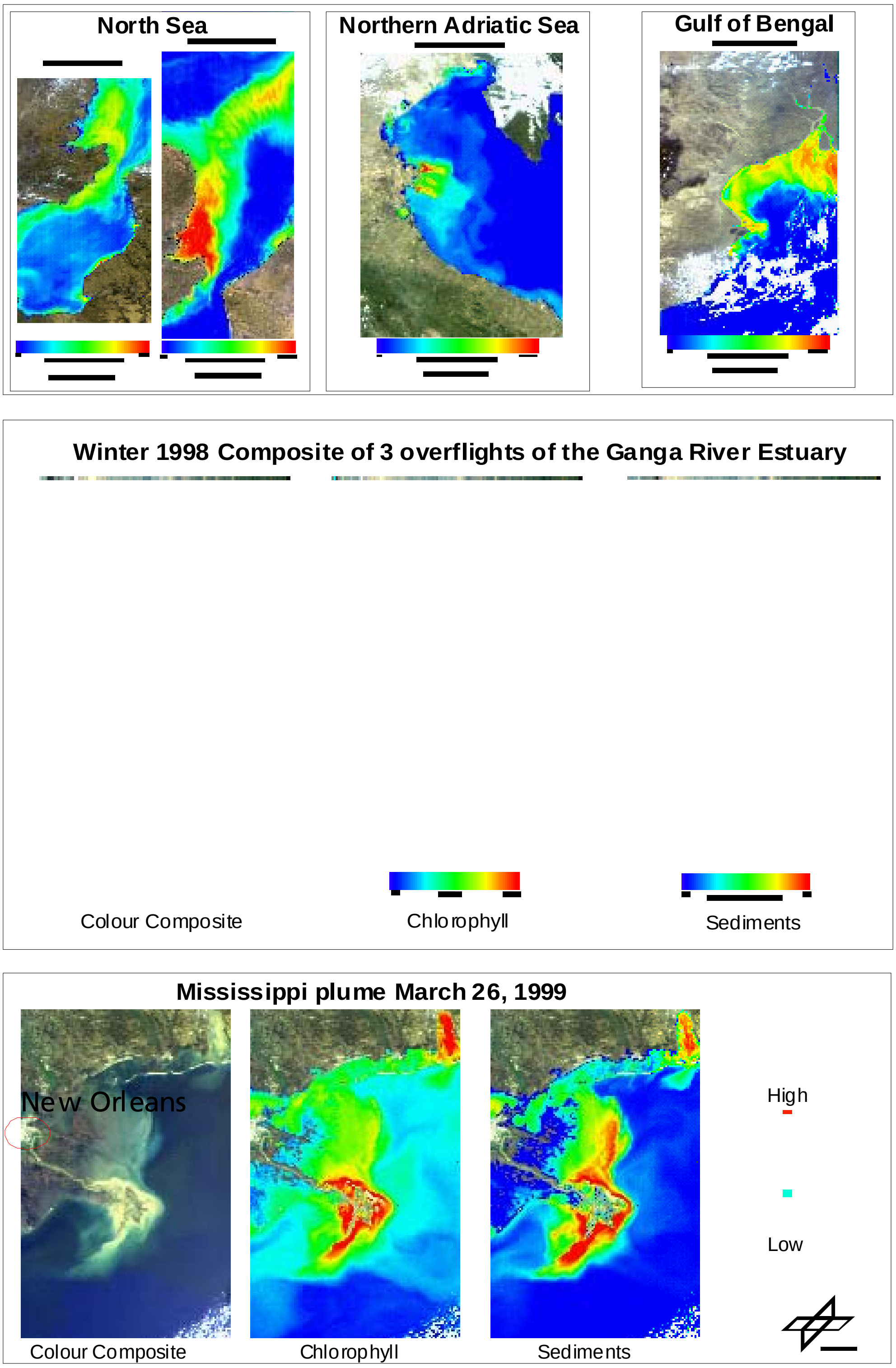

Image No.3: River Discharges and Coastal Pollution