Investigations of innovative algorithms for quantitative high temperature event (fires, volcano eruptions, etc.) emission analysis applying infrared spectrum and image data fusion

Tank V.\(^{(1)}\), Beier K.\(^{(1)}\), Hess M.\(^{(1,2)}\), Lindermeir E.\(^{(1)}\), Lorenz E.\(^{(3)}\), Schreier F.\(^{(1)}\), Zhukov B.\(^{(3,4)}\)

\(^{(1)}\) DLR Remote Sensing Technology Institute, Oberpfaffenhofen, D-82234 Weßling, Germany, Volker.Tank@dlr.de, Kurt.Beier@dlr.de, Erwin.Lindermeir@dlr.de, Franz.Schreier@dlr.de
\(^{(2)}\) Thalkirchner Str. 284, D-81371 München, Germany, michael-hess@gmx.net
\(^{(3)}\) DLR Optical Information Systems, Rutherfordstrasse 2, D-12489 Berlin, Germany, Eckhard.Lorenz@dlr.de
\(^{(4)}\) Space Research Institute (IKI) of the Russian Academy of Sciences, Profsoyuznaya 84/32, 117819 Moscow, Russia, bzhukov@nserv.iki.rssi.ru

ABSTRACT/RESUME
High Temperature Events (HTEs) like vegetation fires, peat/coal seam burning, and active volcanoes emit large quantities of radiative active gases and aerosols into the atmosphere. Quantification of these is required to determine their influence on atmospheric processes. For this purpose a sensor/data fusion technique has been developed to investigate HTEs from space. It combines high spatial, low spectral resolution infrared image and high spectral, low spatial resolution spectrometer data in order to derive parameters such as: HTE type and area, plume gas concentration and temperature, total plume gas contents, etc.

Simulations of the method rendered promising results. Currently there is no dedicated sensor system in space. Application to AIRS/MODIS data of Portugal 2003 fires have confirmed the need for high spectral resolution. The superior spectral resolution of IASI encourages to investigate the IASI/AVHRR combination.

1. INTRODUCTION
High Temperature Events (HTEs) play a major role in the global carbon cycle, with the pyrogenic gases CH\(_4\), CO, and NO specifically affecting the chemical processes of Earth’s atmosphere and CO\(_2\), CH\(_4\), and NO\(_2\) perturbing Earth’s radiative budget. Furthermore, burning of vegetative matter (vegetation fires, combustion of bio-fuels) is the second largest anthropogenic source of sub-micron aerosols, which themselves greatly influence Earth’s radiation budget [1, 2, 3, 4, 5].

Despite numerous studies of individual vegetation fires, the global magnitude of pyrogenic emissions is still not accurately known, moreover it is subject to very large temporal and regional variations. Therefore, an important task is to monitor, characterise and quantify HTE emissions in order to better assess their effect on the whole Earth system. Among specific major European developments to close this gap the ESA project FOCUS [6] was aiming at a stand-alone quantification of HTE characteristics, including especially those of the HTE plume. FOCUS proposed an innovative sensor/data fusion technique to combine high spatial, low spectral resolution image (ideally in four spectral bands, visible VIS, near infrared NIR, mid infrared MIR; and thermal infrared TIR) and high spectral low spatial resolution infrared spectrometer data to derive HTE gaseous emission parameters. The principle feasibility of the method has been proven in simulations during adaptation and/or development of an appropriate radiation transfer model and retrieval algorithms.

First applications were performed within the frame of the ESA study ECOCIRE which was aiming at a comprehensive investigation of the capability of existing remote sensing satellite data to derive quantitative HTE parameters. On 14-AUG-2003 AIRS and MODIS on NASA’s AQUA satellite recorded infrared radiation of a forest fire in the south of Portugal. Combining data of the AIRS spectrometer (circular footprint of 13 km diameter, 0.5 – 2 cm\(^{-1}\) spectral resolution) and MODIS pixels (of 1 km x 1 km size within the footprint) the size of the fire area inside the AIRS field of view (FoV) of a fire location could be determined. The subsequent retrieval applied to the AIRS spectra delivered increased CO concentrations 5 km above the fire (altitude of maximum sensitivity to CO).

Unfortunately AIRS spectral resolution does not meet the requirements derived in simulations of the method.

The spatial resolution of IASI footprint of about 12 km, and AVHRR of 1.1 km are similar to the AIRS/MODIS sensors but the high IASI spectral resolution of 0.35 to 0.5 cm-1 promises advances over AIRS/MODIS. It is proposed to continue the investigations with IASI and AVHRR data of EPS and investigate the capability to derive: HTE type and area, plume gas concentration and temperature, total plume gas contents, combustion efficiency, optical depth and aerosol particle size distribution of plume and smoke.
2. METHODOLOGY

2.1 Sensor fusion

Estimating HTE plume characteristics from spectroscopic infrared space- or air-borne observations is a challenging problem: It requires high spectral resolution in order to distinguish the spectral signatures of the HTE and the atmospheric constituents. It also requires high spatial resolution in order to get information about the aerial distribution of HTE extension, type and intensity (temperature), necessary for scene modeling. Both cannot be achieved in a single measurement instrument that is intended to investigate more than only the very few extreme large HTEs, since radiative flux of HTE plumes viewed from high altitude fast moving platforms and time for measurement integration available are both rather small. Hence a new approach was applied: the joint use of two complementary instruments: a high spectral, low spatial resolution spectrometer and a high spatial, low spectral resolution imaging sensor (Fig. 1). The first provides information about gases and aerosols within the HTE plume and the radiance of the whole scene, whereas the imager provides spatially resolved classification of the scene. Data from both sensors are merged in the analysis methods combining the information acquired.

Figure 1 Satellite sensor fusion principle, co-aligned fields of view of IR spectrometer (white cone) and IR camera (pink fan), over HTE scene

The DLR Fourier transform spectrometer MIROR (Michelson Interferometer with ROtating Retroreflector) and the DLR Imaging sensor ABAS (Advanced BIRD Airborne Simulator) have been combined to constitute FASA, the “Fire Airborne Spectral Analyser”. FASA has been integrated into DLR’s DO 228 research aircraft. After flight testing first experiments will be carried out over a controlled fire (simulated HTE).

2.2 Data fusion

Since several decades remote sensing with spaceborne spectrometers is an indispensable tool of atmospheric science. The retrieval of atmospheric parameters from observed spectra is performed using a well established methodology usually based on numerical optimization combined with appropriate forward models. For HTE analysis the methodology is far from mature: First vertical sounding generally leads to ill-posed inverse problems: The standard approach relies on regularization, i.e. additional information about the solution. However, neither climatologic a priori nor smoothness appears to be useful in case of HTEs. Furthermore, the spectral regions (“micro windows”) traditionally employed for analysis of atmospheric spectra may be unsuitable for analysis of hot gases. Another problem is the strong horizontal inhomogeneity of HTEs. In order to overcome this conflict, the sensor fusion described above will be combined with data fusion allowing two principle approaches:

Sequential data fusion, i.e. image data and spectrometer data are analyzed in two steps: first the relative area contribution of “generic” contributions (flaming, smoldering, smoke, and unperturbed surface within the spectrometers footprint) and surface temperatures are retrieved from the image data. For this purpose, the Bi-spectral technique [7] is applied to clusters of fire-affected pixels in the images obtained in two wide spectral bands selected in the atmospheric windows in the mid-infrared (3.4 to 4.2 µm) and thermal infrared (8 to 12 µm) spectral ranges. This allows quantification of fires that occupy more than 0.3 to 0.5 % of the image pixel area [8]. Using these estimates as input a nonlinear least squares fit of spectral data is performed to determine the plume parameters, i.e. parameters characterizing the vertical structure (temperature, gases, ...) of the generic contributions within the spectrometers field of view.

Global data fusion: In this more sophisticated and computationally challenging approach surface and plume characteristics are retrieved simultaneously by “concatenation” of the image and spectrometer data [9]. A prototype algorithm was developed during the “FOCUS Phase A study” and used for extensive simulations. It was applied to determine well suiting “micro windows” [10] as well as required spectrometer characteristics, some of which are listed in Tab. 1 in comparison to AIRS and IASI parameters. Fig. 2 shows simulation results for
determination of required noise equivalent spectral radiance NESR of the spectrometer.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>required</th>
<th>AIRS</th>
<th>IASI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral range</td>
<td>[cm⁻¹]</td>
<td>650-3000</td>
<td>645-2670</td>
</tr>
<tr>
<td></td>
<td>[µm]</td>
<td>3.3 – 15</td>
<td>3.74-15.4</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>[cm⁻¹]</td>
<td>0.17</td>
<td>0.5-2</td>
</tr>
<tr>
<td>NESR</td>
<td>[µW/(cm² sr cm⁻¹)]</td>
<td>&lt; 1</td>
<td>?</td>
</tr>
</tbody>
</table>

Table 1 Comparison of spectrometer characteristics

The prototype algorithm was further developed in the ESA “Data Fusion Algorithm Development Study” and has been applied to the August 2003 wildfires in Portugal using a combination of AIRS and MODIS data aboard the AQUA satellite.

2.3 IR-Simulation of Biomass Fires and Retrieval of Smoke Particle Parameters

The radiative properties of smoke and gases from biomass burning in the thermal infrared were simulated using the atmospheric radiation transfer models MODTRAN and FASCODC respectively. Two coarse vegetation categories, forest and savannah, were selected to define typical fire scenarios. The scenarios are broken down into the combustion phases ‘flaming’ and ‘smouldering’, ‘smoke over unburnt ground’ and as reference ‘undisturbed background’. The simulations show clear radiation effects from smoke particles in the thermal IR which make it feasible to retrieve the aerosol optical depth. With the assumption of lognormal size distribution for the aerosol particles it is possible to derive the median particle radius and the smoke particle mass of a smoke plume [11], (Fig. 3).

3. APPLICATION: AIRS/MODIS

The ESA study ECOFIRE aimed at the investigation of the feasibility of available remote sensing data from current satellites for HTE detection and analysis and the definition of dedicated sensor system requirements. Within this frame plume analysis was performed on data acquired by the spectrometer AIRS (Atmospheric Infrared Sounder) and the imaging sensor MODIS (Moderate Resolution Spectroradiometer) flown on NASA’s AQUA satellite over the South Portugal fires on 14 August 2003. This is currently the best sensor combination in space on a single platform providing image and spectrum simultaneously, though spectral and spatial resolution are beyond actual requirements (Tab. 1).

Using data of MODIS, the subpixel fire area within its 1 km x 1 km pixel was determined (Dozier method), and subsequently the total fire area of a fire location within the AIRS field of view (circular footprint of 13 km diameter). The weighting functions for CO, i.e. the changes in spectral radiance caused by a given change in height dependent CO concentration, all calculated for a Mid latitude Summer Atmosphere (MLS) and the spectral resolution of AIRS, are shown in Fig. 4. For all CO lines available, the maxima are around 5 km altitude. This means there is no profile retrieval possible with these data and also no direct fire...
emission determination. The retrieval applied to the AIRS spectra (0.5 – 2 cm⁻¹) therefore delivered CO concentrations at 5 km above the fire (Fig. 5). The retrieval parameters were the surface temperature and scaling factors to CO and H₂O profiles (MLS). The errors of these CO concentrations, determined from the covariance matrix, are around 10% to 15%. The initial guess values of the retrieval correspond to the blue colour in Fig. 5. The fire was located in the leftmost pixel with increased CO concentration, and covered about 2.5 % of the AIRS pixel area.

4. OUTLOOK

IASI has about twice as high a spectral resolution as AIRS. In contrast to AIRS the spectral range covered by IASI has no gaps, particularly the CO band around 2200 cm⁻¹ is completely observed. Therefore, there will be better possibilities for CO retrievals at lower altitudes and thus there may be the chance to directly measure CO and other emissions from vegetation fires.

5. References