VIMOS - Autonomous image analysis on board of BIROS

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Abstract: Some events on the Earth's surface require a fast and well coordinated reaction, such as disasters like earthquakes, floods, the occurrence of drifting icebergs or illegal activities like piracy or cleaning of oil tankers polluting the sea. Field help and prompt intervention can be supported by the examination of images recently acquired by Earth observing satellites.
The extraction of useful information out of image data in real-time directly on board a spacecraft can shorten the timespan between image acquisition and an appropriate reaction drastically. This is one of two major aspects of image analysis on board a satellite. Secondly, if the amount of unusable data and/or the degree of cloudiness of a currently acquired scene is known on board, affected images can be (partially) discarded, which leads to an optimized usage of storage and downlink capacity.
VIMOS will be a collection of image processing and remote sensing algorithms, running as an experiment on board of the German satellite BIROS. The purpose of VIMOS is a first demonstration of algorithms applied to data of optical sensors, dedicated to an operation on board a satellite, like e.g. cloud detection, change detection and object recognition. VIMOS will be able to send a trigger message to the autonomous on board mission planning unit, which can check possibly modified conditions on board, and react accordingly e.g. by planning a new timeline.

Keywords: image processing, remote sensing, on board, autonomous, disaster, flood, monitoring, FPGA

1. INTRODUCTION

Some events on the Earth's surface require a fast and well coordinated reaction, such as disasters like earthquakes, floods, the occurrence of icebergs or illegal activities like piracy or cleaning of oil tankers polluting the sea. Usually, after images have been acquired by Earth observing satellites, they have to be stored on board and sent down to Earth when within view of a ground station. Due to the high data volume, several passes may be needed to downlink a complete acquisition (cf. (Dawood et al., 2002)). On ground, the raw image data contained in multiple downlink-packages has to be re-sampled. Some correction like the removal of undesirable sensor effects or band-alignment may be applied before delivering the data to the user. Depending on the circumstances the whole procedure from image acquisition to image analysis can take hours to days.
In case of disasters it is often not necessary to *view* an acquisition, but in the first instance to simply *extract information*, such as coordinates and extent of a flooding. Apart from this, an acquisition may contain data, which are not of interest for the actual purpose, and hence, could be discarded directly on board. This is for instance useful in case of cloud contaminated scenes.
The extraction of useful information out of image data in real-time directly on board a spacecraft can shorten the timespan between acquisition and reaction drastically as well as optimize the usage of storage and downlink resources (Yuhaniz et al., 2005). It is not an alternative to conservative remote sensing image processing accomplished on ground, but provides ancillary support for the scenarios explained above.

VIMOS (Verification of IMage analysis Onboard a Spacecraft) will be a collection of image processing and remote sensing algorithms on board of the German satellite BIROS. The purpose of VIMOS is a first demonstration of algorithms for the analysis of multispectral data, dedicated to an operation on board a satellite. In the first instance VIMOS will focus on cloud detection, flood detection and recognition of larger objects. The usecase scenarios have been selected in accordance with the Center for Satellite Based Crisis Information (DLR-ZKI, see www.zki.dlr.de). VIMOS will show, that the information gathered by on board image analysis bring additional benefit for the intervention in case of unforeseen events on Earth.
Various algorithms have been examined for their usability for an on board processing, especially considering time and resource consumption, part of them being already tested and implemented. Since VIMOS is a running project, its state changes permanently.
Another experiment on board BIROS will be VAMOS (Validation of Autonomous Mission planning on board a spacecraft (cf. Wörle and Lenzen (2013)), which will perform timeline generation and task (re-)scheduling - typically accomplished by mission planning on ground.

VAMOS pursues the aim of making the handling of the satellite more flexible and partially independent of the current availability of a connection to a ground station. For example, if an acquisition was deleted by VIMOS, VAMOS will check the current resources and conditions on board and potentially allow another acquisition, which was not originally scheduled.
For the future, the combination of both, mission planning and image processing, on board a satellite in operational mode will tap more potential of Earth observing satellites.

2. VIMOS

2.1 Challenges of on board image analysis

Looking on a satellite image a human eye can easily identify lakes, bridges over water, islands, icebergs, ships, houses and so on. Also whether a connected region is partially clouded or juts out the scene, can be told by a single view. The human brain is able to group a set of connected pixels together and identify them as a certain object. It can rotate and resize shapes, in order to compare different objects or different transformations of one and the same object.
While, when examining a scene on the ground, a human supervisor can help in case of uncertainties, this is not the case during processing on board a satellite. Therefore one of the main aspects is to develop algorithms running completely autonomous. Coincidentally, compared to state-of-the-art computing environments on the ground, resources on board a satellite are strongly limited and inflexible. Contrary to restricted resource consumption, on board image analysis pursues time-critical intentions. Hence the overall challenge is to combine short runtime, low resource consumption and satisfying quality within one and the same algorithm.

2.2 Ancillary conditions on board of BIROS

As successors of the German BIRD satellite, TET-1 and BIROS are dedicated to the detection of (wild)-fires. The constellation of both will be referred to as the FireBird mission (see www.dlr.de). While TET-1 has already been brought to its orbit in August 2012, the launch of BIROS is currently scheduled to the first quarter of 2015.
Both satellites carry the same primary payload. It is composed of three cameras, one covering the spectral ranges of red, green and near infra-red (NIR). The other two sensors operate in the mid-wave infra-red (MIR) and the thermal infra-red (TIR) region, respectively. Table 1 lists the detailed attributes of the five spectral channels.
The main purpose of FireBird is the detection of hotspots on the Earth's surface (cf.(Ruecker et al., 2011)).

The payload processing unit (PPU) of BIROS is an FPGA (Field Programmable Gate Array) of the Xilinx Virtex4 series. It consists of plain reconfigurable hardware logic and two embedded PowerPC processor cores. On top of the two processors runs RODOS (Real Time Object Oriented Dependable Operating System), adapted to the PPU by a specially designed framework. RODOS supplies quasi-parallel processing and multi-threading (see www.dlr.de/rodos). Several threads can be combined into an application, wherein each thread can run completely independent. Threads and applications can run on different computing nodes, communicating with each other as well as with peripheral devices via a publisher-subscriber-system. Priorities can be (re-)assigned to every thread and processor power will be distributed at any time to the momentarily most prioritized threads.
Some dedicated processes will be implemented directly into the hardware logic of the FPGA. Revised versions of algorithms can be induced to the PPU by an upload from the ground.

2.3 VIMOS - Overall design structure

VIMOS will be an application on the PPU, consisting of two separate threads, VIMOSmain and VIMOSproc.
VIMOSmain will listen to incoming commands and signals every some milliseconds and execute them or activate the corresponding processes. It will also control VIMOSproc, which does the actual image processing. Whether the image processing will be (at least partially) implemented into the FPGAs hardware logic or not, is yet to be determined. In the present state all algorithms described below are coded in software (C/C++).

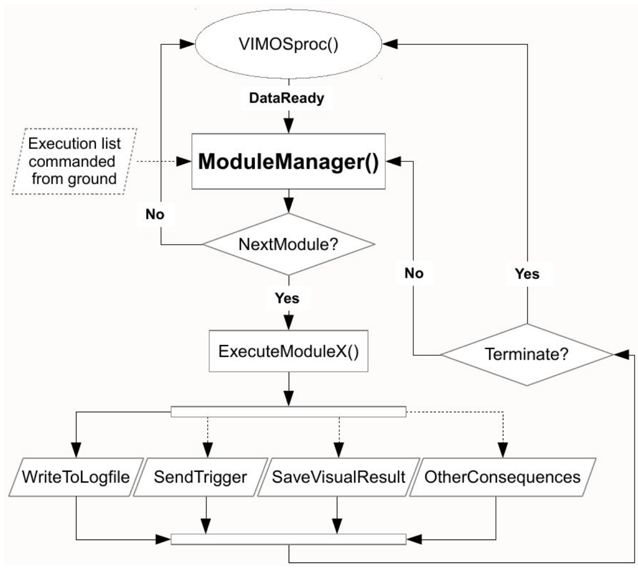


Fig. 1. VIMOS - Design of module execution

VIMOSproc will consist of several modules, which can be individually actuated. A module is a composition of algorithms from image processing and remote sensing designed for a specific purpose such as e.g. cloud detection, flood detection or object recognition. The decision, which modules will be executed at a time, is done on the ground

Table 1. Spectral bands onboard of BIROS

	Band	Spectral range [μm]	Spatial resolution [m]	Swath width [km]
1	Green	0.460 – 0.550	42.2	211
2	Red	0.565 – 0.725	42.2	211
3	NIR	0.790 – 0.930	42.2	211
4	MIR	3.400 – 4.200	178	180
5	TIR	8.500 – 9.300	178	180

according to the knowledge about the orbit of the satellite. Appropriate parameter settings for the current scenario are uploaded. It is planned to accomplish module selection and parameter determination on board in a later extension stage of the experiment.

Figure 1 shows the design flow of the VIMOSproc thread. Most of the time VIMOSproc will be in sleeping mode. After being woken up by VIMOSmain, VIMOSproc will wait for the signal, that image data is ready to be processed. When the signal is received, the ModuleManager will be entered, controlling the execution of the selected modules in a predefined order. Several reactions can be caused depending on the result of the module. For example, a cloudmask may be saved as an input to modules yet to be executed. Further processing may have to be cancelled due to cloud contamination. A trigger may be sent to VAMOS asking for an action. For instance, if an interesting event has been detected by VIMOS, VAMOS shall evaluate, whether a new acquisition can be planned for the next pass and, if positive, generate and/or activate the corresponding timeline. In the case of a flooding event a shape file will be generated, consisting of polygonal lines describing the affected areas, and sent to the ground as fast as possible.
In any case processing and performance results are written to a log file, which will be analysed on the ground for verification, problem solving and further development.

2.4 VIMOS - Image processing

Most of the reasonable usecases for on board image analysis implicate the usage of high resolution data with a ground sample distance $\leq$ 5 m. On BIROS, algorithms identifying ships, traffic, buildings etc. will hardly be applicable.
Therefore VIMOS will focus on cloud detection, change detection and the recognition of larger objects. The algorithms for these purposes will be described in the following. The size of the subscenes VIMOS will be supplied with is not fixed yet. Whether VIMOS will have access to the data of all five channels or only to the three reflective ones, is also not determined by now. Hence, the algorithms presented in this paper are chosen and designed under the assumption of the minimum requirement, that is the access to image data of 1024x1024 pixels size for each of the three reflective bands.
Since BIROS' primary payload will be a clone of TET's, it is self-evident to use images of the latter as training data. Due to TET's launch delay, they are not yet available. Meanwhile, data from Landsat 5 and 7 serve as substitute, since adequate bands (green, red and nir) are present in a similar spatial resolution ($30m$).

Preprocessing Preprocessing of image data includes correction of sensor effects like pattern correction or removal of the influence of dark current, band-alignment and correction of geometrical distortion due to the Earth's curvature and the viewing angle. Since for the primary purpose of BIROS, the detection of fires, these corrections have to be applied to image data as well, it is most likely, that VIMOS will be supplied with data already preprocessed. Therefore, these steps will not be discussed within the scope of this paper.

Different illumination conditions varying with the seasons cause the satellites sensor to measure different radiance values for one and the same material. TOA (top of atmosphere) correction is a band-wise and pixel-wise conversion of the incoming radiance values in the unit of $[Wm^{-2}sr^{-1}]$ into reflection values in [%]. Taking into account the current solar zenith angle and the sun-earth-distance, TOA correction strongly reduces the influences described above. All further algorithms are based on the TOA-corrected images.

Cloud detection The cloud mask will be created by the application of pre-defined spectral criteria to the present TOA-corrected data in combination with a morphological filter. Afterwards the mask will be examined regarding total cloudcover percentage and distribution of the clouds. Most commonly cloudmasks are binary, dividing pixels into cloudy and not-cloudy. On board cloud detection has to serve two purposes: determination of the cloud content for a possible deletion of a contaminated scene and cloud-masking for further processing on board. In the first case an underestimation of the cloud content is preferable in order to not discard acquisitions which could be still usable on the ground. Contrarily, in order to reduce the probability of misinterpretation in the subsequent on board processing, it is more desirable to overestimate the clouds. Therefore, the cloudmask within VIMOS will be ternary, tagging a pixel as high probability cloud, low probability cloud or no cloud. Since the boarders of clouds are always a source of uncertainties, the spectral examination will be combined with a morphological closing, which yields a controlled enlargement of the cloud contours. Pixels, which are additionally marked as clouds by the closing step will automatically belong to the low probability class.
In order to as well account for the distribution of the clouds, the mask is split into four quarters, each of them being examined separately. An overall cloudcover of 20 % for example may make an acquisition unusable for Earth observing, if the clouds are split into small cumuli and spread over the whole scene. Whereas, if the cloudiness is mainly concentrated in one quarter of the scene, the rest of the image may be processed further on.
The trigger signal for the deletion of an acquisition will only be sent to VAMOS if all four quarters exceed a certain high probability cloud percentage. For further on board processing the sum of high and low probability cloud pixels within at least one quarter has to fall below a certain threshold.

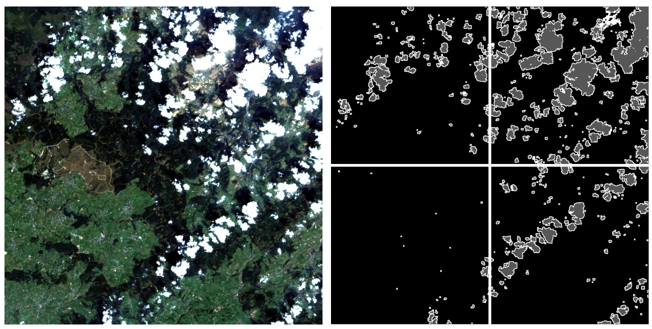


Fig. 2. VIMOS - Cloud dectection
Landsat 7 ETM+ RGB (l), ternary cloud mask (r)

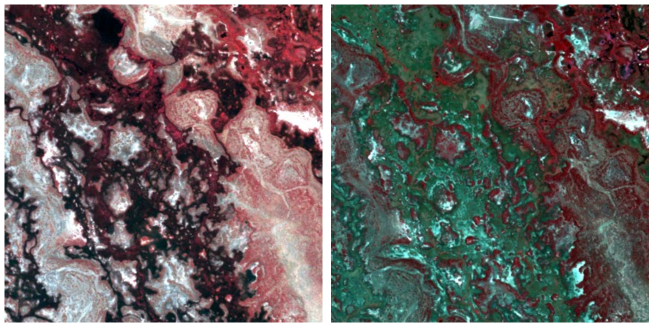
Figure 2 shows the RGB composite of a Landsat 7 ETM+ subscene taken over Germany in September 1999 and the corresponding cloudmask, where high and low probability cloud pixels are depicted in gray and white, respectively. While the top right quarter is highly contaminated, the bottom left quarter is affected only marginally. Hence, the whole scene will be processed further on as well as marked for download to the ground.

Change detection The change of the Earth's surface can coarsely be categorized into slower variations over seasons, decades, centuries etc. and rapid changes happening within hours or minutes. Most of the latter are caused by natural hazards like floods, earthquakes or landslides.
While the examination of slow changes lacks of the higher meaning for on board image analysis, it is highly of interest to detect and monitor rapid changes as fast as possible.
Due to the spectral and spatial resolution of the sensor on board of BIROS, VIMOS will in the first instance focus on the detection of floods.
For this purpose, a recent acquisition will be compared to a previously stored reference. Geometrical transformations will be necessary in order to match both scenes as precise as possible, such that each two pixels show the same piece of surface. The applied co-referencing algorithm will be described in the next paragraph.
Once the images are co-referenced properly, they can be compared pixel-wise. The choice of the method depends on the kind of change which is desired to examine.
Floods, better to say, the changeover from no-water to water, has impact on the whole reflective spectral region. Therefore, the two scenes will be compared pixel-wise using the empirical correlation coefficient:

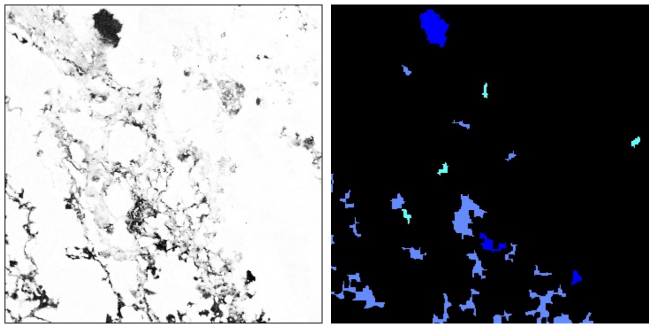
$$\varphi(\boldsymbol{v}, \boldsymbol{w}) = \frac{\sum_{k=1}^{3}(v_k - \bar{v})(w_k - \bar{w})}{\sqrt{\sum_{k=1}^{3}(v_k - \bar{v})^2} \cdot \sqrt{\sum_{k=1}^{3}(w_k - \bar{w})^2}} \in [-1; 1]$$

where $\boldsymbol{v}$ and $\boldsymbol{w}$ are vectors, containing the TOA-reflection values of one pixel of all three reflective bands of each image. The correlation result is a value in the range of $[-1; 1]$. Lower values correspond to a worse correlation and a higher change.

Since VIMOS will be one of several experiments on board of BIROS, its operational phases will be restricted to a couple of time windows and storage capacity will be limited. Hence, change detection must concentrate on locations on Earth, where changes are expected frequently.
The Okavango delta located in the north-west of Botswana in the center of the Kalahari desert will serve as one test site for on board flood detection. Once a year, from January to February, heavy rainfalls over Angola feed the Okavango river with a huge amount of water, which is then carried over a distance of $1200km$ and reaches the Okavango delta approximately in March. During the next five month, while the delta is flooded, it swells to three times its permanent size, what also results in an enormous increase of vegetation growth.
The delta is monitored intensively by the Okavango Research Institute (O.R.I., see www.orc.ub.bw). The frequently updated, detailed measurements of water level, flood extent, climate etc., provide best possible information for validating the results of on board change detection. Due to the dry desert environment clouds and rain are



3 (a): Okavango delta, Landsat 5 TM bands 2, 3, 4
(l) Aug 1998 coreferenced to (r) Feb 1998



3 (b): Correlation using bands 2, 3, 4
(l) Darker gray-levels indicate higher change
(r) Extracted change areas of three severity degrees

rare, what promises adequate opportunities for observing the surface.

Fig.3 (a) shows co-referenced subscenes of the Okavango delta taken by Landsat 5 TM (Thematic mapper) in August and February 1998, respectively. Based on the result of the correlation step (Fig.3 (b), left) connected regions of pixels with high change are grouped together to areas by the means of component labelling (cf. (Ballard and Brown, 1982)). Component labelling allows to treat associated pixels as one entity, and hence, to examine each entity independently. The spectral distribution within one label can be analysed. Geometric characteristics as area, perimeter and shape of a region can be extracted.
Each affected area, which exceeds a certain size, is then examined with respect to the kind of change and its severity. In detail, for each area the TOA-reflection values of both images are compared separately with the surface classes water, vegetation and soil using again the empirical correlation coefficient (cf. Borg (2007)). Here, one vector corresponds to one of the images, the other vector to the typical reflection of a surface material. In the case, that the correlation with the water class is clearly higher for the current acquisition than for the reference, the area will be marked as flooded. Additionally, one of three severity degrees is assigned to each flooded area, as it is depicted on the right side of Fig.3 (b). A darker shade of blue corresponds to a higher degree of change.
If the total content of flooded areas will be considered severe enough, several reactions will be caused. A high priority download tag will be assigned to the acquisition. A trigger signal will be sent to VAMOS, asking for planning an anew acquisition as soon as the location comes into the view of the satellite again.

A shape file will be generated, describing the flooded areas with polygonal lines, and sent down to Earth for examination as fast as possible. Other changes (e.g. vegetation growth or decrease) will be recorded and downlinked, too, but no immediate reaction will be caused.

Co-Referencing The current acquisition may differ from the reference with respect to rotation, translation, viewing angle and distortions originating from the Earth's curvature and rotation. To a certain degree the amount of these distortions can be calculated in advance taking into account the satellite's orbit position, known from the GPS signal, its attitude and the pointing direction of the sensor. However, to match both scenes as precise as possible, such that each two pixels show the same piece of surface, an automated co-referencing based on image features is required.
Most of the common co-referencing algorithms consist of the following steps: feature detection, feature matching, homography calculation and image warping. The SURF algorithm (Speeded Up Robust features, cf.Bay et al. (2008), Evans (2009)) will be used for the first step. It searches the images for points of interest (POIs) by the means of 2D Haar wavelet responses, while making efficient use of integral images. No user interaction is necessary.
For each POI the location in the image is returned as well as a 64-dimensional description vector. Running SURF on the same band (e.g. NIR) of both images yields two independent lists of POIs including their descriptors. The list of POIs for the reference scene will be calculated and stored in advance to the present acquisition.
Within the matching step the descriptors of one list are compared to each of the second list regarding their euclidean distance and the coordinates of matching pairs are stored. Some of these pairs may have similar description vectors, although they do not correspond to the same surface point. These outlier pairs are excluded in the homography calculation by the application of the RANSAC (RANdom SAmple Consensus, cf. Fischler and Bolles (1981)) algorithm. For the computation of the final homography matrix only valid POIs will be taken into account. By convolution with this matrix the recently acquired image is transformed and fitted to the reference scene.

Object recognition Detection and monitoring of objects from space has become an important factor for security management. Locations, which are supposed to be fraught with risk, are surveyed regularly e.g. on behalf of governments. For instance, the previously mentioned Center for Satellite Based Crisis Information, observes the ship traffic in selected regions and monitors certain buildings like for example embassies, government buildings and football stadiums. Two categories of objects have to be distinguished: those, which have a pre-defined appearance and a fixed location, such as buildings, airports or power plants and those, where only their coarse shape is known, like ships and airplanes. In the first phase of the experiment VIMOS will concentrate on larger pre-defined objects. The aim is to provide fast, preliminary information about the state of an object and to advise the crisis management to take it under closer inspection if it was recognized on board only poorly or not at all.

The algorithm proposed here is based on the principle of template matching. For a chosen object a reference shape is created, e.g. by performing edge detection or contour extraction. A base pixel is chosen arbitrarily somewhere within or around the reference shape. The distances of the base point to all pixels on the shape are calculated and stored in advance.
The approximate position and the orientation of the object within the current acquisition is defined by the orbital position and the attitude of the spacecraft. Hence, only an appropriate cut-out has to be examined. The reference shape will be rotated accordingly before performing the recognition step.
Edges or contours will be extracted from the cut-out in the same manner as it was done for the reference. For each point of this result the probability of coincidence with the base point of the reference is calculated. In case that the probability distribution clearly exhibits one singular maximum, the corresponding pixel is marked as valid base point and the object is considered to be recognized properly. Otherwise, if the maximum is identifiable only vaguely or there exist multiple local maxima, the recognition has failed. Consequently, VAMOS will be asked for planning a new acquisition during the next pass and a warning message will be generated for immediate downlink.

Fig. 4 shows the automatic recognition of the Munich airport within a Landsat-7 acquisition from march 2002. The reference shape of the airport was extracted from another image acquired three years earlier. The result on the bottom of the figure shows the base point location (green, encircled) and the shape of the reference (red) overlaid on the result of the edge detection.

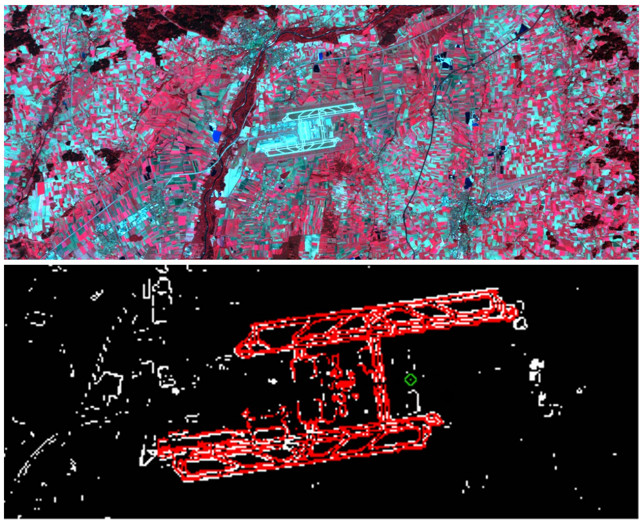


Fig. 4. VIMOS - Object recognition
(t) False colour composite Landsat 7 ETM+
(b) Munich Airport recognized with template-matching

There already exist concepts for the autonomous detection of bridges as described in (Beulig et al., 2012). Naturally only larger bridges can be detected at a spatial resolution of 42.5 m, but the algorithm as such would have to be modified only slightly. A first test yielded promising results.
Another option is the detection of icebergs in the open sea. While the spectral and spatial resolution of BIROS

suit this purpose, two other drawbacks will have to be overcome: The flat angle of the sunlight's incidence in those regions, where icebergs typically occur and the lack of previous knowledge of the occurrence.
As mentioned above, since VIMOS is one of several experiments, it will be limited in operational time, power consumption and storage. Whether and to what extent the processing of further scenarios will be possible, cannot be answered at the present state.

2.5 VIMOS - Current state

Most algorithms VIMOSproc will consist of were originally designed or modified for running on FPGAs. These hardware devices allow parallel computation, which image processing is dedicated to (cf. (Dawood et al., 2002)). Algorithms for segmentation, component labelling, cloud detection, bridge detection, change detection, classification and more have already been implemented into FPGAs by the research group for on board image processing at GSOC, using only hardware-friendly integer arithmetic. Software designs are partially existent, but from experience, porting an algorithm from hardware to software will cost comparably low effort. Some procedures, as for instance component labelling or image filters, are independent of the kind of optical data, since their functionality is the same, regardless spatial or radiometric resolution. Other algorithms, especially those, which involve spectral examination, may have to be modified, in order to fit the sensor's conditions, or may not be applicable at all.
VIMOSmain and parts of VIMOSproc will definitely run on the processor core. First executable versions of cloud detection and object recognition as well as the raw skeleton of VIMOSmain have been implemented on top of the BIROS-specific operating system. VIMOSmain can already receive a command from a dummy interface and configure the also implemented ModuleManager contained in VIMOSproc. Various data-independent filter tools for smoothing, sharpening, edge detection etc. and a software version of component labelling are programmed so far. Special care has been taken to consume as less as possible resources, without making compromises regarding run time.
For development purposes, existing image data from the satellites Landsat 5 and 7 has been used, which has slightly differing spectral bands compared to TET-1 and BIROS and a geometric resolution of 30 m.
Since the interface through which VIMOS will be supplied on board with recently acquired image data is not yet defined, several modifications will have to be made regarding data format and data handling.

3. CONCLUSION

VIMOS will contribute to the vision of smarter satellites by demonstrating that the potential of observing the Earth from space has not been exhaustively utilized by now.
The aim of VIMOS is to validate, that it is possible to extract time-critical information out of image data directly on board of satellites and, as the case may be, initiate appropriate reactions. It has already left the stage of a coarse conception. Since it is a running project, the state of VIMOS changes permanently.

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