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GIS based Integration and Analysis of multiple source Information for Non-Proliferation Studies

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Abstract

In recent years the volume and variety of information that needs to be analysed in the context of non-proliferation have been increasing continuously Therefore, an integrated, all-source information analysis is paramount for an efficient and effective monitoring of the Non-Proliferation Treaty (NPT). The 'Treaty Monitoring' workpackage of the LIMES research project addressed this issue by developing an integrated platform supporting the non-proliferation image analyst in verifying treaty compliance. The main benefits of the platform are (i) integrating information from multiple sources and time-frames, including satellite imagery, site models, open source information, reports, etc; (ii) improved information management using a GIS-based platform and (iii) enhanced methodologies for satellite image analysis. The platform components facilitate the analysis by highlighting changes and anomalies, which are potentially safeguards-relevant and by providing quantitative measurements which are not readily available from the images. It improves the efficiency and effectiveness of the information assessment by providing all-source integration capabilities, which allow to easily access supporting collateral information (e.g. Open Source information) from an image analysis task, an vice versa.

The paper presents the components of the integration platform and the results of the demonstration which monitored the construction of a nuclear reactor in Olkiluoto, Finland.

1. Introduction

In recent years the volume and variety of information that needs to be analysed in the context of non-proliferation have continuously been increasing, for instance through the implementation of the Additional Protocol, increased use of novel technologies and availability of Open Source information. Therefore, an integrated, all-source information analysis is paramount for an efficient and effective monitoring of the Non-Proliferation Treaty (NPT). The work carried out within the LIMES project addressed this issue in general while focusing on the needs of the image analyst in particular.

LIMES (Land/Sea Integrated Monitoring for European Security) is a European research project funded by the European Union under the security-dimension of GMES (Global Monitoring for Environment and Security) [1]. The project, which finished in May 2010, included a workpackage on Treaty Monitoring targeting the non-proliferation image analyst. The objective was to support the analyst in the task of collecting, managing and analyzing satellite imagery - often in conjunction with data from other sources - and extracting non-proliferation relevant information. Typically the analyst's tasks include:

- the verification of NPT declarations provided by a country, in particular of site declarations submitted as part of the Additional Protocol.
- the generation of base-line analyses of nuclear sites
- the continuous monitoring of (construction) activities on nuclear sites.

Following recent developments in non-proliferation the image analyst is faced with new and increased challenges, as for example the detection of clandestine nuclear activities and the assessment of an increasing amount of multi-type information. New satellites such as very high-resolution (VHR) optical and radar sensors further increase the number of possible applications in nuclear non-proliferation and, therefore, also the amount of data to be processed.

Although satellite imagery is already an important tool in nuclear non-proliferation, current usage relies heavily on visual interpretation with little use of automated processing. Furthermore, analysis tools usually provide an isolated view on satellite imagery with little integration of collateral data, such as Open Source information, GIS data, internal databases, etc [2,3].

The Treaty Monitoring workpackage developed a pre-operational platform aimed at demonstrating novel concepts to support the image analyst in these forthcoming challenges [4]. The focus of the platform is to answer to the perceived need for integrating information from multiple sources, multiple time-frames and resolutions, for an efficient and thorough non-proliferation analysis. It includes the following components:

- An *integrated platform* providing a single, map-based point-of-entry for *multi-source analysis* supporting satellite imagery, derived products and required collateral information.
- *Computer-assisted change analysis* based on VHR optical data.
- *Extraction and analysis of 3D information* from stereo satellite imagery.
- *Automated analysis of Very High Resolution SAR* (Synthetic Aperture Radar) imagery.

Section 2 describes the different platform components and section 3 illustrates the results of the platform demonstration. Section 0 provides a summary and conclusion.

2. Platform Description

2.1. Information Management and Integration

A core objective of the Treaty Monitoring workpackage is to provide an integrated platform to the non-proliferation image analyst. In practice this means, that the analyst should have a central point of access, which allows to

- retrieve, view and analyse all available (spatial and non-spatial) information for a given site, including satellite imagery, GIS information, external databases and collateral information.
- access dedicated analysis software performing specialist tasks, such as change analysis, SAR and 3D processing tools as described above. Any results obtained from the tools (e.g. a resulting change maps) should be stored for later retrieval in the integrated platform.

The integration platform developed under LIMES is based on a standard three-tier architecture (database, application server and web client) using common industry standards as illustrated in Figure 1. In order to support information of different types (both spatial and non-spatial), the platform incorporates three independent pillars each serving a particular purpose: a *geographic information system*, a *Wiki system* and a *document repository*, as further detailed below:

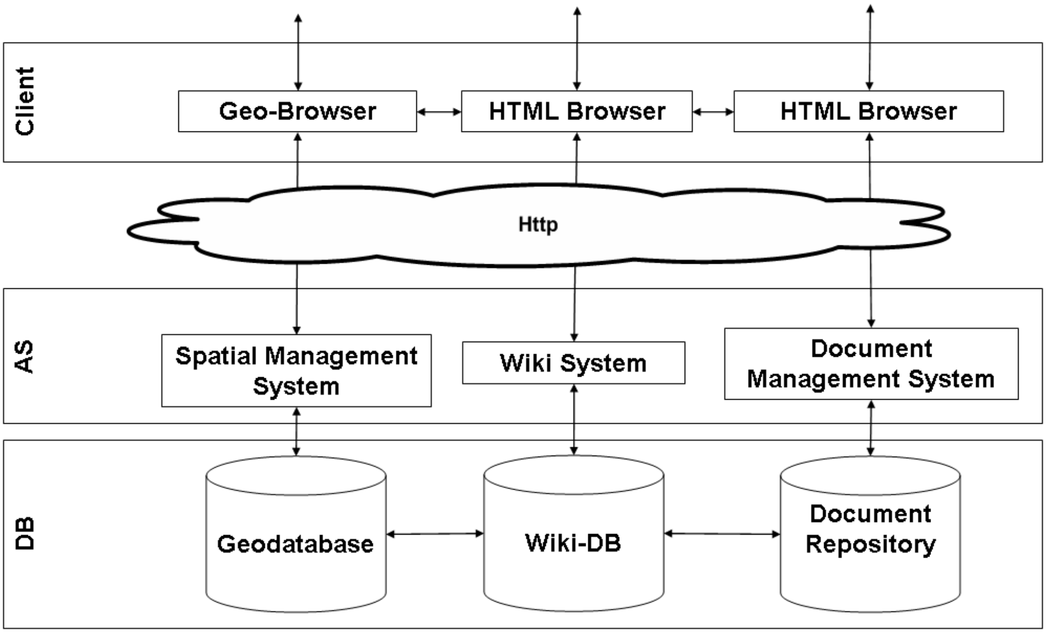

Figure 1: High-level architecture of the Treaty Monitoring integration platform. The system integrates a Geographic Information System (left), a Wiki (centre) and a document repository in order to support spatial and non-spatial information.

- The *Geographic Information System (GIS)* provides an intuitive map-based interface to the user. It allows storing, retrieving and visualising spatial information. Each feature in the geo-database is context-sensitive, i.e. it can be selected from the user interface and cross-linked with other information, such as meta-information, collateral data and analysis results.
- The objective of the *Wiki system* is used to capture unstructured, tacit information available in an organisation. Each feature in the geodatabase (e.g. a particular facility) can have a corresponding Wiki page containing relevant information or previous analysis comments. The Wiki also contains supporting information, for example pages regarding relevant technologies, organisations, treaties, regulations, etc. Wikis are most known as Internet applications (e.g. Wikipedia), where the large number of contributing users ensure reliable and exhaustive content. However, the potential of Wikis is also increasingly recognised in Intranet environments with a smaller number of users, e.g. in corporate Intranets or within intelligence communities [5,6]. A prominent example is Intellipedia, which is an online system for collaborative data sharing used by the United States intelligence community [7,8].
- The *document repository* is designed as a central archive for all relevant documents collected from various sources. In particular, Open Source information is becoming increasingly important to trigger, guide and support imagery-based analysis. Many analysts collect thousands of documents from the Internet covering different types of information. Also restricted documents containing sensitive information might be required during the analysis work. A document repository provides i) a central repository for all documents, ii) advanced functionalities for data upload, search and retrieval, iii) access control and iv) the possibility to define a data model.

The integration platform does not impose additional workload on the analyst for ingesting and maintaining information. Rather, it constitutes a centralised and standardised method to manage i) the information that is collected and validated during the routine work and ii) the knowledge generated during the analysis process. Therefore, the organisation's knowledge base will grow in time as a result of its core activity without creating a large overhead on human resources.

The modular platform architecture allows interfacing different image analysis tools, which are adapted to the analyst needs. In the context of the LIMES project these were focused on change analysis and 3D information extraction as discussed in the following sections.

2.2. Change Detection and Analysis

Two software tools have been developed to assist the image analyst in change detection based on optical imagery: the stand-alone software *ChangeView* and a change detection plug-in for Definiens Developer. *ChangeView* automatically detects and visualizes changes in multi-spectral optical satellite imagery on the image pixel level, whereas the Definiens Developer Plug-in enables to perform object-based change detection. Both tools are based on the Multivariate Alteration Detection (MAD) method [9,10], which is a classical statistical transformation referred to as canonical correlation analysis to enhance the change information in the difference images. MAD was proven to be a very effective change detection method for optical images which separates different categories of changes (e.g. man made changes and seasonal changes) into different layers of the resulting change image [11,12]. Furthermore, MAD requires no radiometric pre-processing of the original image data as it is invariant to changes in the overall atmospheric conditions or in sensor calibrations.

2.2.1 Pixel-Based Change Detection

ChangeView calls for two co-registered multi-spectral images as input without the need for any further user-interaction or parameter tuning. The MAD algorithm runs fast even on very large datasets and reliably produces the corresponding change map. The changes are colour coded according to their type, i.e. seasonal vegetation changes are coded differently from changes due to construction activities. Some of the changes (e.g. seasonal vegetation changes) might, however, not be relevant to non-proliferation. Therefore, a visualization tool supports the analyst in assessing the resulting change map: it provides an overview of the colour-coded change map thus highlighting potential areas of interest. When the user clicks on a particular point in the change map, the tool displays the original imagery of the corresponding area (at both instants of times) and the resulting change map in full resolution (Figure 4). Thus, the change detection tool provides an additional layer of information, which supports the analyst in the visual interpretation of the satellite image.

2.2.2 Object-based change detection

Analysing satellite image data in an object-based way generally extends the possibilities to detect changes between two or more dates. In addition to the change pixel measures listed before, object-based change detection techniques can also estimate the changes of the mean object, such as shape and size, assess the modified relations among neighbouring, sub- and super-objects and identify changes regarding the object class memberships. In this respect, the MAD transformation can also be applied in the image object domain, for instance by using the object features.

A case study was carried out using the bitemporal Quickbird dataset acquired over Olkiluoto in June 2005 and July 2006, where surface changes are due to the construction of a new nuclear facility. The two images were pan-sharpened and co-registered. Object extraction was performed through Definiens Multiresolution Segmentation using all eight pan-sharpened image bands of the bitemporal data set. Changes between the two acquisition times were then calculated by a MAD transformation using 16 colour and Haralick texture features (based on the grey level co-occurrence matrix (GLCM)): mean colour value, the mean colour difference to neighbours, GLCM homogeneity, GLCM mean, each for the four given spectral bands (see Figure 5).

2.3. 3D Information Extraction

Digital Surface Maps (DSMs) extracted from VHR stereo satellite imagery have a resolution and accuracy considerably better than standard Digital Elevation Models (DEMs), e.g SRTM or Aster GDEM. They can be used for several purposes, e.g. i) for an improved geometric correction of the VHR satellite imagery during the image pre-processing phase, ii) for the creation of measurable 3D models and iii) for 3D–based change detection. The focus in Treaty Monitoring workpackage was on 3D change detection as described below.

Standard techniques, which are normally used for the creation of DEMs from lower resolution imagery, often produce unsatisfactory results for the non-proliferation application [13]. For example, man-made structures with sharp contours (such as nuclear facilities) are blurred in the resulting DSM. Also, depth continuities and occlusions as they appear in VHR imagery generate mis-matches thus producing erroneous results. The standard methods have been improved within the LIMES project and implemented in the RSG and Impact software packages provided by Joanneum Research [14].

An estimate of the relative accuracy for the resulting DSM can be obtained by fitting a plane to a planar surface and analysing the fitting error. An analysis was made of the DSMs obtained from the two Olkiluoto stereo pairs acquired with the Ikonos and GeoEye-1 sensors, in 2008 and 2009 respectively. Three planar areas (parking lots) were selected in each of the DSMs and a plane was fitted to each of them. The resulting fitting errors (3 Sigma) are reported in Table 1. It illustrates that the values of the Gaussian noise are well within a range that makes the data suitable for non-proliferation purposes (see Figure 6 and Figure 7).

	Ikonos May 2009	GeoEye-1, May 2009
Area 1	171 cm	99 cm
Area 2	174 cm	81 cm
Area 3	150 cm	87 cm
Average	165 cm	89 cm

Table 1: Error values (3 Sigma) for fitting a plane to three parking lots in the DSMs obtained from an Ikonos and GeoEye-1 stereo pair, respectively.

2.3.1 3D Change Detection and Interpretation

The accuracy obtained from the 2008 and 2009 Olkiluoto stereo pairs allows using them for 3D change detection, which is done by calculating the height difference of the resulting DSMs [15]. It has the advantage that it detects only changes in the geometry of the site which is typically induced through construction activities. Irrelevant changes, e.g. due to seasonal changes are ignored. Besides the simple height difference also information about the change of the land cover is used. Here, the well-known normalized difference vegetation index (NDVI) is calculated to separate vegetation from non-vegetation areas.

2.4. SAR Processing

With the availability of the latest VHR sensors, SAR (Synthetic Aperture Radar) imagery has gained significant importance for non-proliferation applications. The principle advantage of SAR imagery is its all-weather, all-time acquisition capability. Additionally, the potential to compute accurate DSMs and detect small ground movements are of interest. New sensors, e.g. the TanDEM-X satellite, will further increase the capabilities. However, SAR imagery does not come without its limitations. Some of the drawbacks with respect to optical imagery are listed hereafter:

- SAR imagery contains a high amount of **speckle noise**,
- Due to the **acquisition geometry**, the perception of a SAR image is different from an optical system.
- SAR **backscatter** depends on scene acquisition parameters and therefore.

The above issues render visual interpretation of SAR imagery less intuitive than optical imagery and usually an experienced analyst is required for the task. Hence, the Treaty Monitoring platform includes an advanced, automated processing workflow, which addresses some of the problems and directly generates an anomaly map from a multi-temporal SAR series. It uses the CIAO software package, developed by CEA, for detecting anomalies by the means of analysing series of interferograms taken at different instants in time [16]. The analyst first collects the radar images for a given area (which might come from different radar satellites) and then uses the software to generate the coherence images. Figure 2 gives an example of the process applied to an industrial port area.

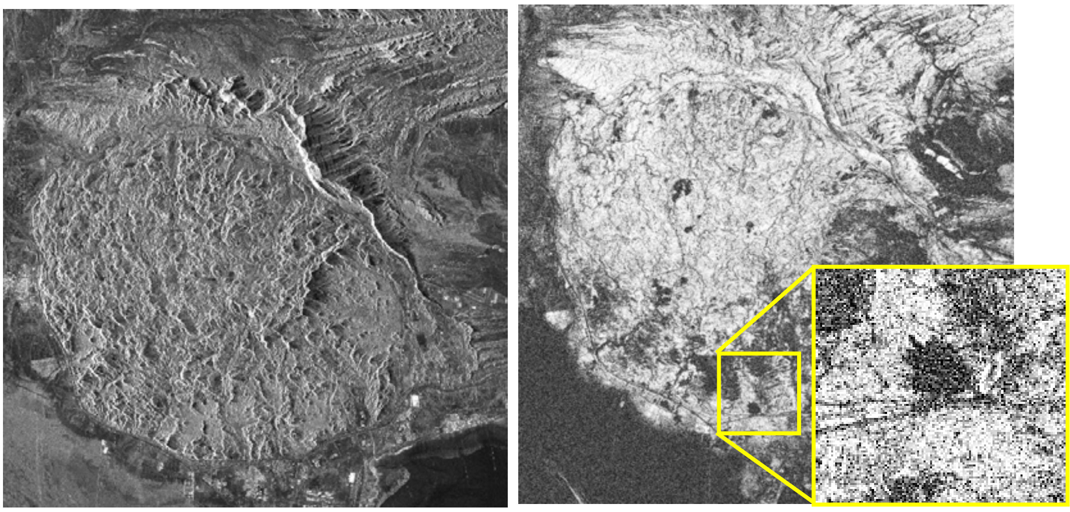

Figure 2: The left image shows a SAR image of an industrial port area. The right image shows the coherence map of the same area obtained from two SAR images. The yellow square highlights a detected anomaly.

Because a coherence image is computed from two radar images acquired at different instants in time, it highlights changes (black areas) between those two acquisition dates. Two coherence images, one corresponding to changes between dates (t1-t2) and the other to dates between (t1-t3), can be used to generate a false-color composite highlighting changes due to the activities between dates (t2-t3).

3. Platform Demonstration

Two platform demonstrations were carried out in July 2008 and October 2009. The objective was to present the developments to interested stakeholders and obtain feedback from potential users. For the purpose of the demonstration, a typical scenario was defined consisting of a initial base-line analysis and the continuous monitoring of a nuclear site. The Finish NPP Olkiluoto was selected as test site for the demonstration scenario. Archived satellite imagery reaching back to 2002 as well as new imagery between 2007 and 2009 are available, thus simulating a continuous monitoring of the site over seven years. The data used for the demonstration include

- VHR optical satellite imagery (2002, 2005, 2006 and 2007)
- VHR optical stereo imagery (2007, 2008, 2009)
- SAR imagery (image series from May to September 2009)
- Open Source information including documents, maps, images and videos.
- Ground information, such as GPS data

Figure 3 to Figure 7 illustrate some of the results obtained during the platform demonstration.

Figure 3: The four images show the site of the EPR reactor before the construction (2002) and at different instances during the construction (2005, 2006 and 2007). The images include the annotations resulting from the standard, visual interpretation carried out by an image analyst.

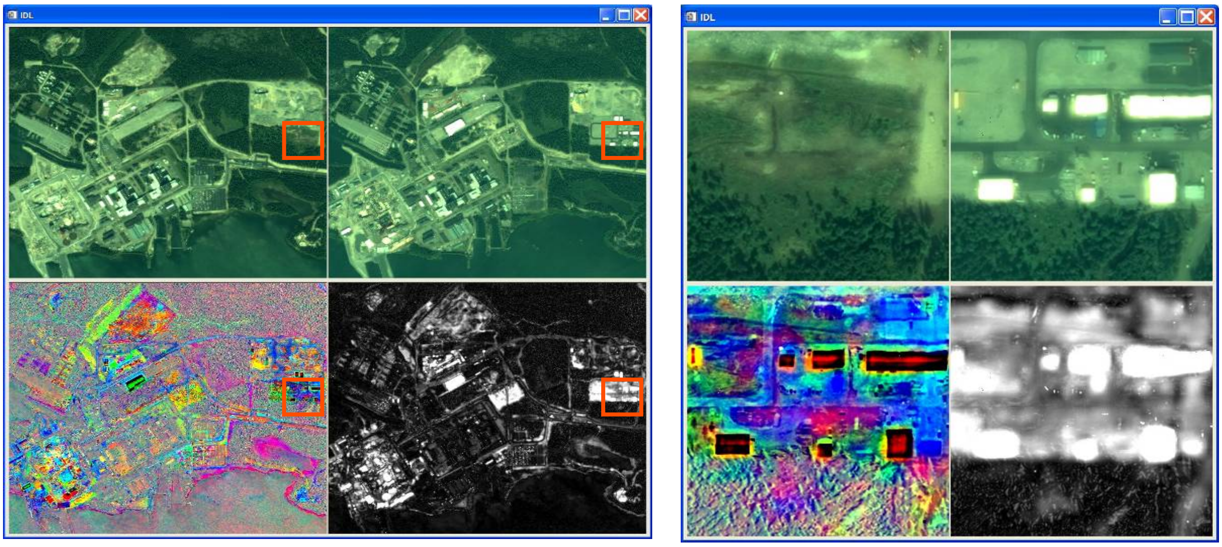

Figure 4: Snapshot of the TUBAF change visualisation tool. The left window displays an overview of the original Olkiluoto images taken in 2005 (upper left) and 2006 (upper right) as well as the resulting change map as colour coded MAD components (lower left) and absolute change intensity (lower right). The right window displays the same information in full resolution.

Figure 5: Results of the object-based change detection for Olkiluoto between June 2005 (left) and July 2006 (right) based on 16 objects, given by the MAD layers 12, 13 and 16 (right)

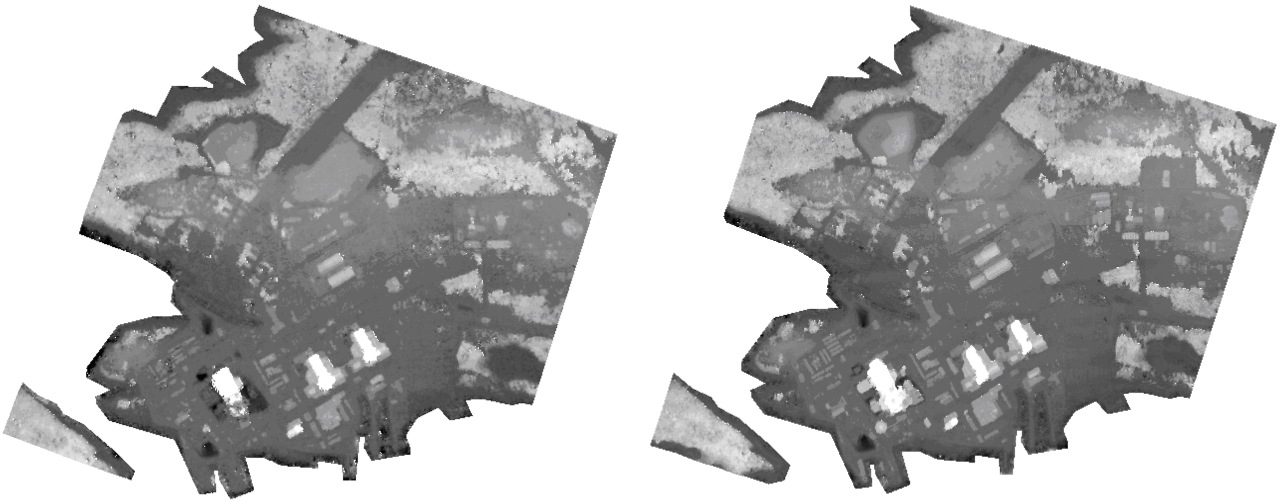

Figure 6: Digital Surface Map (DSM) of the Olkiluoto site generated from an 2008 Ikonos stereo pair (left) and a 2009 GeoEye-1 stereo pair (right)

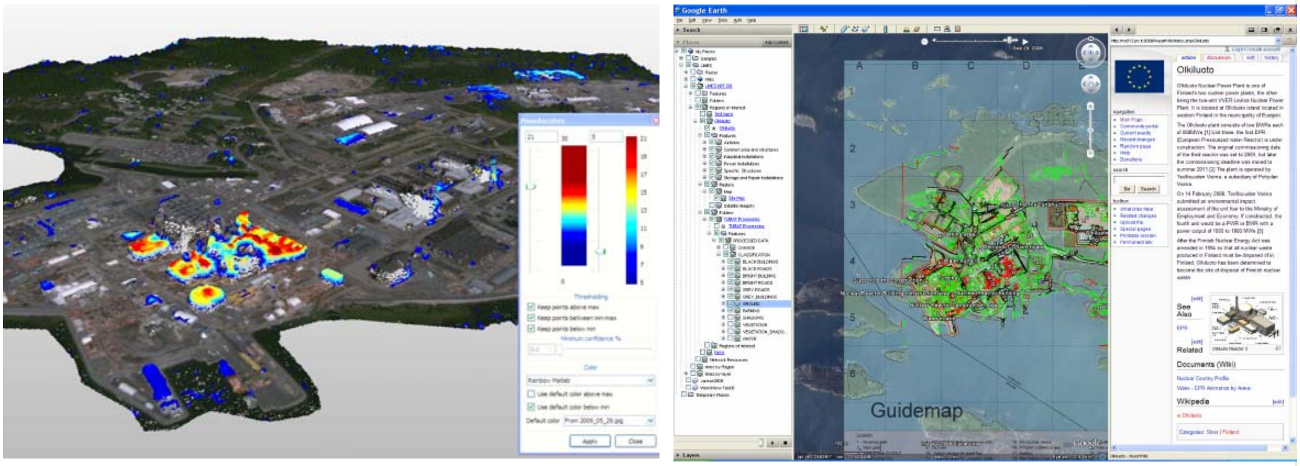

Figure 7: Left: 3D visualisation of the information and changes extracted from the 2008 and 2009 stereo images. All changes with respect to 2008 that are above 5m are colour coded. The main construction works at the Olkiluoto 3 reactor, a number of other new buildings and a deforested area at the top-right of the image can clearly be identified. Right: the client application is visualising the spatial and non-spatial information served by the integration platform. The spatial information (multi-temporal vector or raster information) is selected from the hierarchical tree on the left. For each feature, related non-spatial information can be loaded into the html browser on the right.

4. Summary and Conclusion

Satellite Imagery plays an important role in nuclear non-proliferation. One of the major challenges faced by the image analyst is the monitoring of nuclear sites with respect to new constructions and their operational status, i.e. the detection and analysis of relevant functional changes in multi-temporal images. Currently, operational work relies to a large extend on optical VHR imagery, which is visually interpreted using standard analytical tools. The image analyst is faced with an increasing number of customer requests on one hand and increasing quality and quantity of available input data on the other. The Treaty Monitoring workpackage proposes a number of tools addressing these challenges. The focus of the platform is to answer to the perceived need for integrating information from multiple sources, multiple time-frames and resolutions, for an efficient and thorough non-proliferation analysis. It supports knowledge preservation, which is often an important issue in environments with high staff turn-over. The objective was to devise a high-level architecture and implement a prototype that addresses these issues and at the same time allows demonstrating and evaluating the implementation-independent concepts for an integrated information analysis.

This information integration concept is supported by tools adapted to the needs of the analyst. The tools process raw satellite imagery to extract higher-level information (i.e. change maps, anomalies and 3D information), contributing to the analyst’s efficiency and enhancing the consistency of the resulting product.

By its nature, the integration platform is closely linked to the information infrastructure and policy of a given organisation and therefore needs to be customized to an organization's internal procedures, workflow and security policy before being deployed in an operational context. Consequently, the objective was to implement a prototype that allows demonstrating and evaluating the implementation-independent concepts for an integrated information analysis.

The platform was demonstrated in two user workshops to a number of interested stakeholders including DG-ENERGY, in charge of the implementation of the EURATOM treaty, and IAEA. The general feedback was that the project addressed important issues for the non-proliferation image analyst, regarding both supporting analysis tools and information integration. Clearly, none of the components can replace the analyst in interpreting the images from a non-proliferation point-of-view. However, they put a range of additional tools at his/her disposal, which can facilitate the analysis by highlighting changes potentially of interest and providing quantitative measurements which are not readily available from the images.

Acknowledgements

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