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Potential Ways for Optimization of Multispectral including Infrared (MSIR) Imaging for On-Site Inspection (OSI).

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Summary

In accordance with provision of the Comprehensive Nuclear Test Ban Treaty (CTBT) inspection activities and techniques include "multi-spectral imaging, including infrared measurements, at and below the surface, and from the air, to search for anomalies or artifacts». (Paragraph 69(b) of the Protocol)

According to the model text for the draft OSI Operational Manual (OM) broad categories of anomalies capable to be observed with MSIR-measurements are:

- Hot spots /thermal plumes;
- Disturbed earth and vegetative stress;
- Plumes of material upward migration to ground surface (*to be discussed by dedicated expert group*);
- Human artifacts.

Introduction

According to model text for the draft OM for OSI multispectral imaging is one way of using small windows of wavelengths within or near the visible spectrum to gather information about the terrain.

The essence of this technique is in measuring intensity at many wavelengths with subsequent transformation of gathered data to make composite images that can be used to identify objects.

As for today the CTBT (thereinafter the Treaty) and the OM for OSI have no definition of not only the "multispectral" term but also the following parameters of MSIR-measurements:

- Specific spectral range;
- Number and width of spectral bands (intervals);
- Distinction between multispectral and hyperspectral sensors, which were actively used during the field exercises in 2011-2012 in Hungary (MSFE11 and MSFE12) and the Integrated Field Exercises in 2014 (IFE14) in Jordan.

Specific Operational Requirements for MSIR-Measurements

Depending on the number of spectral bands in which images are made there are 2 types of imaging: multispectral one (from 2 to 10 spectral bands) and hyperspectral (maybe more than 100 channels).

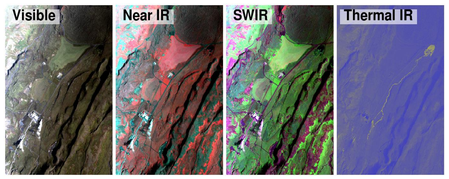
MSIR category should include multispectral imaging within 10 channels. In this case MSIR measurements will be a process of parallel making several images in different narrow spectral intervals Required number of intervals (bands) is provided with application of digital cameras with several lenses and relevant filters .

Based on the outcomes of OSI Workshop-23 held in 2016 the following specific operational requirements for MSIR-measurement system were developed:

- Portable;
- Easy to install and operate;
- Installable on fixed wing and/or rotary aircraft;

Technical specifications developed for MSIR-imaging system include:

- Spectral range from 0,3 to 2,5 micrometers for multispectral images;
- Spectral range from 7 to 14 micrometers for IR-images;
- Integrated field of view: 30-60°;
- System operable between -10°C to +40°C. [1]



Measures for Non-Intrusiveness of MSIR-Measurements

During OSI-related additional overflights (AO) with application of MSIR-measurements the Inspected State Party (ISP) shall have the right to apply general non-intrusiveness measures

- Model text for the draft OM for OSI provides the ISP right to regulate the nature and extent of access to *sensitive information not related to the purpose of the inspection.*
- Per Paragraph 75 Part II of the Protocol the ISP shall have the right to impose restrictions or, in exceptional cases and with reasonable justification, *prohibitions on the overflight of sensitive sites not related to the purpose of the inspection.*
- According to Paragraph 61(e) Part II of the Protocol during on-site inspection the ISP shall have the right to examine all photographic and *measurement products* for the subject of *potential presence of confidential information.*

During an OSI the ISP may be concerned that MSIR-imaging goes beyond the framework of the sole purpose of an OSI – to clarify whether a nuclear weapon test explosion has been carried out and to gather any facts which might assist in identifying any possible violator (Paragraph 35 Article IV). Therefore the model text for draft OM for OSI should provide a procedure for coordination (between inspection team (IT) and the ISP) of well-grounded spectral region for non-intrusive MSIR-imaging.

Phenomenology of Signatures of Underground Nuclear Explosion (UNE) Observable with MSIR-Measurements

Well-grounded spectral region for MSIR-measurements should be based on deep understanding of unique parameters of potential UNE anomalies and signatures, which include:

- *Vegetative stress* – is observed on the basis of different values of reflectance or absorption factor for chlorophyll and water.
- *Human artifacts* – new roads; moved earth; digging products (boreholes, wells, tunnels) with tailing piles, construction engineering, materials, cable lines and others.
- *Disturbed earth resulting from UNE* can be observed through changes in spectral properties of materials for the following reasons:
  - ✓ Changes in chemical composition of sub-surface materials (for instance, as a result of containment failure, releases and etc.);
  - ✓ Changes in moisture content of sub-surface materials (for instance, resulting from changes in hydrogeological regime);
  - ✓ Changes in surface texture (for instance, as a result of mechanical effects).
- *Thermal anomalies from UNE* (hot spots and plumes caused with upward migration of heated water, vapor and gases, thermal arcs, solid and circular areas).

Outcomes of the Multispectral Field Exercises in 2011-2012 (MSFE11 and MSFE12)

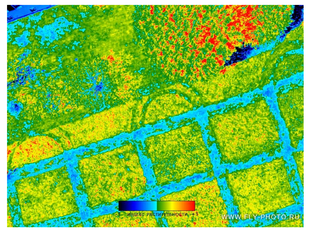
Mimicked UNE observables for the Multispectral Field Exercises in 2011-2012 (MSFE11 and MSFE12) in Hungary included:

- Temporal surface disturbance, caused by the movement of different types of military vehicles;
- Temporal surface disturbance caused by digging;
- Hydrological patterns of thermal anomalies in sub-surface;
- Fluffing of the surface through the detonation of explosives. [2]

Based on the field exercise results the following conclusions were made :

- MSIR-measurements can *identify abnormal areas and resolve their relative chronology (heated zones in sub-surface, as well as signatures, associated with digging activities and impact on vegetation).*
- Long processing time for hyperspectral data is caused with large data volumes

Elevation (m)	Covered Area	Data Volume (GB)	Data Processing Time (hours)
250	Small	12	10
500	Wide	1400	200
1400	Wide	230	45



Potential Spectral Bands of Space-Borne MSIR-Imaging for the Detection of UNE-Relevant Anomalies and Signatures

Russian experts made the overview of multispectral data from the Earth Remote Sensing (ERS) for the identification of vegetation stress and human artifacts [3].

Example:

Spectral Channel	Legend and Signatures Detected with ERS	Wavelengths (micrometers)
Visible Blue (Blue)	Band 1 B1 Soil distinguishing /discrimination from vegetation Detection of anthropogenic structures	0.45-0.52
Visible Green (Green)	Band 2, B2 Reflection of healthy vegetation , identification of anthropogenic structures	0.52-0.60
Visible Red (Red)	Band 3, B3 Contouring /lineation of soils and geological structures, identification of anthropogenic structures	0.63-0.69
Near Infrared -NIR	Band 4, B4, NIR Quantification of vegetation biomass, identification of soils	0.76-0.90
Short Wave Infrared /Middle Wave Infrared SWIR-MWIR	Band 5, B5, SWIR, MWIR Determination of moisture content in vegetation and soil, examination of vegetation health	1.55-1.75
Thermal Infrared –TIR	Band 6, B6, TIR Determination of temperature of underlying surface and heat intensity of detected items. May be used for the detection of geothermal processes / activities.	10.40-12.50
Middle-Wave Infrared MWIR	Band 7, B7, MWIR Searching for geothermal changes, determination of moisture content in rocks and vegetation	2.08-2.35

Characteristics of UNE-Relevant Thermal Anomalies Detectable with Infrared (IR) Imaging

Experimental studies of the Russian experts [4] demonstrated the capability for identification of the following UNE-relevant thermal anomalies in Long-Wave Infrared (LWIR) region:

	Type and Shape of Thermal Anomaly Abnormal ΔT = 8-12 °C IR region = 8-14 micrometers (LWIR)	Sizes of Identified Anomaly	Anomaly Generation/Presence Period
1	Hot spots and plumes during upward migration of heated water, vapor and gases	Within spall region	First hours after UNE
2	Thermal arcs	Within spall region	
3	Solid area	Within spall region 70x50 m	2-25 years
4	Circular area	Within spall region R = 80 - 200 m	2-25 years

Potential Ways for Optimization of MSIR-Measurements for OSI Purposes

Experimental results obtained by Russian experts [3] may become the basis for narrowing those spectral regions which were originally agreed by the Expert Meeting on Multispectral Imaging (MSEM11) before the Field Exercises in Hungary in 2011-2012 [5], that would provide an opportunity to simplify imaging procedure, reduce the volume of obtained MSIR-data and prevent access to excessive information.

Detected Anomalies and Signatures	Spectral Bands (in micrometers)		Time of imaging, time of anomaly generation and presence [1]
	Proposed by the MSIR Expert Meeting in 2011 (MSEM11) [3]	Results from the Russian experts [1]	
Initial survey of territory in nearly natural color. Abnormal signatures: differences between green and dry vegetation resulted from stress. Detection of recent traffic and relevant chronology of traffic on dirt or gravel roads.	Visible -VIS 0.4-0.7	B1 (0.45-0.52) B2 (0.52-0.60) B3 (0.63-0.69)	Daytime imaging. Vegetation stress begins to show itself during the first days after UNE and may be present for several weeks.
Surface disturbance Abnormal signatures: vegetation stress, surface texture changes; changes in hydrogeological regime, territory irrigation or draining, anthropogenic structures Specifically for the detection of surface texture changes Specifically for the detection of vegetation stress Specifically for the detection of geological changes	VIS , NIR, SWIR LWIR useful Thermal IR	B1 (0.45-0.52) B3 (0.63-0.69) B4 (0.76-0.9) B5 (1.55-1.75) B1 (0.45-0.52) B3 (0.63-0.69) B5 (1.55-1.75)	Daytime imaging in dry weather conditions. Anomalies show themselves several hours after UNE and may be present for several weeks. Geological changes may be present more longer time as compared with maximal OSI duration.

On the basis of specific spectral bands it is possible to search for suitable equipment for MSIR-measurements with application of standard commercially available large-format or medium-format multispectral digital aerial cameras from the leading manufacturers.

As a rule standard cameras are certified for application with appropriate aircrafts, which may be chosen for additional overflights for OSI purposes.

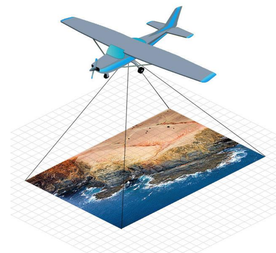
Conclusions

Proposed ways for optimization of MSIR-measurements are focused on optimization of spectral resolution for OSI purposes:

- Limited number of spectral bands (up to 10 channels);
- Combination of narrow wavelength ranges, selected from full spectral interval from 0,3 to 2,5 micrometers for MSIR-images and from 7 to 14 micrometers for IR-images on the basis of matching to realistic UNE-relevant anomalies should streamline data processing and prevent gathering of excessive data in compliance with the sole OSI purpose;
- Application of commercially available multispectral cameras, software and appropriate aircrafts.

While searching UNE-relevant anomalies with MSIR-measurements one should be guided by the following characteristics:

- UNE-relevant anomalies, detectable with MSIR-measurements may have local (point) character or distributed over the ground surface. Most probably such ground surface distribution area will not exceed the sizes of spall region.
- Temperature anomalies ΔT on the ground surface in UNE area may reach up to 8 - 10°C. Such anomalies may be in the form of hot spots or (if transformed) plumes or arc-shaped sections, as well as in the form of solid spatial zones on the ground surface or circular anomalies with 80-250 meter radius.



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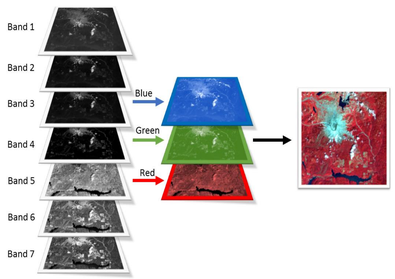

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