Sensitive Change Detection for Remote Monitoring of Nuclear Treaties

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***Abstract*— The application of a sensitive change detection procedure for nuclear treaty verification is examined in case studies involving underground nuclear testing and location of clandestine uranium mining activities.**

Keywords: Nuclear Verification, Change Detection, Multispectral Satellite Imagery

I. Introduction

Triggered in part by the advent of high resolution ($\leq$ 1m) commercial optical satellites, the analysis of open-source satellite imagery has now established itself as an important tool for monitoring nuclear activities throughout the world [CRBL01]. Whereas detection of land cover and land use change is a commonplace application in remote sensing, the detection of anthropogenic changes associated with nuclear activities, whether declared or clandestine, presents a difficult challenge. It is necessary to discriminate subtle, often weak signals of interest on a background of irrelevant or uninteresting changes, see for example [CS03].

In our contribution we focus attention on the use of conventional multispectral earth observation satellite platforms with moderate ground resolution (Landsat TM, ASTER) to detect changes over wide areas which are relevant to nuclear non-proliferation and disarmament treaties. The analysis is based upon the *multivariate alteration detection* (MAD) transformation proposed by Nielsen et al. [NCS98] with the inclusion of a recent refinement which iterates the transformation in order to put weight on establishing an increasingly better background of no-change against which to detect change [Nie05]. The multispectral data are pre-processed by ortho-rectification, image registration to sub-pixel accuracy and, in the case of the ASTER data, wavelet-based panchromatic sharpening. We illustrate the techniques with a number of case studies involving the location of underground nuclear explosions and detection of uranium mining sites.

The work has been carried out in part within the framework of the Global Monitoring for Security and Stability Network of Excellence (GMOSS) initiated by the European Commission.

II. Imagery

A series of Landsat TM and ASTER images covering all or portions of the Nevada Test Site (NTS) in the USA was acquired for the periods 1984-91 and 2000-2003, respectively over Pahute Mesa, one of the two major underground testing regions on the NTS, Table I. In addition, four ASTER images and one high resolution QuickBird image of the Saghand area in Iran were examined. These are also given in Table I.

III. Preprocessing

The ASTER images were ortho-rectified using OTS software (ASTER-DTM Module in ENVI 4.0). After ortho-rectification, the locations of the underground test sites agreed with the published values to within 0.001 degree in latitude and 0.002 degree in longitude. The non-thermal ASTER multispectral bands were combined by pan-sharpening the 6 SWIR bands to the 15m resolution of the 3 VNIR bands using a wavelet transformation scheme [RW00]. Neither ortho-rectification nor pan-sharpening were applied to the Landsat TM imagery.

The multi-temporal Landsat TM and ASTER scenes were registered to each other on the basis of ground control points obtained by invariant feature (contour) extraction and matching [LMM95]. An RST (rotation, scale, translation) transformation with cubic convolution interpolation was used to warp the images. Overall RMS error was ≤ 0.8 pixel in all cases.

IV. Change detection

Changes were discriminated with the MAD (multivariate alteration detection) procedure of Nielsen et al. [NCS98] including an iterative re-weighting scheme [Nie05] intended to enhance sensitivity. After determination of the MAD variates, an MNF (minimum noise fraction) transformation was applied to enhance the signal-to-noise ratio [GBSC88].

V. Case studies

Two case studies with data from the Nevada Test Site, USA, and the Saghand uranium mine, Iran, respectively, are given.

A. The Nevada Test Site

Since 1962, all nuclear tests in the USA have been underground and most of them have taken place at the NTS. A moratorium on underground testing has been in effect since October, 1992. An exhaustive list of US nuclear tests from July 1945 through September 1992 has been published by the US Department of Energy [DOE00] as well as by Springer et al. [SPR$^+$02].

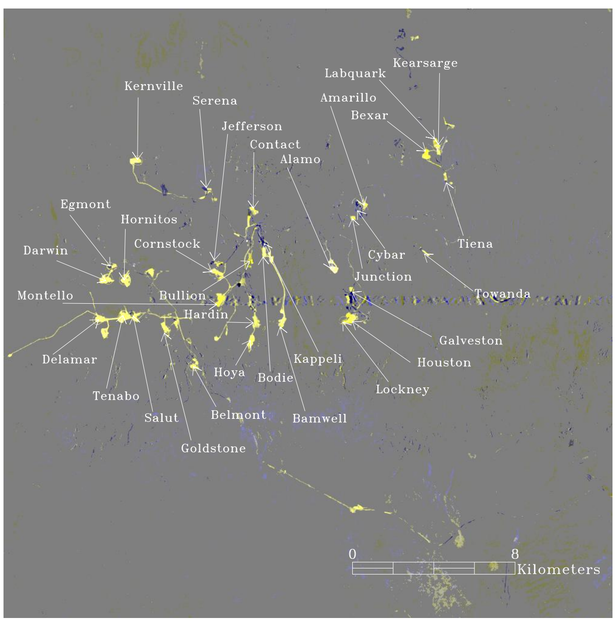

Fig. 1. Landsat TM change image at the Pahute Mesa test area between May 6, 1984 and May 26, 1991 (first 2 MNF components of the 6 iterated MAD variates, stretched to ± 8 standard deviations). Middle gray pixels indicate no change, light, dark or colored pixels indicate changes.

Figure 1 shows a change image for the Pahute Mesa area determined from the images acquired on May 6, 1984 and May 26,1991.[1] All underground tests which took place after the first acquisition are indicated and are seen to be associated with change signals arising from surface preparation activities. The test details are shown in Table II, taken from [SPR$^+$02].

[1]The horizontal feature in the center of the image is due to an instrument error in the 1984 data.

TABLE I
Multispectral satellite imagery over the Nevada Test Site and the Saghand Uranium mining area.

Acquisition Date	Acquisition time	Satellite sensor	Off-nadir	Solar elev.	Solar azim.
NEVADA					
6.05.84	17:48:40	TM5	0.0	58.01	122.40
28.05.86	17:45:38	TM5	0.0	60.41	114.15
6.06.86	17:45:09	TM5	0.0	60.86	110.42
13.04.87	17:44:14	TM5	0.0	50.85	128.50
31.05.87	17:45:35	TM5	0.0	60.70	113.49
3.08.87	17:47:03	TM5	0.0	56.63	119.93
4.09.87	17:47:57	TM5	0.0	50.21	131.95
20.09.87	17:48:19	TM5	0.0	45.99	138.89
24.10.88	17:51:54	TM5	0.0	35.78	150.63
18.04.89	17:50:19	TM5	0.0	53.47	128.71
8.04.91	17:43:09	TM5	0.0	49.03	129.54
26.05.91	17:43:59	TM5	0.0	59.99	114.39
13.07.91	17:44:36	TM5	0.0	58.95	111.04
22.08.91	17:36:16	TM4	0.0	51.16	122.50
15.09.91	17:45:16	TM5	0.0	46.90	135.82
17.10.91	17:45:30	TM5	0.0	37.47	147.01
2.11.91	17:45:30	TM5	0.0	32.69	150.36
4.12.91	17:45:49	TM5	0.0	25.21	152.21
2.06.00	19:00:24	ASTER	8.58	72.55	144.30
21.08.00	18:59:56	ASTER	8.57	62.29	153.64
1.10.00	18:52:58	ASTER	−2.83	47.72	164.13
5.06.01	18:54:09	ASTER	8.59	71.73	140.25
4.03.02	18:46:33	ASTER	5.74	43.44	155.07
6.07.03	18:38:32	ASTER	-1.38	68.93	129.17
SAGHAND					
18.04.01	7:24:24	ASTER	8.50	65.10	146.95
13.07.03	7:13:37	ASTER	8.58	71.14	119.20
2.03.04	7:08:30	ASTER	-0.03	45.84	150.76
22.06.04	7:07:42	ASTER	-0.04	71.96	116.35
4.08.04	6:59:59	QuickBird	10.40	61.80	134.80

Figure 2 shows a similar change image for the same area determined from the images taken on April 13 and May 31, 1987. These acquisitions bracket the two underground tests “DELAMAR” and “HARDIN”. The former produced a subsidence crater of diameter 180m (Table II). Activity on the sites of the subsequent tests “CORNSTOCK” and “LOCKNEY” can be seen, however there appear to be no significant change signals associated with the bracketed tests.

Figure 3 shows a change image for the Pahute Mesa determined from the ASTER images taken on June 5, 2001 and July 6, 2003. Considerable construction activity is evident in the northeast, near the site of the underground test code named “SERPA”, which took place in December, 1980.

B. The Saghand Uranium mining area

Saghand uranium mines are located in northeast of Yazd province, in the central Iran desert. The Saghand uranium ore deposit in Yazd covers 100-150 square

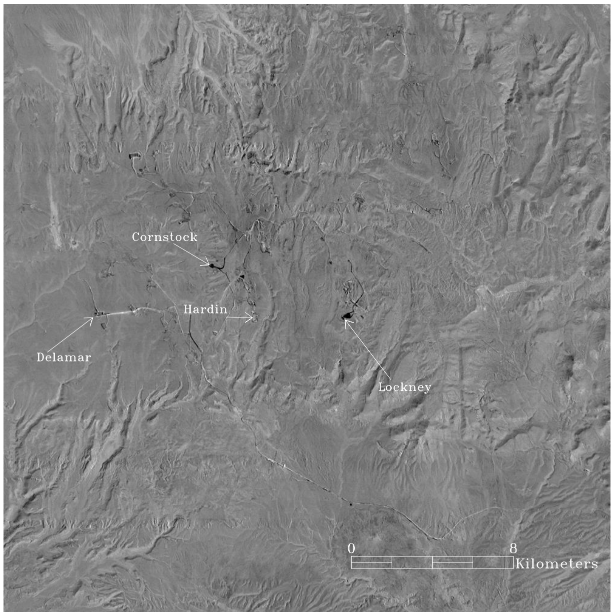

Fig. 2. Landsat TM change image at the Pahute Mesa test area between April 13, 1987 and May 31, 1987 (first MNF component of the 6 iterated MAD variates, stretched to ±8 standard deviations). Middle gray pixels indicate no change, light or dark pixels indicate changes.

kilometers, with reserves estimated at 3,000-5,000 tons of uranium oxide. The mine project is located 185 km north-east of Yazd, and covers an area of 20 hectares. Ores with grades above 300 ppm will be sent to the uranium mill, while ores with grades between 100 and 300 ppm will be exploited by heap leaching.

Figure 4 shows a change image derived from two of the ASTER images of Table I, covering the town of Saghand and its immediate vicinity. The most evident changes are associated with construction of a railway bed, most likely for Uranium ore transportation. The significant changes in Figure 5, determined from the April 2001 and March 2004 ASTER images, mark the actual position of mining excavations, about 32 km to the east.

VI. Conclusions

The case studies considered in this investigation involve very arid terrains upon which man-made activities tend to leave persisting signatures, signatures which, in turn, are not confused by changes in natural vegetation. Moreover, deliberate concealment did not play a role in the scenes investigated. Under these admittedly rather favorable circumstances, wide area change detection, with the algorithms used here, has been demonstrated to be useful for nuclear activity monitoring purposes. Detection of changes corresponding to subsidence crater formation at the NTS was in general possible but difficult at the 30m ground resolution of the Landsat TM sensor. Changes associated with test site preparation, on the other hand, are easily discriminated and well-correlated with the ground reference data. Temporal correlation is poor due to sometimes long lead times between preparation and the actual test explosion. Clandestine activities in remote, arid areas can be detected with the aid of the change detection algorithm used here, as is particularly evident from Figure 5. However additional information, e.g. high-resolution data, is obviously necessary to establish their relevance to nuclear monitoring.

TABLE II

Underground tests on Pahute Mesa after May 6, 1984.

Code Name	Date	Yield (kt)	Lat (deg)	W Lon (deg)	Diam
KAPPELI	25.07.84	20-150	37.268	116.412	-
EGMONT	9.12.84	20-150	37.270	116.498	-
TIENA	15.12.84	20-150	37.281	116.306	-
TOWANDA	2.05.85	20-150	37.253	116.326	-
SALUT	12.06.85	20-150	37.248	116.490	-
SERENA	25.07.85	20-150	37.297	116.439	-
GOLD-STONE	28.12.85	20-150	37.238	116.474	-
JEFFER-SON	22.04.86	20-150	37.264	116.441	-
DARWIN	25.06.86	20-150	37.265	116.500	103
CYBAR	12.07.86	20-150	37.279	116.356	-
GALVE-STON	4.12.86	20-150	37.240	116.369	-
LABQUARK	30.09.86	20-150	37.300	116.308	-
BELMONT	16.10.86	20-150	37.220	116.463	-
BODIE	13.12.86	20-150	37.263	116.413	-
DELAMAR	18.04.87	20-150	37.248	116.510	180
HARDIN	30.04.87	20-150	37.233	116.424	-
LOCKNEY	24.09.87	20-150	37.228	116.376	-
KERN-VILLE	15.02.88	20-150	37.314	116.472	122
CORN-STOCK	2.06.88	<150	37.260	116.442	55
ALAMO	7.07.88	<150	37.252	116.378	-
KEAR-SARGE	17.08.88	100-150	37.297	116.307	98
CONTACT	22.06.89	20-150	37.283	116.413	-
AMARILLO	27.06.89	20-150	37.275	116.354	-
HORNITOS	31.10.89	20-150	37.263	116.492	164
BAMWELL	8.12.89	20-150	37.231	116.410	-
BULLION	13.06.90	20-150	37.262	116.421	-
TENABO	12.10.90	20-150	37.248	116.495	-
HOUSTON	14.11.90	20-150	37.227	116.372	-
BEXAR	4.04.91	20-150	37.296	116.314	-
MONTELLO	16.04.91	20-150	37.245	116.443	-
HOYA	14.09.91	20-150	37.226	116.429	-
JUNCTION	29.03.92	20-150	37.272	116.361	-

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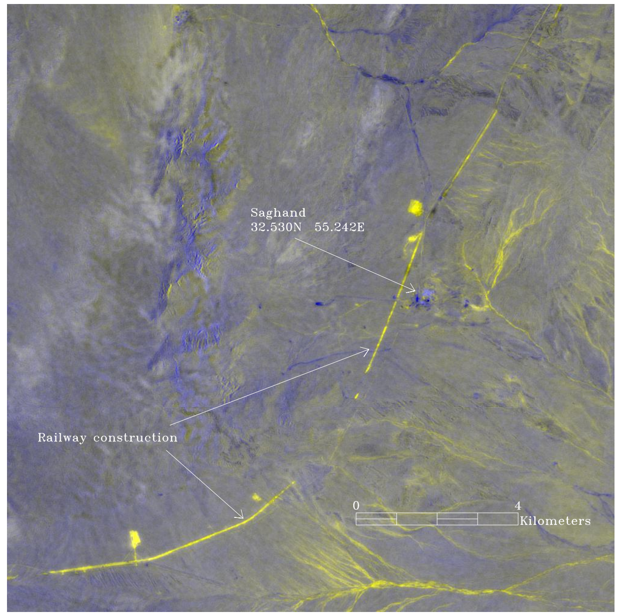

Fig. 4. ASTER VNIR+SWIR change image near the town of Saghand between July 13, 2003 and June 22, 2004 (first 2 MNF components of the 9 iterated MAD variates, stretched to ± 8 standard deviations). Middle gray pixels indicate no change, light, dark or colored pixels indicate changes.

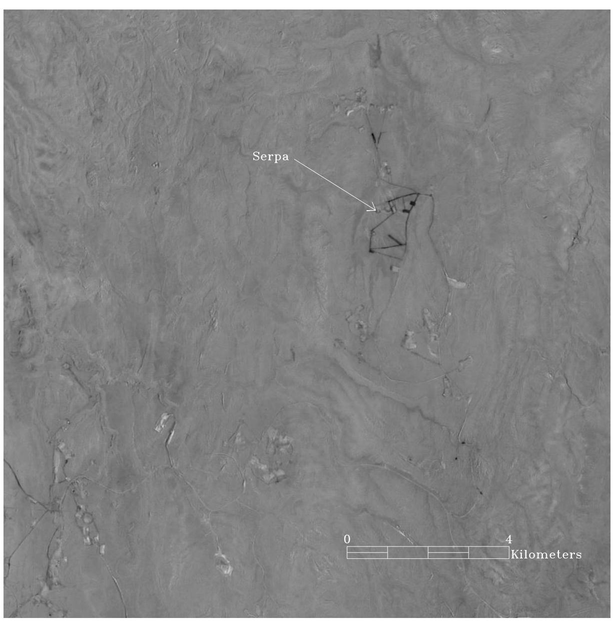

Fig. 3. ASTER VNIR+SWIR change image at the Pahute Mesa test area between June 5, 2001 and July 6, 2003 (first MNF component of the 9 iterated MAD variates, stretched to ± 8 standard deviations). Middle gray pixels indicate no change, light or dark pixels indicate changes. The site of the "SERPA" test is at coordinates 32.328N 116.314E.

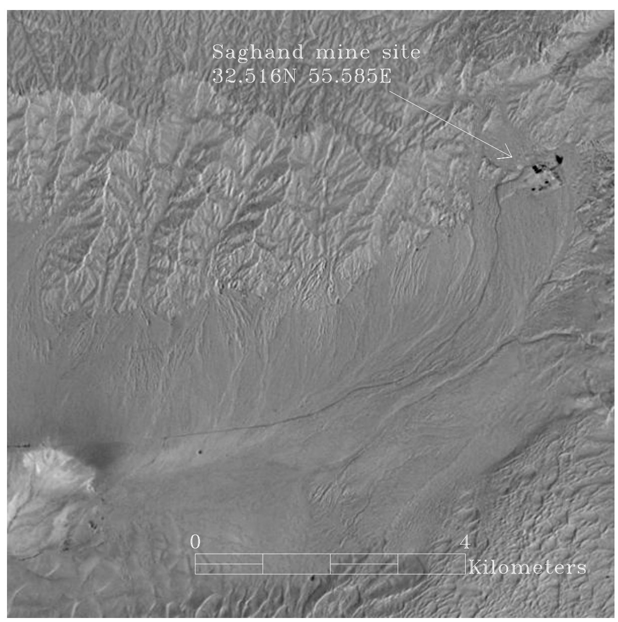

Fig. 5. ASTER VNIR change image in the Iranian highlands east of Saghand between April 28, 2001 and March 2, 2004 (first MAD component of 3 iterated MAD variates). Middle gray pixels indicate no change, light or dark pixels indicate changes.