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Remote sensing and earthquakes: A review

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Abstract

The current situation in earthquake space research indicates a few phenomena related with earthquakes: Earth's deformation, surface temperature growth, gas and aerosol exhalation, electromagnetic disturbances in the ionosphere. Both horizontal and vertical deformations scaled about tens centimetres and meters were measured after the earthquake events. Radar satellites using InSAR technique record such deformations with confidence. Pre-earthquake deformations are rather small – centimetres. A few cases of deformation mapping before and after the earthquake using satellite data are known at present time. Numerous observations have indicated an increase in surface and near-surface temperature of the order of 3–5 °C prior to earthquakes. Modern IR satellite sensors simply record such thermal anomalies. A few cases of gas and aerosol content change before the earthquake are also known. Remote sensing technologies allow us to retrieve the concentrations of gases in the atmosphere: O_3, CH_4, CO_2, CO, H_2S, SO_2, HCl and aerosol. However the spatial resolution and sensitivity of modern sensors are still low. First promising results were obtained only for ozone, aerosol and humidity. Electromagnetic researches of ionosphere in relation with earthquakes are widely spread now. Stable statistical estimations of ionosphere–lithosphere relation were obtained, and a few new ionospheric satellites were launched recently.

Keywords: Remote sensing; Earthquake; Deformation; Temperature; Gas

1. Introduction

Remote sensing has been used for earthquake research from '70s, with the first appearance of satellite images. First of all it was structural geological and geomorphological researches. Active faults and structures were mapped on the basis of satellite images (Trifonov, 1984). This method cannot be used for time series analysis, so that there is no possibility to measure short term processes before and after the earthquake.

The current situation of remote sensing application for earthquake research indicates a few phenomena related with earthquakes: Earth's deformation, surface temperature and humidity, air humidity, gas and aerosol content. Both horizontal and vertical deformations scaled about tens centimetres and meters after the shock. Such deformations are recorded by interferometric SAR (InSAR) technique with confidence. Pre-earthquake deformations are rather small – centimetres. A few cases of deformation mapping after the shock using satellite data are known at present time. Future development lays in precision SAR systems with medium spatial resolution and in combination with GPS technique. There are numerous observations of surface and near-surface temperature growth of the order of 3–5 °C prior to Earth's crust earthquakes. Methods of earthquake predictions have been developed using thermal IR survey. Well-known cases of gas and aerosol content change have been observed before the earthquake. Satellite methods allow us to restore the concentrations of gases in the atmosphere: O_3, CH_4, CO_2, CO, H_2S, SO_2, HCl and aerosol. However the spatial resolution and sensitivity of modern systems are still low. First promising results were obtained only for ozone, aerosol and air humidity.

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2. Radar observation

The technique of interferometric synthetic aperture radar (InSAR) is used to examine small-scale features in the deformation field associated with the earthquakes. Satellite interferometry is based on multitemporal radar observations. InSAR is a method by which the phase differences of two or more SAR images are used to calculate the differences in range from two SAR antennae having slightly different viewing geometries to targets on the ground. As a result, displacements on the Earth's surface can be measured in a range of centimetres and millimetres. The InSAR results show significant deformation signatures associated with faults, fractures and subsidences. The interferogram also clearly indicates surface deformation related to earthquakes.

First application of satellite interferometry for earthquake research was demonstrated in '90s by Massonnet et al. (1993). The well-known "butterfly" image of the Landers earthquake ($M = 7.3$, 28 June 1992) was compiled on the basis of pre-seismic image of April 24, 1992 and post-seismic scenes: August 7, 1992; 3 July, 1992 and June 18, 1993. Similar images were obtained for the Kobe earthquake, Japan, 16.01.1995, $M = 6.8$, Hector Mine earthquake, USA, $M = 7.1$, 16.10.99, Izmit earthquake, Turkey, 17.08.1999, $M = 7.8$ and others. All these cases demonstrate co-seismic and post-seismic deformations. There were no applications showing the pre-seismic deformation. Only recent results from Japan (Fig. 1) indicates probable pre-seismic deformation in the Tokai region (Kuzuoka and Mizuno, 2004). The vertical deformation recorded on the basis of InSAR data coincides with ground GPS observation.

The further enhancement of difSAR technology will allow us to record very fine differences in surface displacement. The planned COSMO/SkyMed mission aims to provide daily observations by 2007, overcoming limited observational frequency by using a constellation of four satellites. Existing satellite INSAR instruments have C-band (a wavelength of 5.66 cm) offering high resolution, but they only provide reliable interferograms for coherent, non-vegetated surfaces. Data from the JERS-1 satellite demonstrated during its lifetime that L-band satellites offer reduced resolution but provide interferograms over a far greater range of surface cover types. The next planned L-band SAR is the Japanese PALSAR on the ALOS satellite, which was launched successfully on January 24, 2006. Unfortunately, this instrument is designed to test applications other than interferometry, so it will provide only limited support for deformation analysis.

3. Thermal data

The modern operational space-borne sensors in the infra-red (IR) spectrum allows monitoring of the Earth's thermal field with a spatial resolution of 0.5–5 km and with a temperature resolution of 0.12–0.5 °C. Surveys are repeated every 12 hours for the polar orbit satellites, and 30 minutes for geostationary satellites. The operational system of polar orbit satellites (2–4 satellites on orbit) provides whole globe survey at least every 6 hours or more frequently. Such sensors may closely monitor seismic prone regions and provide information about the changes in surface temperature associated with an impending earthquake.

Natural phenomena and data availability stimulated the analysis of the long time series of thermal images in relation to earthquake hazard. Historically, the first application of thermal images in earthquake study was carried out in '80s for Middle Asia (Tronin, 1996). Later, similar researches were carried out in China (Qiang and Du, 2001), Japan (Tronin et al., 2002), India (Singh and Ouzounov, 2003), Italy (Tramutoli et al., 2001), Spain and Turkey, USA (Ouzounov and Freund, 2003) and other countries. Thermal observations from satellites indicate the significant change of the Earth's surface temperature and near-surface atmosphere layers. Significant thermal

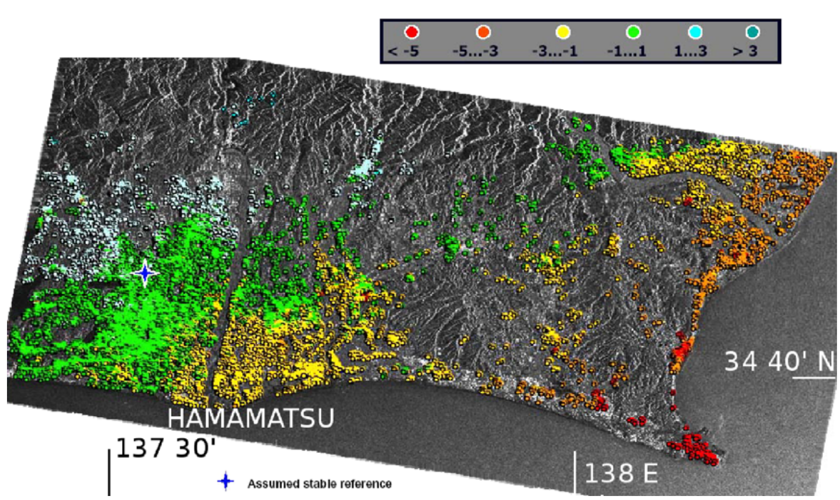

Fig. 1. Average displacement rate – 1992–2000 years, mm/year. Tokai area, Japan (after Kuzuoka and Mizuno, 2004).

anomalies prior to earthquakes related to high seismic areas have been reported in Middle Asia, Iran, China, Turkey, Japan, Kamchatka, India, Turkey, Italy, Greece and Spain. Large volume of thermal data were collected. Middle Asia database include seven years of observations for more than 100 earthquakes. Statistically significant correlation between thermal anomalies and seismic activity was performed (Tronin, 1996, 1999, 2000, 2002). Chinese scientists started operational earthquake forecast with thermal satellite data (Qiang and Du, 2001).

The Destructive Bam earthquake in Iran took place on 26 Dec 2003. The magnitude of the earthquake was 6.6 and the city of Bam was destroyed. Before the earthquake the background distribution of the surface temperature was observed (Fig. 2a), and five days before the earthquake on 21 Dec 2003 a thermal anomaly was detected to the south of Bam city (Fig. 2b). The anomaly existed for five days before the earthquake. The result of image interpretation is shown in Fig. 3.

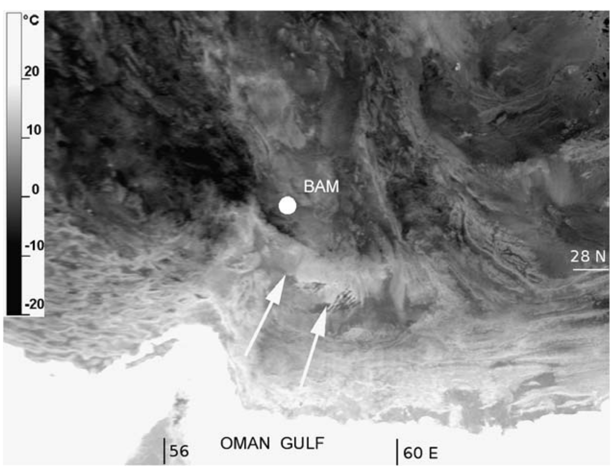

Fig. 2a. NOAA thermal image, South Iran, background situation, 23 Dec 2003. Arrows show thermal anomalies, and white circle – earthquake epicenter on 26 Dec 2003.

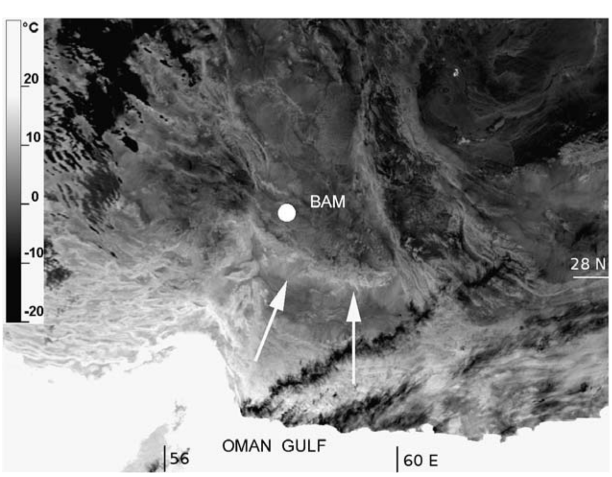

Fig. 2b. NOAA thermal image, South Iran, thermal anomaly, 25 Dec 2003. Arrows show thermal anomalies, and white circle – earthquake epicenter on 26 Dec 2003.

The observed thermal anomalies are related to the strong lithosphere-atmospheric coupling (Tronin et al., 2004). The causes of the thermal anomalies lie in the lithosphere and are related to the change of stress. The geological structures (faults, cracks, fractures etc.) act as preferred conduits because the convective flow of fluids and gas in the upper levels of the lithosphere, and thereby the transport of heat, is one order of magnitude higher than the diffusive flow. The thermal anomalies are typically observed above large faults and their intersections. Depending on the geological and tectonic setting, near the surface, at depths of a few kilometres, the fluid is divided into water and gas. The water causes change of debit and chemical composition in the wells and springs. Gas (H_2, He, CH_4, CO_2, O_3, H_2S, Rn) moves to the atmosphere. Depth and magnitude of the earthquake and geological conditions determine the mosaic character of phenomena on the Earth's surface.

The heat, water vapour and gas reach the Earth's surface, as a result of the lithosphere-atmospheric coupling. A few mechanisms of interaction are considered. First, convective heat flux (hot water and gas) changes the temperature of the Earth's surface. Second, change of the water level with usual temperature leads to a change in soil moisture, and consequently the physical properties of the soil. The difference in physical properties determines the different temperatures on the surface. Third is the greenhouse effect, when the optically active gases are escaped from the surface.

Result of thermal satellite data application for different areas looks similar: (1) thermal anomalies appeared about 6–24 days before and continued for about a week after an earthquake; (2) the anomalies are sensitive to crustal earthquakes with magnitude greater than 4.5; (3) the size of anomaly is ~100 km in length and ~10 km in width; (4) thermal anomaly has a mosaic internal structure with average element size about 40×130 km; (5) the amplitude of the anomaly is about 3–6 °C; (6) thermal anomalies are attached to large faults; (7) the nature of thermal anomalies is not clear now; (8) the response of water in wells and surface temperature in thermal anomaly on earthquake look similar; (9) increase of air and surface temperature as a consequence of the hot water eruption a few days before strong earthquakes could lead to atmospheric perturbations (atmospheric gravity waves) and could be helpful to explain an origin of some preseismic electromagnetic effects (in the ULF, VLF, LF frequency range) (Gokhberg et al., 1982; Hayakawa and Molchanov, 2002).

4. Other methods

Case studies of various remote sensing applications for earthquakes were reported recently. Pinty et al. (2003) have found the significant emergence of surface moisture growth after the Gujarat earthquake, 26 Jan 2001, using MISR data. Dey and Singh (2003) found significant surface latent heat flux change prior to the Gujarat earthquake. Dey et al. (2004) found a change in the total water vapour column after the Gujarat earthquake (Fig. 4). Water content was retrieved by SSM/I microwave radiometer on Tropical Rainfall Measuring Mission (TRMM) satellite. Okada et al. (2004) found changes in atmospheric aerosol parameters after the Gujarat earthquake. Aerosol above sea surface was recorded by SeaWiFS satellite. Singh et al. (2002) found changes in water colour and Earth's surface related to the Gujarat earthquake using IRS satellite data. A few examples of ozone concentrations changes are measured by TOMS related with earthquakes (Fig. 5) are reported by Tronin (2002). They ware also supported by

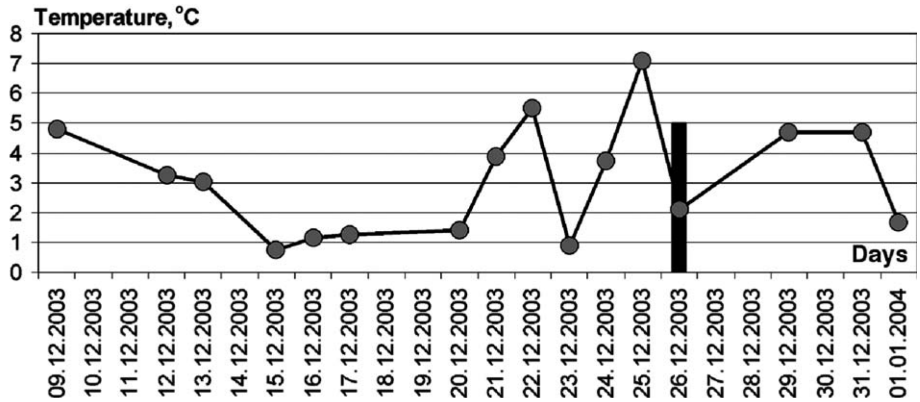

Fig. 3. Thermal anomaly temperature response for the earthquake on 26 Dec 2003 in Bam, Iran. Column shows the earthquake.

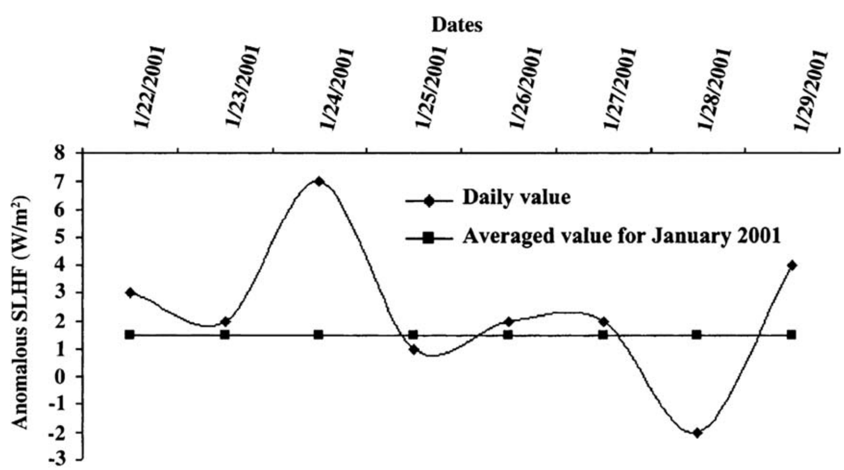

Fig. 4. Surface latent heat flux at the epicentre region of Gujarat earthquake on 26.01.01 in India (after Dey et al., 2004).

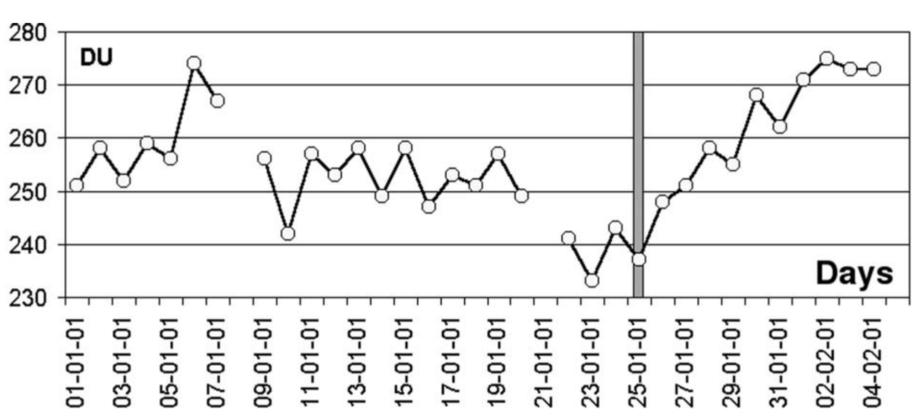

Fig. 5. Stratosphere ozone distribution above the epicentre of Gujarat earthquake on 26.01.01 in India.

ground ozone observations (Akselevich and Tertyshnikov, 1995). Night ionosphere fluorescence was discovered by ground observations in the end of a ’80s (Fishkova et al., 1985), and the fluorescence was associated with E layer (85–110 km). A few hours before the earthquake the intensity of oxygen lines 5577 A and 6300 A fluorescence increased. Significant changes in cloud formation associated with earthquakes have been reported by Morozova (1996).

5. Conclusion

The review of modern remote sensing technologies for earthquake research indicates the following conclusions: (1) Remote sensing is widely applicable for earthquake research; (2) Various methods are used – from optical sensors to radar systems; (3) The list of parameters studied by remote sensing are: Earth’s deformation, surface temperature, air humidity, gas and aerosol content, clouds distribution. We can suggest future development of remote sensing application for earthquakes by making full use of new methods: long wave radar systems, high-resolution microwave radiometers, gas analyzers.

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