Early Warning and Earth Quake Monitoring Using New Earth Observation Radar Techniques

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Abstract

Space technologies have proved to play key role in the sustainable development in national, regional and global levels. Earth observation techniques are considered of great importance amongst these technologies. Radar remote sensing is one of the new earth observation technologies with promising results. InSAR is a sophisticated radar remote sensing technique for combining synthetic aperture radar (SAR) complex images to form interferograms and utilizing their phase contribution to land topography, surface movement and target velocity. In recent years considerable applications of Interferometric SAR technique are developed. It is an established technique for precise assessment of land surface movements, and generating high quality digital elevation models (DEM) from spaceborne and airborne data. InSAR is able to produce DEM with the precision of a couple of ten meters whereas its movement map results have sub-centimeter precision. The technique has many applications in the context of earth sciences such as in topographic mapping, environmental modelling, rainfall-runoff studies, landslide hazard zonation, and seismic source modelling.

In this paper the experience gained on this new satellite technology in course of the continuous research work since 1994 in the Iranian Remote Sensing Center and the Iranian Space Agency is given and different case studies on the variety of the phenomena including Izmit quake of August 1999, the Bam quake of December 2003, and other calamities of recent years with specific focus on monitoring disasters, early warning and mitigating the effects are discussed.

Introduction

Radar remote sensing is accounted for as a new earth observation technology with promising results and future. Its potentials and capacities by itself and being a strong complementary tool for optical and thermal remote sensing are undeniable currently. In course of the years of explorations and examining the new radar technologies, their unique possibilities to comply the needs and answering the questions that the classic optical and thermal remote sensing techniques have been unable or difficult to tackle has grown the expectation that radar technologies can play a key role in bridging the gaps in this connection.

Nowadays, radar remote sensing in general and Synthetic Aperture Radar (SAR) technique in particular represent their values and potentials increasingly. Radar is a useful tool for land and planetary surface mapping. It is a good mean for obtaining a general idea of the geological setting of the area before proceeding for field work. Time, incidence angle, resolutions and coverage area all play important role at the outcome.
Newly emerging InSAR techniques

SAR interferometry (InSAR), Differential InSAR (DInSAR) and Persistent Scatterer (PSInSAR) are the new techniques in radar remote sensing. By using InSAR technique very precise digital elevation models (DEM) can be produced which privilege is high precision in comparison to the traditional methods. DEM refers to the process of demonstrating terrain elevation characteristics in 3-D space, but very often it specifically means the raster or regular grid of spot heights. DEM is the simplest form of digital representation of topography, while digital surface model (DSM) describes the visible surface of the Earth (Fig.1).

InSAR is a sophisticated processing of radar data for combining synthetic aperture radar (SAR) single look complex (SLC) images to form interferogram and utilizing its phase contribution to generate DEM, surface deformation and movement maps and target velocity. The interferogram contains phase difference of two images to which the imaging geometry, topography, surface displacement, atmospheric change and noise are the contributing factors. Orbit baseline changes can produce varying phase shifts while the parallel baseline component plays key role in producing interferograms (Fig.2).
Considerable applications of InSAR have been developed leaving it an established technique for high-quality DEM generation from spaceborne and airborne data and that it has advantages over other methods for the large-area DEM generation. It is capable of producing DEMs with the precision of a couple of ten meters while its movement map results have sub-centimeter precision over time spans of days to years. Terrestrial use of InSAR for DEM generation was first reported in 1974. It is used for different means particularly in geo-hazards and disasters like earthquakes, volcanoes, landslides and land subsidence.

Data sources and software

Satellite-based InSAR began in the 1980s using Seasat data, although the technique’s potential was expanded in the 1990s with the launch of ERS-1 (1991), JERS-1 (1992), Radarsat-1 and ERS-2 (1995). They provided the stable well-defined orbits and short baselines necessary for InSAR. The 11-day NASA STS-99 mission in February 2000 used two SAR antennas with 60-m separation to collect data for the Shuttle Radar Topography Mission (SRTM). As a successor to ERS, in 2002 ESA launched the Advanced SAR (ASAR) aboard Envisat. Majority of InSAR systems has utilized the C-band sensors, but recent missions like ALOS PALSAR and TerraSAR-X are using L- and X-band. ERS and Radarsat use the frequency of 5.375GHz for instance. Numerous InSAR processing packages are also used commonly. IMAGINE-InSAR, EarthView-InSAR, ROI-PAC, DORIS, SAR-e2, Gamma, SARscape, Pulsar, IDIOT and DIAPASON are common for interferometry and DEM generation.

InSAR and DEM generation methods

DEM is important for surveying and other applications in engineering. Its accuracy is paramount; for some applications high accuracy does not matter but for some others it does. Numerous DEM generation techniques with different accuracies for various means are used. DEMs can be generated through different methods which are classified in three groups that are DEM generation by (i) geodesic measurements, (ii) photogrammetry and (iii) remote sensing.

In DEM generation by geodesic measurements, the planimetric coordinates and height values of each point of the feature are summed point-by-point and using the acquired data the topographic maps are generated with contour lines. The 1:25000-scale topographic maps are common example. The method uses contour-grid transfer to turn the vector data from the maps into digital data. For DEM generation by photogrammetry, the photographs are taken from an aircraft or spacecraft and evaluated as stereo-pairs and consequently 3-D height information is obtained.

Fig.3: Differential interferometric SAR data collection scheme
DEM generation by remote sensing can be made in some ways, including stereo-pairs, laser scanning (LIDAR) and InSAR. There are three types of InSAR technique that is single-pass, double-pass and three-pass (Fig.3). In double-pass InSAR, a single SAR instrument passes over the same area two times while through the differences between these observations, height can be extracted. In three-pass interferometry (or DInSAR) the obtained interferogram of a double-pass InSAR for the commonly tandem image pairs is subtracted from the third image with wider temporal baseline respective to the two other images. In single-pass InSAR, space-craft has two SAR instrument aboard which acquire data for same area from different view angles at the same time. With single-pass, third dimension can be extracted and the phase difference between the first and second radar imaging instruments give the height value of the point of interest with some mathematic method. SRTM used the single-pass interferometry technique in C- and X-band. Earth’s height model generated by InSAR-SRTM with 90-m horizontal resolution is available while the DEM with 4-to-4.5-m relative accuracy is also available for restricted areas around the world.

Comparison

InSAR ability to generate topographic and displacement maps in wide applications like earthquakes, mining, landslide, volcanoes has been proven. Although other facilities like GPS, total stations, laser altimeters are also used, comparison between InSAR and these tools reveals its reliability. Laser altimeters can generate high resolution DEM and low resolution displacement maps in contrary to InSAR with the spatial resolution of 25m. However, most laser altimeters record narrow swaths. Therefore, for constructing a DEM by laser altimeter, more overlapping images are required. Displacement map precision obtained by terrestrial surveying using GPS and total stations is similar or better than InSAR. GPS generally provides better estimation of horizontal displacement and with permanent benchmarks slow deformations is monitored for years without being concerned about surface de-correlation. The most important advantage of InSAR over GPS and total stations are wide continuous coverage with no need for fieldwork. Therefore, wide and continuous coverage, high precision, cost effectiveness and feasibility of recording data in all weather conditions are its main privileges. However, it is important that the InSAR displacement result is in the line-of-the-sight direction and to decompose this vector to parallel and normal components the terrestrial data or extra interferograms with different imaging geometry are required. It is shown that DEM generated by photogrammetric method is more accurate than the others. It has approximately 5.5m accuracy for open and 6.5m for forest areas. SRTM X-band DSM is 4m less accurate for open and 4.5m less accurate for forest areas.

Data availability and atmospheric effects limit using InSAR, however processing of its data is challenging. For each selected image pair, several processing steps have to be performed. One of the current challenges is to bring the techniques to a level where DEM generation can be performed on an operational basis. This is important not only for commercial exploitation of InSAR data, but also for many government and scientific applications. Multi pass interferometry is affected by the atmospheric effects. Spatial and temporal changes due to the 20% of relative humidity produce an error of 10cm in deformation. Moreover, for the image pairs with inappropriate baseline the error introduced to the topographic maps is almost 100m. In topographic mapping this error can be reduced by choosing interferometric pairs with relatively long baselines, while in the displacement case the solution is to average independent interferograms.

Why InSAR DEMs are better?

Distinction between SAR imaging and the optical systems are more profound than the ability of SAR to operate in conditions that would cause optical instruments to fail. There are basic differences in the physical principles dominating the two approaches. Optical sensors record the intensity of radiation beamed from the sun and reflected from the features. The intensity of the detected light characterizes each element of the resulting image or pixel. SAR antenna illuminates its target with coherent radiation. Since the crests and troughs of the emitted electromagnetic wave follow a regular sinusoidal pattern, both the intensity and the phase of returned waves can be measured.

InSAR has some similarities to stereo-optical imaging in that two images of the common area, viewed from different angles, are appropriately combined to extract the topographic information. The main difference between interferometry and stereo imaging is the way to obtain topography from stereo-optical images. Distance information is inherent in SAR data that enables the automatic generation of topography through interferometry. In other words
DEM\text{s} can be generated by SAR interferometry with greater automation and less errors than optical techniques. Moreover, using DInSAR surface deformations can be measured accurately.

Different DEM generation methods of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) stereoscopy, ERS tandem InSAR, and SRTM-InSAR are used. Both the ERS-InSAR and SRTM DEMs are free of weather conditions, but ASTER DEM quality may be affected by cloud coverage in some local areas. InSAR has the potential of providing DEMs with 1-10cm accuracy, which can be improved to millimeter level by DInSAR. Its developments are rapid however it is our requirements that say which one is better for use.

**InSAR applications**

InSAR techniques are developing rapidly and increasingly. Its civil applications includes,

- Oceanography – Ocean wave, ocean currents, wind, circulation, bathymetry
- Hydrology – Wetland assessment,
- Glaciology – Glacier motion, polar research
- Seismology – Co-seismic displacement field
- Volcanology – Prediction of volcano eruption
- Subsidence and uplift studies
- Change detection
- Coastal zones
- Forestry – Forest classification, deforets monitoring
- Cartography – DEM, DTM, topographic mapping
- Geology – Geological Mapping, tectonic applications
- Soil Science – Soil moisture
- Agriculture – Crop monitoring
- Environment – Oil spill, hazard monitoring
- Archaeology – Sub-surface mapping

while the non-civilian application are as below:

- Reconnaissance, surveillance, and targeting
- Treaty verification and nonproliferation
- Navigation and guidance - Sandia National Lab. 4-inch SAR
- Foliage and ground penetration
- Moving target detection
- target detection and recognition.

**Using InSAR technique for earthquake monitoring and detecting precursors**

In course of the years since 1994, studies and verifications by the Microwave Remote Sensing Group that is currently based at the Mahdasht Satellite Receiving Station affiliated to the Alborz Space Center of the Iranian Space Agency has been carried out continuously; good and valuable achievements gained on InSAR technology applications. The results achieved by combining the available SAR image pairs of the areas hit by the quakes look interesting and promising. If the geodynamic phenomena in general and earthquakes in particular are the result of
different processes and interactions in Sun-Earth System and beyond, then the occurrence of such phenomena would be detectable by investigation and continuous monitoring of the dynamism and changes in the features. The studies include verifying and investigation of the variety of the phenomena namely Izmit quake of August 1999, Bam quake of December 2003, L’Aquila quake of April 2009, Haiti earthquake of January 2010 and Chile earthquake of February 2010. However empirical field checkups are still necessary and the job will be followed up for examining other sites around the globe.

Examples of our practical studies and achievements

(1) In Fig. 4, the top images at the left and right show the tandem amplitude data of 12 and 13 August 1999 (4 and 5 days pre-quake) of Izmit, Turkey (where hit by an earthquake of the magnitude 7.4 in Richter scale on 17 August 1999) as master and slave images respectively. The research team conducted by the author used the ERS-1&2 data provided by the European Space Research Institute (ESRIN), and the Earth-view and SAR Toolbox softwares to generate the variety of related products. The normal baseline for the image pair is 224.2 m and parallel baseline is 91.1 m. The image at the bottom left is the coherence image while the right image at the bottom depicts the DEM image where the interferogram is overlaid on it. For each product the relevant histogram is seen as inset. The similarity of the histograms of master and slave images is considerable due to the high correlation of the images that
is clearly seen in coherence image. It is important to note that lowest coherence values (darkest values) correspond both to steep slopes or vegetated areas (especially visible in the lower part of the image) and to the lakes (image center and left). DEMs generated from the tandem images are accurate because of the high correlation between master and slave images. Although both the master and slave images are pre-earthquake data of the earthquake of August 17, 1999, the strain in the disaster area is visible a week before the quake (as fore shocks). It could be a useful precursor for the advent of a disaster like the earthquake in Izmit.

Fig.5 compares the image pairs of before and after quake of Izmit area. Images in the right side shows the combinations of before quake (as fore shocks) and those in left side shows the combinations of images acquired after quake (as post shocks). The image in top right is produced by combining the ERS SLCI pairs of 20 March 1999 and 24 April 1999 (113 days and 144 days before quake), with the normal baseline of 228.264m and parallel baseline of 27.607m. The image in bottom right is produced by combining the ERS tandem image pairs of 12 and 13 August 1999 (4 and 5 days before quake) with the normal baseline of 224.190m and parallel baseline of 91.097m. The image on top left is produced by combining the ERS tandem image pairs of 10 and 11 September 1999 (23 and 24 days after quake) with normal baseline of 183.313m and parallel baseline of 73.239m. The image in bottom left is produced by combining the ERS tandem image pairs of 16 and 17 September 1999 (1 month after quake) with normal baseline of 234.443m and parallel baseline of 103.386m. In all of the cases the anomaly around the place where the quake was occurred is distinguishable apparently.

Fig.5: Comparison of the InSAR products of before and after Izmit quake of western Turkey

(II) Advent of the awful earthquake of December 26, 2003 in Bam, Iran has drawn the attention of the many scientific and humanitarian organizations to study the phenomenon and its causes and origins as well as its impacts and developments. Fig.6 shows the position of the area on a satellite image with the photos of the pre and post-
quake views of the Citadel Bam as insets. In Fig.7, the left image is the topo-DInSAR product acquired from the Envisat-ASAR data of 11 June and 3 December 2003, while the image at right is the topo-DInSAR product generated by combining the SLC images of 3 December 2003 and 7 January 2004. The team conducted by the author used the data provided by ESRIN, and the DORIS and IDIOT softwares to generate the products. The middle image obtained by NASA scientists is the 3-D perspective view of vertical displacement of the land surface south of Bam during the 3.5 years after the 6.6 earthquake of December 26, 2003 that is derived from analysis of radar images. Blue and magenta tones show where the ground surface moved downward; yellow and red tones show upward motion (particularly in south of Bam). Displacements are superimposed on a false-color Landsat Thematic Mapper image taken on 1 October 1999. In the right image that is obtained from the ASAR data pre and post-earthquake the curl-shape pattern south of Bam is distinguishable where such the torsion is not visible in the left image that is obtained from pre-earthquake data. For the left image the normal baseline is 476.9 m and parallel baseline is 141.6 m, while for image at right the normal baseline is 521.9 m and the parallel baseline is 268.3 m. The right image demonstrates that the related interferogram includes four lobes. Since the displacement in the east is greater than that in the west, the related lobes are larger. The displacements measured along the radar line-of-sight direction are 30cm and 16cm at south-east and north-east lobes of the interferogram, respectively. However, the displacement related to the western part of the area is about 5cm along the radar line-of-sight direction.

(Image credit: Parviz Tarikhi)

Fig.6: Satellite view of Bam area with the pre and post-quake photos of the Citadel Bam as insets
The 2009 L’Aquila earthquake occurred in the region of Abruzzo, in central Italy. The main shock was registered at 3:32 local time on April 6, 2009, and was rated 5.8 on the Richter scale and 6.3 on the moment magnitude scale. Its epicenter was near L’Aquila, the capital of Abruzzo, which together with surrounding villages suffered most damage. There have been several thousand foreshocks and aftershocks since December 2008.
more than thirty of which had a Richter magnitude greater than 3.5. The earthquake was felt throughout central Italy; 308 people are known to have died. The investigation and study work on this event was started by the Microwave Remote Sensing Research Core conducted by the author since early July 2010. Thanks to the availability of the radar data provided by the European Space Research Institute (ESRIN) affiliated to the European Space Agency (ESA), using Synthetic Aperture Radar (SAR) Interferometry technique the investigation and research work on the data which includes the single look complex images (SLCI) of the C-band Advanced Synthetic Aperture Radar (ASAR) image mode system of Envisat satellite in addition to other type of data, was carried out.

The two image sets included in Fig.8 and Fig.9 respectively are the samples of the products generated by combining the Envisat ASAR images pair of March 11 and June 24, 2009 (27 days before and 78 days after the trembling) with 239.54 meters virtual baseline, and the images pair of January 28, 2007 and May 17, 2009 (798 days before and 41 days after the quake) with 580.82 meters virtual baseline.

Fig.9: Image products generated by combining the Envisat ASAR image pair of January 28, 2007 and May 17, 2009 (798 days before and 41 days after the quake) with 580.82 meters virtual baseline and 216.10 meters parallel baseline
Fig. 10 compares the phase-flattened products of L’Aquila area. On top row those products are given which their relevant SLCIs are all acquired before the L’Aquila earthquake of 2009 (fore shocks) while in the bottom row the products generated from the combination of SLC image pairs which one is acquired before and the other after quake are given. The anomalies in the first row images are considerable. Like the case of Izmit quake of 17 August 1999 in Turkey (see Fig. 5) they could be considered as precursors for the incidence of the quake on 6 April 2009.

Fig. 10: Comparison of the phase-flattened products of L’Aquila area, central Italy

(IV) Fig. 11 shows the sample of data products in the framework of the research and study work on Haiti earthquake. On January 12, 2010, Tuesday a huge quake measuring 7.0 rocked the Caribbean Haiti. It destroyed mainly the capital of Haiti, Port-au-Prince toppling buildings and causing widespread damage and panic. Using the radar data provided by the European Space Research Institute (ESRIN) affiliated to the European Space Agency (ESA) an investigation and research work on the available data has been carried out since early March 2010. The data included 47 single look complex images (SLCI) of the C-band Advanced Synthetic Aperture Radar (ASAR) image mode system of Envisat satellite in addition to other type of data. The results sound good and the samples of phase flattened products below generated for the area of study. The products are generated by combining the Envisat ASAR post-quake descending image pairs acquired on 20 January 2010 and 24 February 2010 (baseline 434.40m), 26 January 2010 and 2 March 2010 (baseline 279.98m), and post-quake ascending images of 30 March 2010 and 19 January 2010 (baseline 165.61m). All three products refer to post shocks.
Fig. 11: InSAR products of Haiti area in North America

Fig. 12: InSAR products of Chile area in South America that was hit by the earthquake of 8.8 Richter on 27 February 2010
For the Chile study area following the disastrous earthquake of 27 February 2010, with the magnitude of 8.8 in Richter scale a sample of the results of combination of image pairs is given in Fig.12. It shows the combination of the post-quake SLC image pairs of 26 March 2010 and 30 April 2010 with the baseline of 251.05m (post shock).

Conclusions and suggestions

The results achieved by combining the available SAR image pairs of the study areas suggests that if the geodynamic phenomena in general and earthquakes in particular are the result of different processes and interactions in Sun-Earth System and beyond, then the occurrence of such phenomena are detectable by investigation and continuous monitoring of the dynamism and changes in the features. SAR Interferometry is a useful technique for this purpose. By applying the technique the anomaly around the place where the quake occurs is detectable and visible apparently. Detecting the anomalies, fore shocks could be the precursor of the incidence of the dynamic phenomena like a quake/s. Detected anomalies that refers to fore shocks and post shocks are the indication of oscillatory behavior of the fault system. It can be modeled if sufficient data and information is accessible.

Newly developed InSAR techniques like PSInSAR (Persistent or Permanent Scatterer) technique and SqueeSAR technique could lend a good hand of assistance and usefulness in detecting and change detection of anomalies and dynamism. Persistent Scatterer Interferometry (PSI) is a revolutionary new technique for measuring ground displacements to a degree of accuracy and over time periods previously unachievable using conventional interferometry methods. Monitoring the seismic faults and volcanic areas, subsidence and uplift, and landslide and instability phenomena are amongst the common applications of PSInSAR technique. The ease with which PS data can be updated suits the improvement of early warning systems in matters of Civil Protection. Whether by natural failure or from manmade activities (e.g. extraction of water/gas/oil), the PS technique provides regular updates on displacement patterns. It is particularly suited to monitoring urban subsidence where conventional methods of survey cannot match the information density, at similar cost. The PS technique is also capable of identifying the extent of unstable land and the corresponding rate of movement, when slow movements occur. The integration of PS data within a GIS and regular updating of PS data significantly increases the potential of microwave remote sensing for landslide investigations.

References


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Contributor’s brief CV

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involved with the United Nations Committee on the Peaceful Uses of Outer Space (UN-COPUOS) since 2000, including as Second Vice-Chair and Rapporteur in 2004-06 of the committee bureau. Since 2001 he has co-chaired Action Team number 1 of UNISPACE-III with the mission ‘to develop a comprehensive worldwide environmental monitoring strategy’. From 2004-07 he led the Office for Specialized International Cooperation of the Iranian Space Agency. He is also a freelance journalist and technical writer. He has made in the meantime years of research and study on the developments and status of space science and technology with a particular focus on Iran.