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Geohazard Monitoring with Space and Geophysical Technology

- An Introduction to the KJRS 21(1) Special Issue -

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Abstract : National Research Lab Project "Optimal Data Fusion of Geophysical and Geodetic Measurements for Geological Hazards Monitoring and Prediction" supported by Korea Ministry of Science and Technology is briefly described. The research focused on the geohazard analysis with geophysical and geodetic instruments such as superconducting gravimeter, seismometer, magnetometer, GPS, and Synthetic Aperture Radar. The aim of the NRL research is to verify the causes of geological hazards through optimal fusion of various observational data in three phases: surface data fusion using geodetic measurements; subsurface data fusion using geophysical measurements; and, finally fusion of both geodetic and geophysical data. The NRL hosted a special session "Geohazard Monitoring with Space and Geophysical Technology" during the International Symposium on Remote Sensing in 2004 to discuss the current topics, challenges and possible directions in the geohazard research. Here, we briefly describe the special session papers and their relationships to the theme of the special session. The fusion of satellite and ground geophysical and geodetic data gives us new insight on the monitoring and prediction of the geological hazard.

Key Words : Geohazard Monitoring and Prediction, Data Fusion, Superconducting Gravimeter, InSAR, GPS, Gravity and Magnetics.

1. Introduction

In recent years, our planet Earth has been subjected to devastating geological hazard (geohazard) with terrible consequences in terms of loss of human life and property damage such as Kobe (Japan in 1995) and Izmit (Turkey in 1999) earthquakes. A series of these events was included one of the world's most powerful

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Can massive earthquakes and volcanic eruptions be directly detected from space? It is not an easy question to answer, but at least they can be indirectly detected via surface and subsurface deformation or the external electromagnetic (EM) disturbance resulting from those events. The surface displacement by earthquakes can be measured by modern imaging radar (Synthetic Aperture Radar, SAR) technology, while subsurface deformation can present signals in the ionosphere resulting from varying induced magnetization that can be measured from the space sensors. The EM disturbance associated with earthquakes is now ready to be exploited by other state-of-the-art satellite technologies.

The NASA scientists Chao and Gross (2005) noted that the last year's earthquake off the west coast of Indonesia affected the Earth's rotation, decreased the length of day (LOD) by 2.68 μ seconds, slightly changed the planet's shape, and shifted the North Pole by 2.5 cm in the direction of 145°E. In general, LOD varies when any mass on or in the Earth moves, affecting the state of its angular momentum. The seasonal change in the trade winds and monsoons, for example, is a well-known factor on the LOD. Chao and Gross (2005) compared the amount of mass shifted as a result of the earthquake to the Three-Gorge reservoir in China when it is filled with 40 km^3 of water. That shift of mass would increase the length of day by only 0.06 μ seconds and make the Earth only very slightly more round in the middle and flat on the top. It would shift the pole position by about 2 cm. They concluded the earthquake and tsunami caused a LOD change too small to detect, but it can be theoretically calculated. In principle, with high quality data from Satellite or Lunar Laser Ranging (SLR or LLR), Very Long-Baseline Interferometry (VLBI), and GPS, if compiled over decades, the variations in the LOD can be traced to particular causes. The International Earth Rotation Service (IERS) calculates and maintains the LOD.

Last year's earthquake also caused a barely detectable oblateness change, and a pole shift large enough to be possibly identified. Detection of the LOD signal and pole shift by geodynamic disturbance due to geohazard could be possible when geophysical and geodetic data from ground based and spaceborne sensors are analyzed.

In 2003, the Ministry of Science and Technology of Korea designated the Geohazard Information Laboratory of Sejong University as a National Research Lab (NRL). The research activities of the NRL have focused on the geohazard analysis by data fusion of geophysical and geodetic instruments under the project entitled "*Optimal Data Fusion of Geophysical and Geodetic Measurements for Geological Hazards Monitoring and Prediction.*"

The NRL hosted a special session "Geohazard Monitoring with Space and Geophysical Technology" in Jeju Island, Korea on 27 October 2004 during the International Symposium on Remote Sensing 2004 to discuss the current topics, challenges and possible directions in the geohazard research. This study briefly describes the NRL project and the papers that were presented at the special session in terms of their interrelationships.

2. National Research Lab Project:

"*Optimal Data Fusion of Geophysical and Geodetic Measurements for Geological Hazards Monitoring and Prediction*"

Advanced techniques from the fields of geophysics and geodesy are now capable of detecting minute earth surface displacement as well as subsurface geodynamic motion. These technologies encourage research activities to verify the causes and the processes of geohazards such as earthquakes, volcanic activities, subsidences, and landslides. Geophysical instruments such as the superconducting gravimeter, seismometer and magnetometer, and geodetic instruments such as GPS, Total Station and InSAR (**In**terferometric **S**ynthetic **A**perture **R**adar) are deployed to make precise measurements and, eventually the heterogeneous data from these instruments are optimally integrated for further analysis and interpretation.

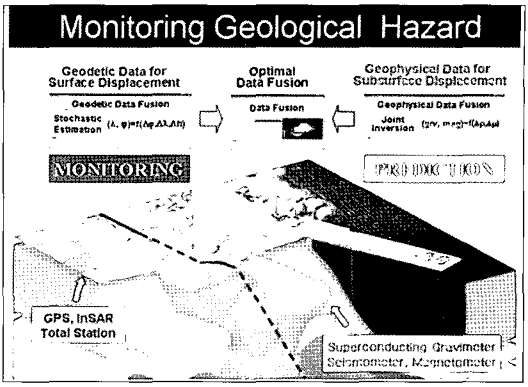

Fig. 1. Concept of the National Research Lab Project "*Optimal Data Fusion of Geophysical and Geodetic Measurements for Geological Hazards Monitoring and Prediction.*" Various geodetic and geophysical measurements of the surface and subsurface are integrated for optimal analysis.

The aim of the NRL research is to verify the causes of geological hazards through optimal fusion of various observation data in three phases: surface data fusion of geodetic measurements; subsurface data fusion of geophysical measurements; and, finally the fusion of both geodetic and geophysical data. The results of this research will be effectively applied to the prediction and prevention of abrupt and long-term geodynamic motion caused by geological hazards such as earthquakes and tsunami, volcanic eruptions, landslides and subsidence. Geophysical instruments such as the superconducting gravimeter, seismometer, and, magnetometer; and geodetic instruments such as GPS, InSAR, and Total Station will be deployed to gather precise information of both surface and subsurface geodynamics. The observations from these instruments will then be optimally integrated.

Fig. 1 demonstrates the basic concept of the NRL research. In many cases of geologic hazard, subsurface deformation is accompanied by detectable surface displacement or motion. In order to monitor and further predict the geohazard, both surface and subsurface data are required. Geodetic data are required for surface displacement analysis, while geophysical data such as gravity, magnetic, and seismic data are required for subsurface mass movement and deformation. These independently measured data, however, must be optimally integrated for geohazard analysis. In Fig. 2 geophysical and geodetic instruments for the NRL research are illustrated.

Stochastic Estimation, for example, may achieve geodetic data fusion. Joint Inversion of gravity and magnetic measurements (Zheng and Arkani-Hamed, 1998) is an example of geophysical data fusion because involving the simultaneous inversion of combined geophysical data sets to recover the corresponding independent model in contrast to the traditional methods that are appropriate if the two models have the same geophysical property. Joint inversion is reasonable only if the geophysical properties can be related to each other. When gravity and magnetic field anomaly variations are detected due to a common geodynamic event, the two geopotential data can be modelled by the joint inversion. The optimal data fusion technology developed in each research phases will be evaluated by field collection and processing of experimental data from selected sites. Evaluation results from the prior phase will be used as feed back for the next phase enabling further maturing

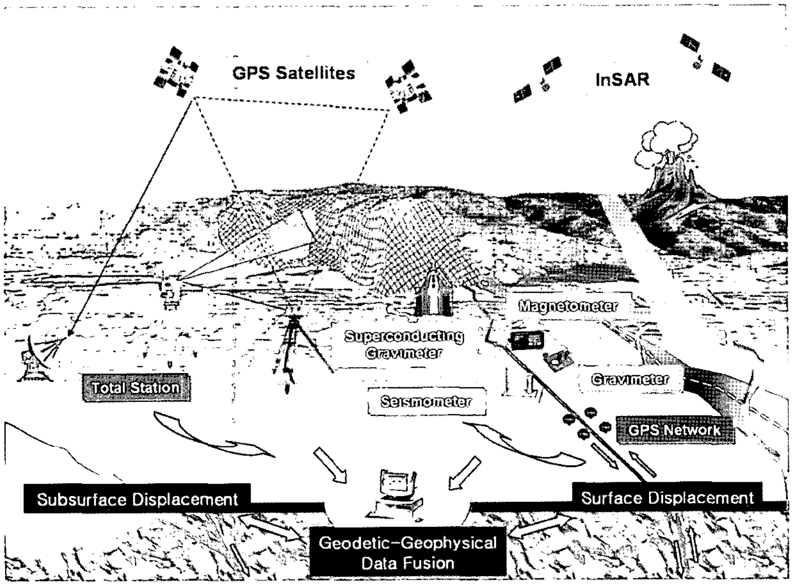

Fig. 2. Geophysical and geodetic instruments for monitoring and predicting geological hazards for the NRL research. Instruments include GPS, InSAR, Total Station, Superconducting Gravimeter, Seismometer, and Magnetometer.

of the technology.

The NRL research project "Optimal Data Fusion of Geophysical and Geodetic Measurements for Geological Hazards Monitoring and Prediction" contains two major research components; data acquisition and analysis by data fusion. Different instruments, methodologies, theories, and models are required for the different types and scales of geohazard in the research as summarized in Table 1. The eventual results of this research effort will contribute to effective national and global prediction and monitoring of geohazard as well as the implementation of a real time geohazard prediction and management system.

Table 1. Instruments, methodologies, theories, and models for geological hazard analysis in the National Research Lab Project.

Geohazard	Instrument/Methodology	Theory/Model
Earthquake	- Seismological Network - GPS Network - InSAR - Superconducting Gravimeter - Satellite Potential Field	- 3-D Displacement/Velocity by GPS Network Adjustment - Displacement by InSAR - Surface Deformation by GPS/InSAR Data Fusion - Geopotential Field Anomaly Fusion - Modeling and Visualization
Landslide Subsidence	- GPS - Total Station - InSAR	- Local and Regional Ground Motion Model - Deformation by Differential InSAR - Surface Deformation by GPS/InSAR Data Fusion
Volcanic Eruption	- InSAR, - GPS - Gravity and Magnetics	- Joint Inversion and Modeling of Geopotential Anomalies - Isostatic Modeling - Deformation by Differential InSAR

3. Geohazard Analysis by Space and Geophysical Technology

1) Measuring Gravitational Acceleration Change due to Geohazard from Ground to Space

Precise global measurements of the Earth's gravity field are essential to answer a couple of important questions in geophysics: What changes in gravity are associated with slow and creeping earthquakes, tectonic motions, sea-level changes and post-glacial rebound? ; Can we monitor the location of the rotation pole of the Earth on a short-period time scale? The Global Geodynamics Project (GGP) monitors changes in the Earth's gravity field at periods of seconds and longer. The GGP is tasked to indicate the application of gravity data to the solution of a number of geodynamic problems. The key instrument for the GGP is the Superconducting Gravimeter (SG).

The SG uses persistent supercurrents, which are trapped in superconducting magnets, to produce an ultra stable magnetic field that levitates a superconducting sphere (GWR). The SG is mainly composed of gravity sensing unit and the liquid helium tank with refrigeration. The sensing unit includes the superconducting magnets, the sphere, energizing the coils, temperature control circuitry and magnetic shielding, while the cooling system which keeps the sensing unit close to 4.2°K to maintain the superconducting state. In 1993, GWR introduced the commercial SG and became the exclusive manufacturer of SG. The SG is currently used to monitor Earth tides, nearly diurnal free wobble, core modes, atmospheric, hydrospheric, and ocean loadings effects, Earth rotation and polar motion, and free oscillation of the Earth (GWR).

As a part of the NRL project, an SG is currently being installed at MunGyung Seismic Station maintained by Korea Earthquake Research Center (KERC) of Korea Institute of Geoscience and Mineral Resources (KIGAM). GWR's SG (S/N 045) gravity unit and cryogemic tiltmeters in Fig. 3 will be operational from March, 2005, along with CMG-3TB borehole seismometer, GPS, and other geophysical sensors at the site. This will be the first μ Gal level or better precision gravimeter in Korea. This SG will form an East Asian cluster that complements three SGs in Japan (Kyoto, Esashi, and Matsushiro) and another one in Wuhan, China.

Crossley and Hinderer (2005) demonstrated that the gravity effect of coseismic deformation and deformation associated with silent slip events in subduction zones is at the few μ Gal level and probably best detected using an array of SGs. Ground monitoring of silent slip events also can be detected with SGs together with an Absolute Gravimeter. When combined with existing GPS networks, we hope to learn more about the type of deformation involved in a silent slip event, especially in a situation where there is repeated slip at regular

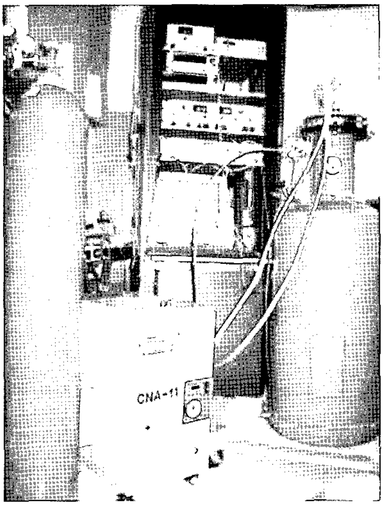

Fig. 3. GWR's SG (S/N 045) gravity unit and cryogemic tiltmeters that will be installed installed at MunGyung Seismic Station operated by Korea Earthquake Research Center.

intervals. It would also be particularly interesting to identify any pre-cursor signals that might appear before a major thrust event.

Crossely and Hinderer (2005) also mentioned that as far as volcanoes are concerned, the gravity effect is much larger, up to 100 μ Gal or more. The requirement for dense station coverage suggests the use of SGs as primarily base stations. They concluded that the combination of different instruments makes for a much more reliable and accurate observational program that should give insight to the mass motions that occur beneath active volcanoes. The East Asian SG cluster may play an important role for this activity.

Connecting this ground-based technique connected to space technology may be done simply by GPS satellite, for example. The GPS technique can achieve a positioning precision in the mm range for displacement variation, i.e., height variation of a point on the Earth's surface, e.g., for the SG site. To achieve this precision, one needs a GPS network of a minimum of two stations. The reference station may be considered as fixed and error free and the relation to the coordinate variations of the other station located at the SG site that must be determined. Adding more reference stations can improve the precision of the result. The coordinates of the reference station must be known before processing for better than 1 cm. This can be achieved by using the GPS network data of the International GPS Service (IGS) or using the IGS stations as reference stations (Neumeyer, 2005).

One of the objectives of new-generation satellite gravity missions such as CHAMP (**Cha**llenging **M**ini-Satellite **P**ayload) and GRACE (**G**ravity **R**ecovery **A**nd **C**limate **E**xperiment) is the recovery of the Earth's temporal gravity field variations. Of fundamental interest is the combination of satellite-based and ground gravity measurements. Because GRACE's temporal resolution ranges from one month to years, ground gravity measurements must have a long-term stability, which only the superconducting gravimeters fulfil. It has been shown that SG (point) measurements are representative for a large area if the local gravity effects are removed (Neumeyer *et al.*, 2004).

Neumeyer (2005) pointed out that volcano monitoring is possible by combination of SG and GPS measurements thru detecting mass re-distribution (by SG) and ground deformation (by SG and GPS). A correlation of the combined signal with seismic, electromagnetic, chemical measurements etc will bring us new information. Accordingly, mass movement and crustal deformation in tectonically active zones is also feasible to study. Detection of silent earthquakes can be done by a combination of SG, GPS and seismic measurements. In the Cascadian subduction zone, for instance, displacements in the cm range were successfully observed by Rogers and Dragert (2003).

Shum *et al.* (2005) presented their current state-of-the-art research using GRACE mission data for potential detection of several solid Earth "slow" deformations. They concluded that GRACE has the ability to observe basin-scale hydrological signals and that alternate processing techniques could enhance the spatial and temporal resolutions. Solid Earth deformation processes such as plate convergence, large earthquakes and its co-seismic cycles are difficult to detect using GRACE unless data is averaged over a long period (e.g., several years) with better accuracy.

2) Imaging Topography and Surface Displacement from Space

Dramatic geohazard features mapped by radar remote sensing decorated the cover page of "Nature" twice in 1990s. In the two Nature Issues, Massonnet *et al.* (1993; 1995) used satellite radar interferometry in those two issues of Nature, commonly referred to as InSAR (Interfetrometric Synthetic Aperture Radar) to dramatically demonstrate the displacement of the Earth surface by the Landers earthquake and Mount Etna.

InSAR is an active microwave remote sensing technique. A spaceborne or airborne SAR bounces a radar signal off the ground surface and echoes are processed to image the ground surface and sometime the subsurface. Each element of an image contains intensity and phase information. Intensity is used to characterize the physical property as shown in many traditional applications, while phase information is used somewhat differently (Sabins, 1997). Even traditional radar images are renderings of only the amplitudes and mainly tell us about the surface reflectivity.

In late 1960, scientists realized phase information could be also used to measure topography. For this, two different images of the terrain taken from slightly different viewing points are combined to produce a single image. The phase at each point in the resultant image is equal to the difference in the phase of the point in the original two images. From these phase differences, topography can be acquired (Prescott, 1993). When the two images could be taken from the same spot, the phase difference is zero unless points in the image have moved. In practice, the images are never taken from the same spot, and hence the effect of topography must be eliminated before motion of the surface can be detected. Instead of using three images (i.e., two images for topography and a later image for displacement), Masonnet *et al.* (1993) used a DEM (Digital Elevation Model) to remove topography and map the changes from just a pair of images; one before and one after the Landers earthquake. They clearly revealed the Earth's surface displacement as the "*Image of an Earthquake*."

Lu *et al.* (2005) presented their on-going investigations of the Aleutian volcanoes with SAR images from ERS, Radarsat, and JERS1 satellites. They implemented state-of-the-art InSAR technology to show how the Aleutian volcanoes work and to enhance the capability for predicting future eruptions and the associated hazards with examples of nine volcanoes. As a result, they revealed that magma accumulation in the middle to upper crust can be observed long before the onset of the short-term precursors to an eruption.

Korean scientists have analyzed possible surface deformation of the historically active Mt. Baekdu located on the border between China and North Korea (Kim *et al.*, 2001a; 2001b; Kim and Won, 2005b). A major eruption of the mountain in 968±20 A.D. (Horn and Schmincke, 2000) is considered as one of the most powerful eruptions during the era (Smithsonian Institution, 1996). Mt. Baekdu has been inactive since the last eruption in 1702. However, gaseous emissions, hot springs and minor earthquakes have been continuing. Kim and Won (2005b) recently applied the two-pass interferometric technique to ERS-1/2 and JERS-1 SAR data set for detecting possible slow surface deformation in the mountain. They showed that interferograms over Mt. Baekdu revealed a correlation between interferometric phases and topography that is related to the tropospheric effect and after removing the tropospheric effect, they obtained a displacement of about 3mm/yr of inflation from 1992 to 1998, indicating possible slow and upward moving deformation around the volcano.

Kwoun *et al.* (2005) showed another environmental application of InSAR to monitoring polar ice. Poplar ice mass balance is significant in predicting sea level and subsequent global climate change. Accordingly, Kwoun and his colleagues constructed an improved geocentric Digital Elevation Model (DEM) and estimated tidal dynamics and ice stream velocities over the West Antarctic Ice Shelf from ERS DInSAR (Differential InSAR). In particular, they used ICESAT laser altimetry profiles as ground control points for the DEM generation. By doing this, vertical accuracy of the DEM is estimated by comparing elevations with laser altimetry data from ICESAT. As a part of the their results, Kwoun *et al.* (2005) suggested the maximum and mean speeds of the ice shelf that can be used to study the mass balance and sea level change, and global climate change.

In the conventional remote sensing, change detection is the process of identifying differences in the state of an object or phenomenon by observing it at different times. In fact, the ability to measure and analyze these changes on the Earth's environment,which has been regarded as one of the major advantages of the modern remote sensing, can be further applied to monitor the geohazard with detectable surface deformation or movement. Lee (2005)utilized a spatial region growing segmentation and a classification using fuzzy membership vectors to detect the changes in the images observed at different times, i.e. before and after the hazard. He considered two co-registered images for the same target, one of which is supposed to have the class map at the observation time. With the simulated synthetic images, Lee (2005)'s method performed the unsupervised segmentation and the fuzzy classification for the other image, and then detected the changes in the scene by examining the changes in the fuzzy membership vectors of the segmented regions in the classification procedure. He showed the proposed method is effective for the change detection, and, hence, the hazard monitoring. In particular, this method is more effective when the images were acquired from the sensors with different characteristics such as range, number, and width of the spectral bands.

3) Detecting EM Disturbances due to Earthquakes and Volcanic Eruptions

The existence of electrical and magnetic disturbances associated with earthquakes has long been observed. Particularly over the last 15 years, several studies have been devoted to this subject. They tend to indicate that such phenomena may occur during and after earthquakes, but also several hours before. This could contribute to better forecasting of seismic motion, and help to improve disaster preparedness.

Efforts have been made to detect these EM disturbances from spaceborne sensors by France and Italy. Recent microsatellites, such as the French DEMETER (**D**etection of **E**lectro **M**agnetic **E**missions **T**ransmitted from **E**arthquake **R**egions) and Italian ESPERIA (**E**arthquake investigations by **S**atellite and **P**hysics of the **E**nvironment **R**elated to the **I**onosphere and **A**tmosphere) were designed specifically to investigate these disturbances at the satellite altitudes. DEMETER was launched last year, while ESPERIA is still being prepared for launch. The purpose of the satellites is to study disturbances in the upper atmosphere related to natural geophysical phenomena, such as earthquakes, volcanic eruptions, and tsunamis.

4) Detecting Geomagnetic Variation from Polar Geodynamic Activity

Sources of the geomagnetic field are located both within and external to the Earth. The internal sources are within the Earth's core and in the crust and upper mantle. The latter are referred to as the geomagnetic anomaly fields from lithosphere (Langel and Hinze, 1998). The geomagnetic field from the core is referred to as the main or core field that is represented by spherical harmonics. In addition to long-term variations of the main field, shorter-period geomagnetic field variations originate outside the Earth. Since the Earth itself is a conductor, these time-varying fields induce currents in the Earth that subsequently produce secondary fields. Here, the original and induced fields are considered together as the external field. There are two patterns of variations in the external field; diurnal and random, normally with abrupt initiation. Diurnal variations that are in the Earth's ionosphere are mainly because of differential plasma interactions and heating on the day and night side of the Earth, while the random variations can have manifold origins. Solar activity externally plays an important role, however, the abrupt massive agitation may also contribute to internal variations (Langel and Hinze, 1998).

Since satellite magnetic data are acquired above the ionospheric region, the satellite measures some portion of the ionospheric field as well as core and lithospheric fields. In fact, satellite magnetometer data have been used to model the long wavelength magnetic fields generated by variations of mantle's electric conductivity (Constable and Constable, 2004).

Therefore, it is a relevant conjecture that surface and subsequent internal geodynamic events may vary the attitude of the Earth's magnetic field on a global scale so that may possibly be detected at satellite altitude. In particular, if the mantle convection pattern has been affected by the shift of a rotation pole, the magnetic external fields coupled with the electric fields generated by the mantle's conductivity may also vary accordingly. This abrupt, short-term variation caused by a sudden geodynamic impulse from a global-scale geohazard may be detectable in the satellite magnetometer observations.

In an effort of separating static lithospheric components from the CHAMP mission data, Kim *et al.* (2005a) demonstrated the possibility of detecting minute changes in the induced portion of the ionospheric field due to geohazard resulting from massive mass redistribution. Kim *et al.* (2005a) pointed out, however, that it would be so difficult to detect the core field variations in addition to its secular variations due to the wobbling of the outer core. In order to overcome the difficulty, Kim *et al.* (2005a) implemented state-of-the-art data processing techniques to separate lithospheric components from the CHAMP data in Antarctica. By eliminating these components along with the core field from the satellite observations, new insight can be obtained on the time-varying external fields of the polar region where geodynamic variations greatly disturb external fields.

4. Conclusions

In this paper, we briefly described the National Research Lab Project entitled "Optimal Data Fusion of Geophysical and Geodetic Measurements for Geological Hazards Monitoring and Prediction" supported by the Korea Ministry of Science and Technology. The research has focused on the geohazard analysis with geophysical and geodetic instruments such as the superconducting gravimeter, seismometer, magnetometer, GPS, and InSAR. The aim of the NRL research to verify the causes of geological hazards through optimal fusion of various observational data at the surface through geodetic measurements, at the subsurface using geophysical measurements, and, finally fusing both geodetic and geophysical data.

The NRL hosted a special session "Geohazard Monitoring with Space and Geophysical Technology" during the International Symposium on Remote Sensing in October 2004 to discuss the current research topics, challenges and possible directions of geohazard monitoring. The special session papers were briefly synthesized in terms of their relationships within the context of the four sections. The fusion of state-of-the-art satellite and ground geophysical and geodetic data gives us important new insights on the monitoring and prediction of geological hazards.

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