SSC12-XII-1

Satellite contributions to disaster monitoring
- Japanese Earthquake and Tsunami Case in 2011 -

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ABSTRACT

In March 11, 2011, Japan was hit by a large earthquake followed by huge Tsunami. They gave tremendous damages to especially Tohoku-area with more than 18,000 lost and missing persons and more than 360,000 all or half destroyed houses. Furthermore, Fukushima Daiichi Nuclear Power Plant has been suffering from severe reactor problems caused by the electric power failure by tsunami, and still quite a large number of people cannot stay within their homes near the plants. Japan is now making every effort to restore the previous status of the people's living, economics and industry power. In this presentation, we first give the overview of the disaster. Then we focus on how satellite images, not only captured by small satellites but also by mid and large satellites, were utilized to monitor the disaster, reconstruction planning and operations. Many satellites took part in the data acquisition related to the disaster, which provided useful information on tsunami inundations and landslides, etc. To enhance satellite utilization, we finally discuss what kind on disaster monitoring system would be valuable in future, including low-cost small/micro satellite constellation and orbit maneuver.

INTRODUCTION

The Tohoku-Oki earthquake at 14:46 JST on March 11, 2011 shook the Tohoku area in the northern part of Honshu island of Japan with a momentum magnitude of 9.0. It was the most powerful earthquake ever to have hit Japan and exceeded the magnitude that was predicted by researchers previously. The surface near the epicenter, which was located at 70 km east of the Pacific coast of Tohoku, displaced c.a. 10–30 m horizontally and a few meters vertically. A tsunami with the height of tens of meters was generated and travelled up to 10 km in land. The GPS networks located with the distance of c.a. 20 km detected the shift of Honshu island, which was reported to be 5.3 m horizontally and 1.2 m vertically at maximum.[1] This large earthquake triggered aftershock earthquakes, not only in the Tohoku-Oki area but also inland. Figure 1 shows the epicenters of earthquakes from 3/11 14:00 - 3/12 15:00.

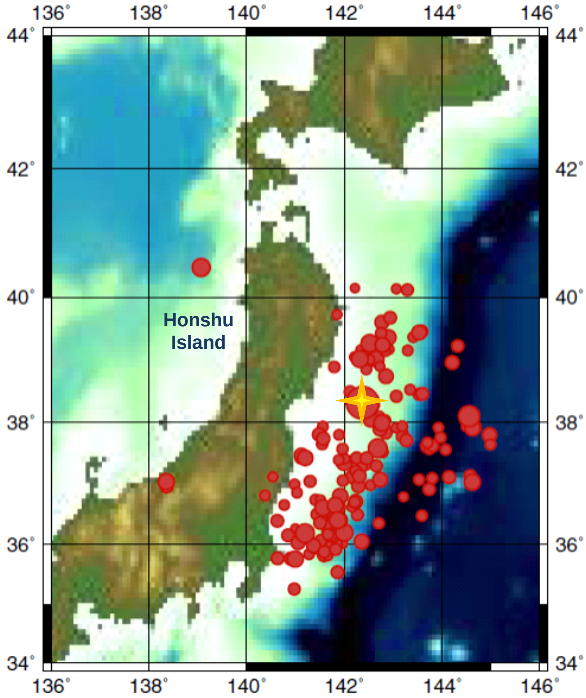

Figure 1: Northern part of Honshu and epicenters

Nuclear power plants in Tohoku area suffered from the electric power failure due to earthquake and tsunami. Among them, Fukushima Daiichi Nuclear Power Plant had severe reactor problems caused by the electric power failure, which made it difficult to cool the plants. Three nuclear reactors suffered explosions due to

Table 1: Earth Observation Satellite Used in First 5 Days after the Earthquake

Day	2011/3/11	2011/3/12	2011/3/13	2011/3/14	2011/3/15
Optical	EarthQuake	ALOS/AVNIR-2		ALOS/AVNIR-2	ALOS/AVNIR-2
Sensor	14:46:18	ALOS/PRISM			
		FORMOSAT-2	FORMOSAT-2	FORMOSAT-2	FORMOSAT-2
		RapidEye*2	RapidEye	RapidEye*2	
		LANDSAT-7	LANDSAT-5		
		IKONOS	GeoEye-1	GeoEye-1	IKONOS
		SPOT-5	SPOT-5	SPOT-5	SPOT-4
		WorldView-2	QuickBird	WorldView-1, 2	WorldView-1,2
		ASTER (TIR)		ASTER	
			EO-1		
		THEOS		HJ	
				KOMPSAT-2	
				CARTSAT-2	
				EROS-B	EROS-B
Synthetic			ALOS/PALSAR	ALOS/PALSAR	ALOS/PALSAR
Aperture		CosmoSkymed*4	CosmoSkymed*4	CosmoSkymed	CosmoSkymed*3
Radar		TerraSAR-X	TerraSAR-X	TerraSAR-X	TerraSAR-X
		RADARSAT-2	RADARSAT-2		RADARSAT-2

hydrogen gas that was generated in the reactor buildings. Radioactive iodine was detected in the wide area of east Japan. Residents within a 20 km radius of the plants were evacuated, and are still inhibited from returning to their homes near the power plants.

The disaster gave tremendous damages to especially Tohoku area with 15,857 lost and 3,057 missing persons (as of May 1, 2012). The numbers of all or half destroyed houses are 129,944 and 258,839, respectively (as of June 6, 2012). There are still 341,235 evacuated people as of May 10, 2012. Debris caused by the disaster amount to 22.5 million tons, one tenth of which is only disposed.[2]

Japan starts to restore the previous status and reconstruct the infrastructure robust to disasters. We, many engineers and researchers in space engineering fields got the feeling that we should again consider whether the space development and utilization can really contribute to the people's welfare in such disaster situation, and if yes, how.

In this work, we will first give the overview of the disaster. Then we will focus on how satellite images, not only captured by small satellites but also by mid and large satellites, were utilized to monitor the disaster, reconstruction planning and operations. We had lots of lessons learned as to what kind of information which might be acquired by satellites would be valuable at what stage, before and after earthquake and Tsunami, which we will discuss next. Finally we will discuss what kind on disaster monitoring system would be valuable in future, including low-cost small/micro satellite constellation, or satellite and aerial photo collaborations, and orbit maneuver, etc.

EARTH OBSERVATION ACTIVITY

International Charter

The International Charter that was established in 2000 aims at providing a unified system of space data acquisition and delivery to those affected by natural or man-made disasters through Authorized Users. Each member agency has committed resources to support the provisions of the Charter and thus is helping to mitigate the effects of disasters on human life and property.[3] 21 space organizations including national space agencies and private companies take part in the activity. As soon as the earthquake occurred, the Charter was activated. The activity ended on March 20.

Time Chart of Satellite Based Observation[3,4,5,6,7]

Table 1 summarizes the earth remote sensing satellites used in the first five days after the earthquake. There are two types of observation systems, one is an optical imager and the other is synthetic aperture radar (SAR). Since the earthquake occurred on 14:46 JST, the observation time for optical imager, normally around 10:00, was past. The observation time for SAR, normally sunrise or sunset for dawn-dusk orbit, was too close to send the uplink command. Therefore, the initial observation from low earth orbit started on March 12.

COnstellation of small Satellites for the Mediterranean basin Observation (COSMO-SkyMed) system, which is composed of four satellites with different orbit, observed the first SAR images from 8:30 to 9:30 using four satellites. COSMO-SkyMed constellation showed the multi-observation performance using ascending and descending orbit because the SAR system provides data in both day and night time.

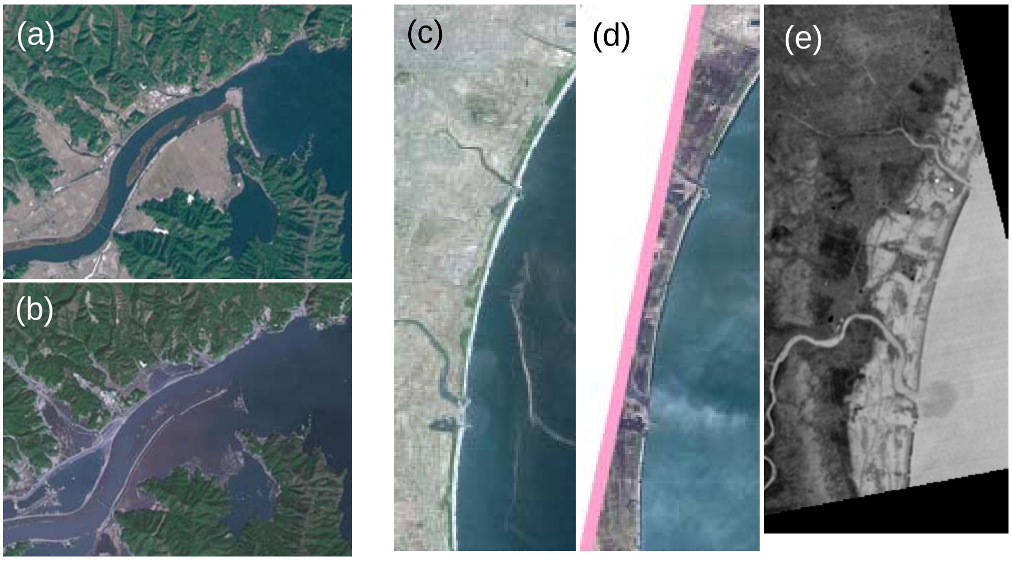

Figure 2: Satellite imagery obtained by ASTER. Original data is delivered by METI and NASA. VNIR images (a) before and (b) after (March 14) the tsunami at Ishinomaki. Natural color is applied for those who are not familiar with satellite data. VNIR images (c) before and (d) after (March 14) the tsunami at Sendai. TIR image (e) after (March 12) the tsunami, where the inundated area is seen as bright area on the land..

Next FORMOSAT-2, which takes a sun synchronous orbit with one revisit day, observed the Sendai area with a large pointing angle. Therefore, the observation time is about 9:15, earlier than the nadir observation time. FORMOSAT-2 continued the everyday observation of damaged area until the end of March.

Advanced Land Observing Satellite (ALOS) is the flagship satellite of Japan, which carries a multispectral (AVNIR-2), panchromatic stereo (PRISM) and SAR (PALSAR). On March 12, the AVNIR-2 and PRISM observed the inland area of Tohoku because there are lot of mountains where they were afraid of landslides and dam burst. On March 13, ALOS/PALSAR acquired L-band SAR images. Using the interferometric SAR technique, the displacement caused by the earthquake was revealed, which coincided well with the GPS measurement. ALOS continued the observation intensively and provided the deformation map all over the east Honshu island; however, its activity ended due to the electric power failure on April 22.

IKONOS and GeoEye-1 obtained very high resolution images of the damaged area. After the end of International Charter, they continued the data acquisition, especially for Fukushima Daiichi Nuclear Power Plant, and provided the 35 scenes till the end of April. Quickbird, WorldView-1 and -2 also provided very high resolution images. Using three satellites and pitch maneuver, time resolution of data acquisition was increased, which resulted in observing explosion of Fukushima Daiichi Nuclear Plants 1 minute before by WorldView-1 and 3 minutes after by WorldView-2. Satellite observation was effective for targets that were difficult to close in.

TerraSAR-X and RADARSAT-2 provided the SAR data, which was used to detect the inundated area by comparing the backscattering strength before and after the tsunami because backscattering is week for water surface. For TerraSAR-X, Both sides of antenna beam illumination were used to increase the observation frequency.

RapidEye, which is composed of five satellites, observed the targets with a high frequency. Until the end of April, the observed area reached to 435,000 km^2. SPOT-5 also obtained the optical images frequently. The wide swaths of these satellites were effective in viewing wide damaged area. Since Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on Terra could not send the command to the satellite, the data acquisition on March 12 was not carried out on the coastal line; however, the observation in the night time was successful using the thermal infrared sensor on the March 12. Figure 2 shows the example of processed data of visible and thermal infrared region. It was found that the thermal infrared image also provided information not only for fires but also for inundated area using the difference in the heat capacity of water and soil.[6] Landsat-7, which covers 180 km swath and takes 30 minutes before Terra/ASTER, observed the coastal area in a normal operation on March 12.

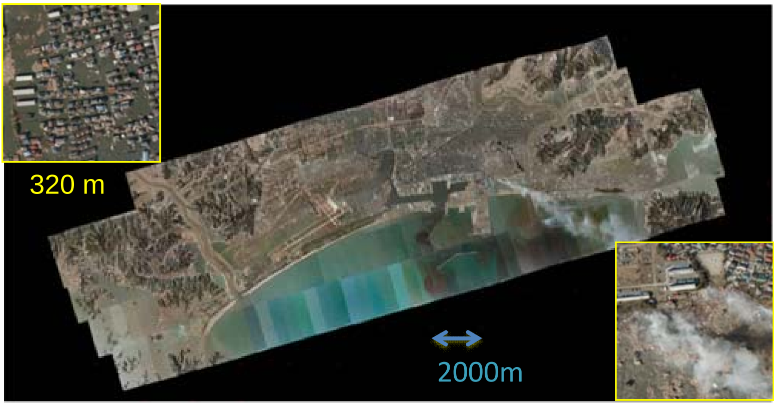

Figure 3: Aerial photo of Ishinomaki acquired on March 12. Original data is freely delivered by GSI

Aircraft Photo Activity

According to the agreement with Geospatial Information Authority of Japan (GSI) on emergency photo-flight for great disaster, aerial photos were taken immediately after the events by Japanese survey companies. Seven companies belong to this agreement because the effective data acquisition was not carried out during the Chuetsu Earthquakes on October 23, 2004 due to the overlapping and deficit of the observation area.

The aerial photo flights started on March 12, soon after the earthquake. Effective share of the observation was realized and the total coverage of the damaged coastal area was carried out in a week in spite of huge observation area of 4,018 km^2. 2053 pictures were obtained during 74 flights. Figure 3 shows the mosaic aerial photo at Ishinomaki on March 12.[1] Fine images compared with the spatial resolution of 80 cm were obtained, as shown in Fig.3. The upperleft picture shows inundated houses, whereas the lowerleft one shows the fires. The airplane of GSI, "Kunikaze", carried out the data acquisition from April 1 to 5 and covered 2,082 km^2 during 25 flights. Other data, such as oblique pictures and laser profiler, were also useful.

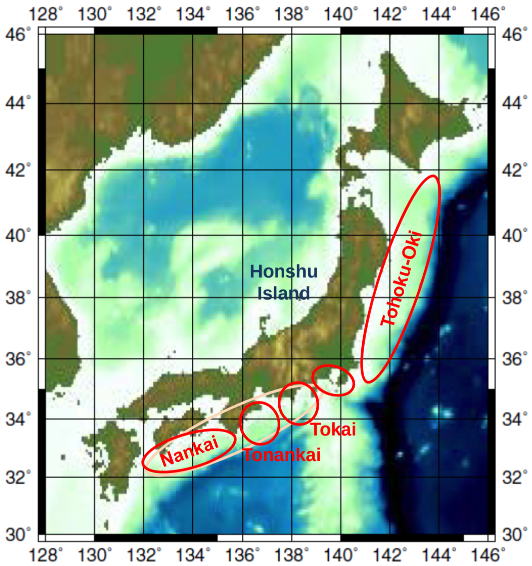

Figure 4: Predicted earthquake areas in Japan

ANALYSIS OF EARTH OBSERVATION

Many satellites took part in the observation and International Charter was very useful to cover wide area. This is because the coastal line of Tohoku area is almost along the descending orbit. SAR satellites obtained scenes through clouds during ascending and descending orbits. Using the backscattering properties, areas under water were detected by comparing with the previously acquired data. Authorized users were needed to make out other phenomena. Optical images, especially very high resolution data, were effective to detect buildings, bridges. Observation of nuclear power plants under problems was carried out using constellation system of optical sensors every day although clouds interrupted. To abstract information, many man powers were needed. Information provided by many sensors was not gathered to unified information but delivered to the disaster center; however, those who accustomed to satellite image were not so many. Although aerial photos covered relatively wide area in a week and provided reliable data, satellite data were useful before the aerial photo set was gathered or after monitoring to prepare the aftershock.

Figure 4 shows the predicted earthquake areas in Japan. Since the possibility that Tokai, Tonankai and Nankai earthquakes will occur simultaneously is pointed out, satellite system to observe large area extending in the crosstrack direction thoroughly is mandatory for future space systems and its cooperative share.

FUTURE VISION OF SMALL SATELLITES

Enhancement of Maneuverability

One reason why small satellites had not large contributions to the disaster monitoring of Tohoku-oki earthquake is that there were not so many small satellites which had earth observation capability at that time; if there are much more number of satellites operating in constellation manner, then we can observe and contribute a lot with quick or frequent observations. Therefore, when there were not so many small satellites on orbit, it would be very hard or unfair to say that small satellites were not so useful for disaster monitoring. However, we should think up some methods to show the usefulness of even a small number of small satellites for such a quick observation of areas under disaster.

Enhancement of maneuverability is one promising method to improve revisit or responsiveness features of satellites; when a disaster occurs, one of the satellites may change its orbit so that it can come over the disaster area with shorter latency or even it can come into a recurrent orbit with one or two days revisit interval. If such capability is implemented on each member of small satellite constellations, of course with limited ΔV ability, we will probably have different type of orbit optimization suitable for disaster monitoring, and we are able to show that even a small number of satellites can have large contributions to disaster monitoring. Therefore, in this section, we will discuss how the maneuverability can enhance the capability of quick observation for small satellites.

Firstly, we propose a way how a satellite can effectively change its orbit with small ΔV by using J_2 perturbation effect, and show its effect in simulations.

Assumption of Maneuverability

Here, it is assumed that the satellite is in a circular sun synchronous sub-recurrent orbit with altitude 639.4km, inclination i = 97.965 deg, LAN = 0 deg and recurrent period P_{rec} = 4 days. In addition, the nadir angle of the satellite is 5 degree, and it has no pointing function. Table 2 shows the assumptions of the locations of the Earth points to be observed.

Figure 5 shows that the satellite SSP track near location No.9. Recurrent orbit always follow the same track, and so it's impossible to observe the No.9 point without changing the orbit. The simplest way to come over No.9 location is to change right ascension of ascending node (RAAN), but changing RAAN by orbital plane change maneuver usually require very large ΔV, which is impossible for small satellites. In contrast, by using J_2 perturbation effect, we can change orbit with fewer ΔV, but of course at the cost of more time.

Table 2: Latitude and longitude of observation points

No.	latitude, deg	longitude, deg
1	34.42	132.75
2	45.26	12.2
3	34.01	-118.14
4	29.45	-95.24
5	41.49	12.19
6	6.42	80.25
7	-15.47	-47.53
8	0.3	-91.33
9	-43.33	172.39
10	-33.27	-70.4

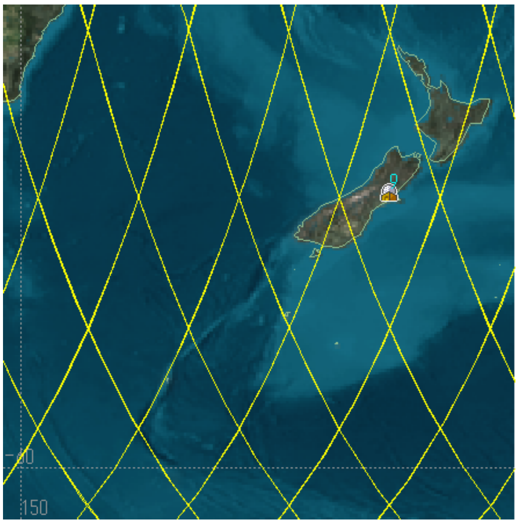

Figure 5: Ground track around point No.9

Such orbit change using J_2 perturbation can be made with the following steps:

1. Enter the transfer orbit whose semi-major axis and eccentricity are a little different from initial orbit.
2. The difference of J_2 effect between the two orbits changes RAAN little by little from the initial orbit.
3. When the difference of ascending node is equal to the target value, go back to the initial semi-major axis and eccentricity.

Let us calculate the required ΔV and time to change.[8] The first maneuver to change semi-major axis and eccentricity requires the following ΔV.

Table 4: Start time from Jun 1st to 4th

Case No.	day	start time
1	Jun 4	2:15:42
2	Jun 3	13:06:38
3	Jun 4	23:15:04
4	Jun 4	19:43:40
5	Jun 2	18:32:33
6	Jun 1	10:26:49
7	Jun 2	8:46:22
8	Jun 2	22:23:55
9	Jun 4	11:23:13
10	Jun 4	3:28:02

$$\Delta V = \sqrt{\frac{\mu}{r_1}}\left(\sqrt{\frac{2r_2}{r_1+r_2}}-1\right), \qquad (1)$$

where μ = Earth's gravity constant; r_2 = apogee radius; and r_1 = perigee radius.

When the ascending node is coming to the desired value after some waiting time, the satellite must use the same ΔV to go back to the initial semi-major axis. Therefore, the total ΔV is;

$$\Delta V_{TOTAL} = 2\Delta V \cdot \qquad (2)$$

Now let us calculate how much time is needed to change RAAN. Firstly, J_2 effect can be computed by the following equations.

$$\begin{aligned} \frac{\partial\Omega}{\partial t} &= -\frac{3}{2}J_2\left(\frac{R_e}{p}\right)^2 n\cos i \\ \frac{\partial\omega}{\partial t} &= \frac{3}{4}J_2\left(\frac{R_e}{p}\right)^2 n\left(5\cos^2 i-1\right) \\ \frac{\partial\sigma}{\partial t} &= \frac{3}{4}J_2\left(\frac{R_e}{p}\right)^2 n\eta\left(3\cos^2 i-1\right) \end{aligned} \qquad (3)$$

Here, $p = a(1-e^2)$; $n = \sqrt{\frac{\mu}{a^3}}$; $\eta = \sqrt{1-e^2}$; a = semi-major axis at epoch; e = eccentricity; and Re = Earth equatorial radius.

The ascending period T_{an} after consideration of these effects is;

$$T_{an} = \frac{2\pi}{n+\dot{\sigma}+\dot{\omega}} \qquad (4)$$

Table 3: Access Report from Jun 1st to 4th

No.	Number of access
1	2
2	None
3	1
4	None
5	None
6	None
7	None
8	1
9	None
10	None

We can calculate T_{antx} from J_2 effect in the transfer elliptic orbit in same way. The difference of ascending node between initial orbit and transfer orbit is;

$$\Delta\Omega = T_{antx}\left(\omega_e - \dot{\Omega}_{tx}\right) - T_{an1}\left(\omega_e - \dot{\Omega}_1\right), \qquad (5)$$

where ω_e = Earth's rotation rate; and Ω = right ascension of ascending node.

The number of rotations N_c for changing the ascending node until desired value can be calculated as;

$$N_c = \frac{\Delta\Omega_0}{\Delta\Omega} \cdot \qquad (6)$$

With maximum allowable ΔV, we can derive the minimum N_c, which decides the required time to change RAAN.

Using these formulae, now Monte Carlo simulation is performed to estimate the required time for RAAN change with limitation of ΔV to fly over the locations of points in Table 2. Other assumptions are;

(A) In one simulations, randomly 10 "start times" are set as the occurrence of disaster as in Table 3, and the required times to fly over the target locations are calculated.

(B) The maximum allowable Δ*V* is set at 20m/s, 40m/s and 80m/s.

Results of Satellite Simulation

In the initial orbit, seven locations cannot be observed by the satellite such as in Table 4 (No.2, 4, 5, 6, 7, 9, 10).

For these locations, the satellite performs the maneuver as described in the previous section and the average

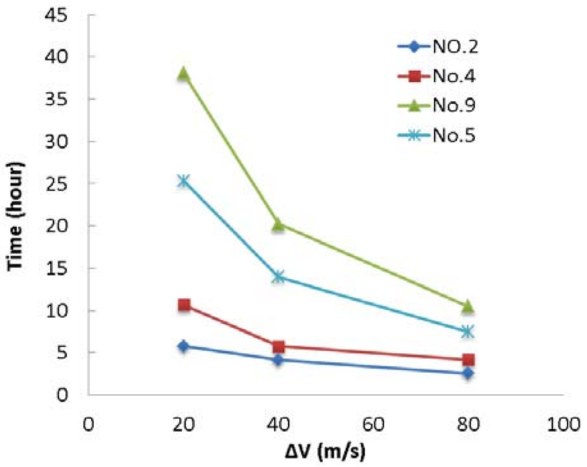

Figure 6: The elapsed time from start to the target orbit

(The required ΔΩ for No.2, 4, 5, 9 is

-0.36 deg, -0.66 deg, -1.54 deg and 2.28 deg)

time required to fly over the above locations are obtained. Figure 6 shows the results for four locations (No. 2, 4, 5, 9) in three cases of allowable ΔV.

Discussion on Satellite Simulation

By employing this way of orbit (RAAN) change, even one small satellite with small ΔV capability can have more possibility to cover the disaster areas within a certain time. For example, if ΔV=80m/s can be used, 2.28 deg RAAN difference can be covered within 1 day, which enhances the utility of even one satellite very much. If we use Hydrazine with Isp 220 sec, the ΔV =80 m/s requires 1.9kg fuel weight for 50kg satellite, which is within permissible range even for small satellite.

We are now developing software for optimizing constellation orbit design assuming that each satellite has a certain level of ΔV capability; the optimized orbits in terms of observation latency or revisit interval will probably be different from the case when no such ΔV capability is assumed for each satellite.

CONCLUSION

Remote sensing satellite activity started soon after the earthquake. Many satellite data were obtained along the coastal lines along descending orbit path, some of which were available to the public free of charge through internet. Data archives that were obtained before the earthquake were mandatory to find the damaged area due to the earthquake and tsunami. Data analysis was carried out by companies, universities and research institute in order to assist relief teams and rapid damage assessment. The results were public through internet, which gave information on the inundated area due to tsunami, offshore debris and surface displacement. Failure in the nuclear power plants was observed frequently using very high resolution imager. There remains a task to unify and deliver information obtained from earth observation. Considering future earthquakes and other disasters, satellite systems to enable frequent observation by using maneuver makes a way for small satellite community to be more useful to such phenomena. Coupling various satellites, robust infrastructure is realized.

ACKNOWLEDGMENTS

The application to small satellites is investigated under the support of the Cabinet Office, Government of Japan for funding under the "FIRST" (Funding Program for World-Leading Innovative R&D on Science and Technology) program. We would like to thank those who contributed the disaster in the Tohoku-Oki earthquake.

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