Processing of FORMOSAT-2 imagery for site surveillance

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Abstract: The successful launch of FORMOSAT-2 on 21 May 2004 has proved the concept that the temporal resolution of a remote sensing system can be much improved by deploying the high-spatial-resolution sensor in a daily revisit orbit. The sun-synchronous and geo-synchronous orbit makes FORMOSAT-2 an ideal satellite for site surveillance. The unique orbit and the arrangement of the CCD lines on-boarded FORMOSAT-2, however, has also raised new challenges in image processing. This paper describes the procedures that are employed by the Disaster Prevention Research Center at National Cheng-Kung University to process FORMOSAT-2 imagery. The major focus is to develop a fast and automatic approach to process a large amount of FORMOSAT-2 images for the purpose of site surveillance, including level-2 product generation, pan-sharpening and quasi-orthorectification. One example of sequential three-day images of Hsin-Chu taken by FORMOSAT-2 with results of automatic change detection is given and discussed. Experience obtained from this work would benefit the system design and image processing of the future satellite missions with similar specifications, such as the Pléiades HR scheduled to be launched in 2008.
Keywords: FORMOSAT-2, daily revisit, site surveillance, coregistration, pan-sharpen, georeferencing, Pléiades HR

1. Introduction

Remote sensing is the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation [1]. The performance of a remote sensing system is determined by its spatial, temporal, spectral and radiometric resolutions [2]. Up until now, most of the efforts in the development of remote sensing system are focused on increasing spatial resolution. Another trend is to enhance the spectral resolution by deploying the hyper-spectral sensor in the orbit, such as the space-borne Hyperion sensor onboarded the EO-1 satellite launched in November 2000. These existing observation systems, while capable of increasing spatial or spectral resolution, are all limited in temporal resolution. From the consideration of site surveillance, however, the temporal resolution is even a critical characteristic that might override other desirable qualities. An ideal remote sensing system for site surveillance should enable us to monitor dynamic phenomena, especially the on/off events, at the highest temporal frequency and the similar viewing condition. The inconsistency in geometric shape of the same object among various images can be avoided by keeping the same viewing angles. Therefore, such an arrangement will be of benefit to the automatic processing of the time series observations. It is expectable that the subtle changes occurred in a local area can be automatically identified from the entire area of observation with comparative higher accuracy. Such an ideal system of site surveillance, however, has never been available until the successful launch of FORMOSAT-2 on 21 May 2004.

FORMOSAT-2 is not only the first Taiwan-owned satellite, but also the first remote sensing system that circulates the earth on a daily revisit orbit. The remote sensing instrument (RSI) on-boarded FORMOSAT-2 is built by EADS Astrium SAS, France, which makes the FORMOSAT-2 imagery available for 2m resolution in panchromatic (pan) and 8m in four multispectral (ms) bands from visible to near-infrared with scene coverage of 24km x 24km. Together with its equipped high torque reaction wheels for all axes, FORMOSAT-2 is able to point to $\pm 45^0$ along track and $\pm 45^0$ across track. The high agility of the platform and the high temporal resolution of the sensor, as well as the innovative orbit and operational concepts, have been followed by the Pléiades HR, the next French earth observation system scheduled to be launched in 2008 [3]. The Pléiades HR is basically a constellation of two satellites that are very similar to FORMOSAT-2, except for an improved spatial resolution of 70cm.

Based on the cooperative agreement between the Disaster Prevention Research Centre (DPRC) of National Cheng Kung University and the National Space Organization (NSPO) of Taiwan, DPRC serves as an official image application and distribution centre (IADC) that receives, processes and archives FORMOSAT-2 imagery on a daily basis. After more than a year of operation, DPRC has successfully applied FORMOSAT-2 imagery to disaster preparedness, rescue and environment monitoring, such as the event of the South Asia tsunami [4]. It has also been aware that the unique orbit and the arrangement of the CCD lines on-boarded FORMOSAT-2 raises new challenges in image processing. This work attempts to develop a fast and automatic approach to process the daily FORMOSAT-2 images for the purpose of site surveillance, including inter-band coregistration, pan-sharpening and georeferencing. Several examples with results of automatic change detection are given and discussed. Experience obtained from this work would benefit the system design and image processing of the future satellite missions with similar specifications, such as the Pléiades HR scheduled to be launched in 2008.

2. FORMOSAT-2

In a broad sense, the daily revisit orbit of FORMOSAT-2 is a special case of the exactly repeating plus the sun-synchronous orbit with a period of one day. Rees [5] provides a detailed derivation of a simple condition that must be fulfilled by this type of orbit:

$$\frac{P_n}{P'_E} = \frac{n_1}{n_2}, \qquad (1)$$

where P_n is the nodal period, P'_E is one solar day of 24 hours, n_1 determines the time interval between successive opportunities to observe a given location, and n_2 governs the density of the sub-satellite tracks on the Earth's surface. In the case of FORMOSAT-2, to achieve the daily revisit orbit (n_1=1) under the given condition of fourteen sub-satellite tracks (n_2=14), P_n needs to be set at a value of 102.86 minutes. This is attained by placing FORMOSAT-2 at an altitude of 891km with the inclination of 98.99^0.

The exactly repeating orbit is not a brand new idea, but FORMOSAT-2 is indeed the first satellite with a high-spatial-resolution sensor placed in a daily revisit orbit. FORMOSAT-2 is able to capture any scene in its coverage area each day. In the mean time, each accessible scene can be systematically observed from the same angle under the same lighting conditions. Fig. 1 shows the accessible areas and the ground track of FORMOSAT-2 orbits with $\pm 45^0$ viewing angle across track (side looking).

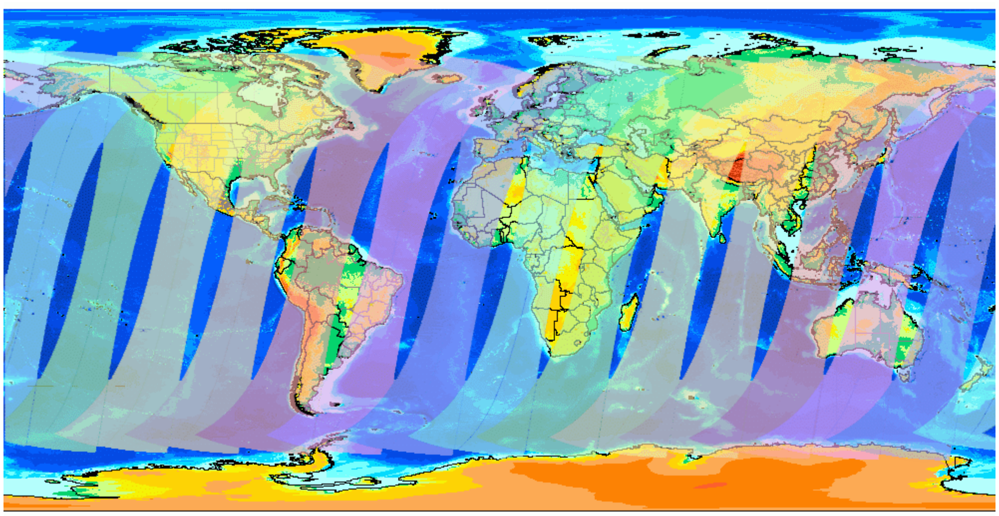

Fig. 1. The accessible areas and the ground track of FORMOSAT-2 orbits with $\pm 45^0$ viewing angle across track (side looking).

As denoted outside the shaded area in Fig. 1, FORMOSAT-2 has to make a slight sacrifice of the coverage area in low latitudes to achieve the daily revisit orbit. These gaps can be filled by placing a duplicate of FORMOSAT-2 in the identical orbit but overpassing the center of each gap. This is exactly what the Pléiades HR proposes to attain by deploying a constellation of two satellites. Although the accessible area of current FORMOSAT-2 orbit is limited in low latitude, this limitation can be removed by manipulating FORMOSAT-2 at a large viewing angle across track. In the event of recent South Asia tsunami, for example, NSPO made an attempt to increase the viewing angle to as high as $\pm 53^0$ and demonstrated that all areas can be imaged with a slight sacrifice in spatial resolution [4].

Even though FORMOSAT-2 can repeat the same orbit everyday, not all accessible areas denoted in the shaded region in Fig. 1 actually enjoy the continuous acquisition of images. The first year's experience of archiving and processing FORMOSAT-2 imagery at DPRC shows that achieving the largest coverage area is still the major consideration of FORMOSAT-2 operation. The mapping grid of FORMOSAT-2 in Taiwan Island is illustrated in Fig. 2. Even if FORMOSAT-2 is completely devoted to acquire the image of Taiwan Island at its first orbit, the temporal resolution still reduces to at least seven days. The actual temporal resolution for each grid is denoted in Fig. 2(a). If those images with cloud cover higher than 30% are not taken into account, the actual temporal resolution would be even lower (Fig. 2b). It is therefore necessary to investigate the applications of FORMOSAT-2 imagery that can fully utilize the advantages of daily revisit orbit, and reevaluate the current consideration of FORMOSAT-2 operation.

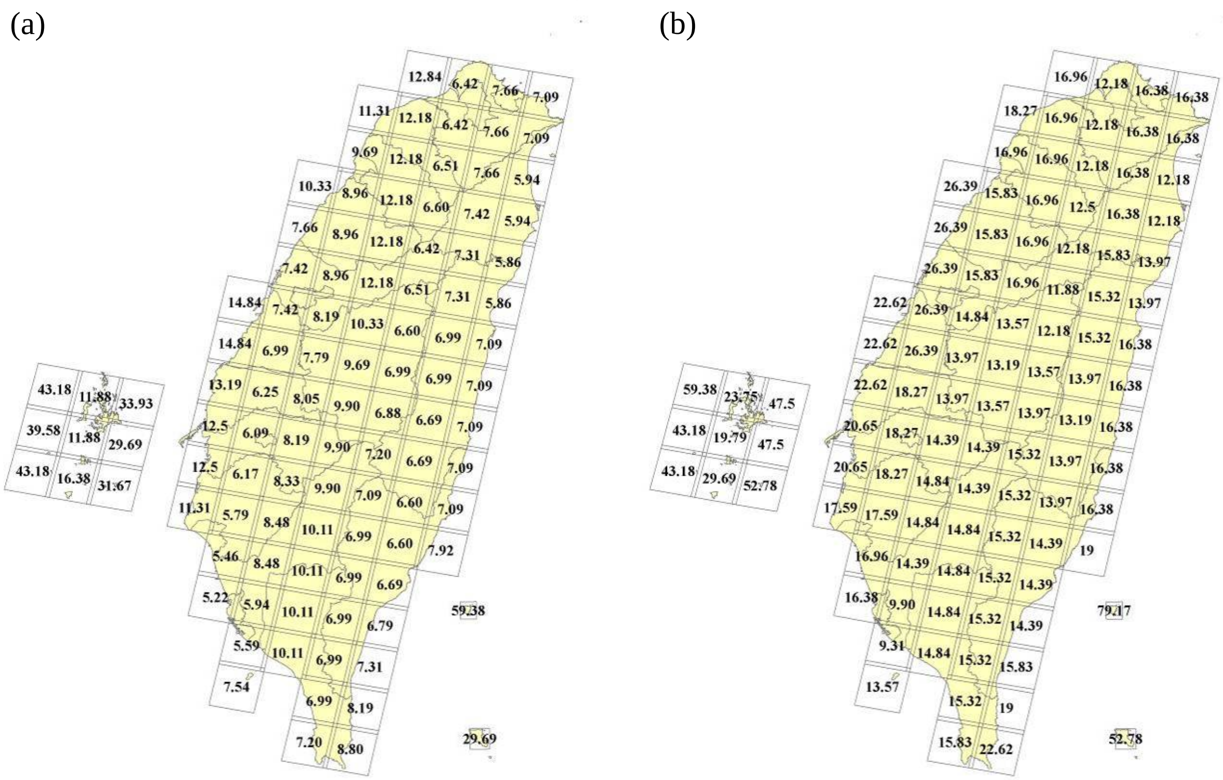

Fig. 2. The mapping grid of FORMOSAT-2 in Taiwan area. The digital numbers denote the temporal resolution for each grid based on the first year's archive of FORMOSAT-2 imagery, where (a) all available images are included, and (b) only those images with cloud cover less than 30% are included.

3. Image processing

Satellite images can be processed with various levels of complexity at different costs of time, depending on the information required for a specific application [4]. The major focus of this work is to develop a fast and automatic approach to process a large amount of FORMOSAT-2 images for applications on site surveillance. The procedures described below have been implemented by DPRC to monitor the dynamic phenomena in Taiwan area.

1) Level-2 product generation

To assist the IADC to process the substantial amount of FORMOSAT-2 imagery on a daily basis, NSPO and Tatung System Technologies Inc. developed an image processing system, namely FORMOSAT-2 terminal, which includes the data management subsystem, the data processing subsystem, and the planning and scheduling subsystem [6] [7]. The raw data of FORMOSAT-2 image received by the NSPO ground station is transmitted to the FORMOSAT-2 terminal at DPRC via Taiwan's Advanced Research and Education Network (TWAREN) every morning. Although the average size of FORMOSAT-2 data in Taiwan area is as large as 5 GB everyday, the reserved 10GB bandwidth of TWAREN allows all data to be transmitted in less than ten minutes. Without installing an expensive antenna, the FORMOSAT-2 terminal and TWAREN together make DPRC nearly the same capacity as the NSPO ground station.

Once all raw data are transmitted the FORMOSAT-2 terminal, they can be further processed to the level-1A product by applying the basic radiometric calibration. This product is geometrically distorted and lacks any georeference information, therefore, cannot be used to assess the disaster area. The level-1A product usually serves as the base for more rigorous processing to derive other higher level products. The FORMOSAT-2 terminal is also able to generate the level-2 product by projecting the raw image onto a spheroid using the ephemeris data on-board to correct the satellite orbit and altitude. The geometrics of ground features are retained well and it takes merely twelve minutes to process one standard scene of FORMOSAT-2 imagery (24x24 km). The on-ground and in-orbit calibration results concluded that the standard deviation of geometric accuracy for the FORMOSAT-2 level-2 product is around 150 meters [8]. Note that the generation of both level-1A and level-2 product is completely automatic. The FORMOSAT-2 terminal is therefore ideal for processing a large amount of images for applications of the site surveillance.

2) Pan-sharpening

For applications of the site surveillance, the pan-sharpening techniques that integrate a lower spatial resolution ms image with a higher spatial resolution pan image is preferred because both the spectral and spatial information can be retained and represented in one single image. The prerequisite to generate a pan-sharpened is an accurate pan-to-ms and band-to-band coregistration. This prerequisite, however, has been a major problem of image processing ever since the launch of FORMOSAT-2. Liu *et al.* [4] discussed this problem in depth and proposed a practical solution for this problem. The reason of pan-to-ms and band-to-band misregistrations can be briefed as follows.

The remote sensing instrument on-boarded FORMOSAT-2 is equipped with a monolithic linear CCD array with 12,000 pixels for pan band and a quad-linear CCD arrays with 3,000 pixels for each of the ms bands. The individual ms CCD lines are shifted against the pan CCD-line combination in the sampling direction in the focal plane. Such an arrangement makes the pan CCD line and each of the ms CCD lines scan the ground sequentially with a slight time lag rather than simultaneously. As a result, the effects of pan-to-ms misregistration and band-to-band misregistration are significant and visually obvious in the FORMOSAT-2 image. Taking the Earth's rotation and orbital instability into account, these effects are even more serious when the satellite is operating in large angle ranges in the along and/or across track directions.

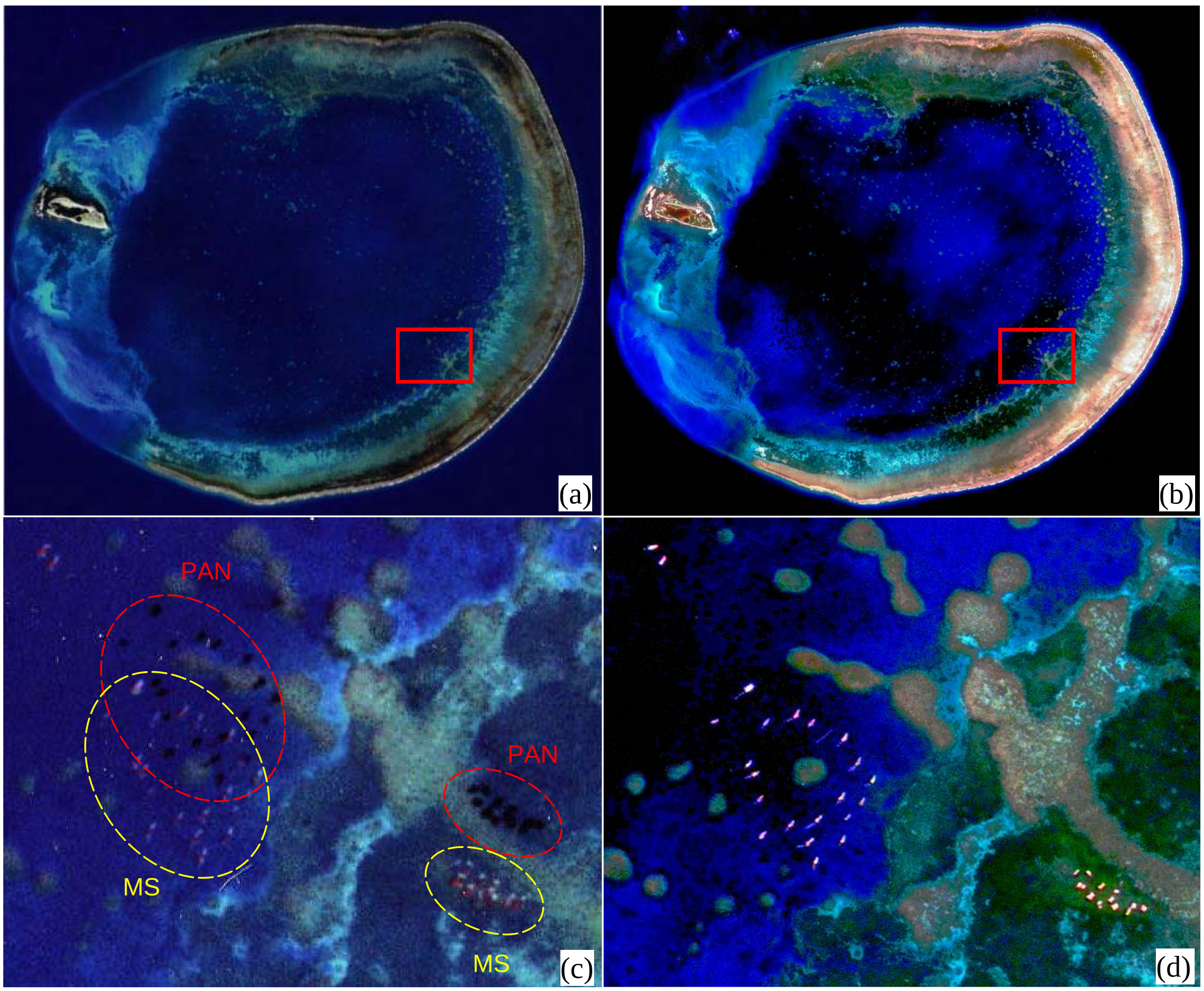

Fig. 3. A pair of (a) misregistered and (b) coregistered FORMOSAT-2 imagery of Dong-Sha Islands, where the region denoted in red box is enlarged in (c) and (d), respectively for illustration. The Dong-Sha Islands consist of Dong-Sha island (the only terrestrial portion of the islands), Dong-Sha Atoll (the only atoll in Taiwan), the North Vereker Bank and the South Vereker Bank (two coral reef groups). The effects of pan-to-ms misregistration are significant and visually obvious in the east part of the atoll if only the Dong-Sha island in the west part of the atoll is manually coregistered.

Considering the fact that the miscoregistration is caused by the time lag of various CCD lines and the same scene is taken under the same illumination conditions, the technique of Fast Normalized Cross Correlation (FNCC) is proposed to coregister the level-2 product of FORMOSAT-2 image [9]. Crippen [10] developed a new technique, imageodesy, to measure the sub-resolution terrain displacements near the fault after an earthquake, based on the normalized cross correlation (NCC) between a pair of cross-event SPOT images. The NCC is defined as

$$R(u,v) = \frac{\sum_{x,y}[f(x,y) - \bar{f}_{u,v}][t(x-u,y-v) - \bar{t}]}{\sqrt{\sum_{x,y}[f(x,y) - \bar{f}_{u,v}]^2 \sum_{x,y}[t(x-u,y-v) - \bar{t}]^2}}, \tag{2}$$

Where $\bar{t}$ is the mean of the feature and $f_{u,v}$ is the mean of $f(x,y)$ in the region under the feature. This new technique is widely used to calculate the co-seismic displacement, such as in the work of van Puymbroeck et al. [11]. To further speed up the processing, Liu and Ma [12] developed a fast NCC (FNCC) algorithm based on the work of Lewis [13] to calculate the co-seismic displacement of the earthquake of magnitude 8.1 on the Richter scale that occurred on November 14th 2001 along eastern Kunlun Mountains. The FNCC technique is not only fast enough to process a large amount of images using a personal computer, but also accurate enough to detect the sub-pixel level of shift between a pair of cross-event images. Therefore, it is ideal for the task of automatic co-registration [9].

A pair of misregistered and coregistered FORMOSAT-2 imagery of Dong-Sha Islands is given in Fig. 3(a) and 3(b), respectively for illustration. The Dong-Sha Islands consist of Dong-Sha island (the only terrestrial portion of the islands), Dong-Sha Atoll (the only atoll in Taiwan), the North Vereker Bank and the South Vereker Bank (two coral reef groups). The area of the atoll is more than 300 km^2 with an average depth of 10 m. Although the entire region of Dong-Sha Islands falls within one swath of FORMOSAT-2 (24 km), the effects of pan-to-ms misregistration would be significant and visually obvious in the east part of the atoll (Fig. 3c) if only the Dong-Sha island in the west part of the atoll is manually coregistered. It has been aware that the pan-to-ms misregistration is not homogeneous [4]. Fig. 3(b) and 3(d) shows the results of the coregistration using the FNCC technique. The improvement is significant when both the band-to-band and pan-to-ms coregistrations are accomplished.

Another important consideration of pan-sharpening is to preserve the spectral information. The general approaches of pan-sharpening, such as the HSI transform [14] and Brovey transform [15], are widely used and implemented in several commercial software. These approaches, however, cannot avoid distorting the image's spectral properties. To improve the spatial details yet preserve the spectral properties, it is necessary to develop a new approach that is able to produce color composites with sharper spatial details with high spectral fidelity. Thanks to the specific spectral ranges of the FORMOSAT-2 pan and ms, the summation of the ms bands is a low resolution replica of the high resolution pan band image, except for a small gap between ms band 3 and 4. Based on the principle of published SFIM technique [16], Liu *et al.* [4] proposed a new technique, namely Spectral Summation Intensity Modulation (SSIM), to improve the spatial details yet preserve the spectral properties.

To illustrate the differences of the image's spectral properties resulted from various sensors and various pan-sharpening techniques, the images of Song-He Community taken by SPOT-5, FORMOSAT-2 and unmanned helicopter are compared in Fig 4. Due to the geological composition and the topography, the Song-He Community is always under threat of landslide and debris flow during the raining season. Fig. 4(a) was taken in 2004 by SPOT-5 with a spatial resolution of 2.5 m. This is achieved by staggering its dual HRS sensors. Since the HRS sensor does not have a blue band, the color image presented in Fig. 4(a) is actually a "simulated natural color" rather than a "true natural color". Note that all color information of the buildings is lost in the image. After the hit of Typhoon Mindulle on 2 July 2005, a devastating debris flow ravaged the Song-He Community and caused severe damages of properties and lost of lives. FORMOSAT-2 took the image of Song-He Community right after the disaster. The HSI and SSIM techniques were employed to generate the pan-sharpened images, and the results are shown in Fig. 4(b) and 4(c), respectively. Fig. 4(d) shows the image of the same area taken from the unmanned helicopter flying at low altitude. Visually comparing these images demonstrates that FORMOSAT-2 indeed provides a more realistic colorful image. In addition, the SSIM pan-sharpened image (Fig. 4c) possesses a higher fidelity to original spectral properties in comparison with HSI pan-sharpened image (Fig. 4b).

The applications of site surveillance prefer to use the pan-sharpened images because both the spectral and spatial information can be retained and represented in one single image. Although the arrangement of the CCD lines on-boarded FORMOSAT-2 has raised a new problem of misregistration. The FNCC based imageodesy technique is successfully applied to coregister the level-2 product of FORMOSAT-2 image at high accuracy and speed. Together with the SSIM technique, the pan-sharpened image can be generated to meet the requirements of FORMOSAT-2 for site surveillance.

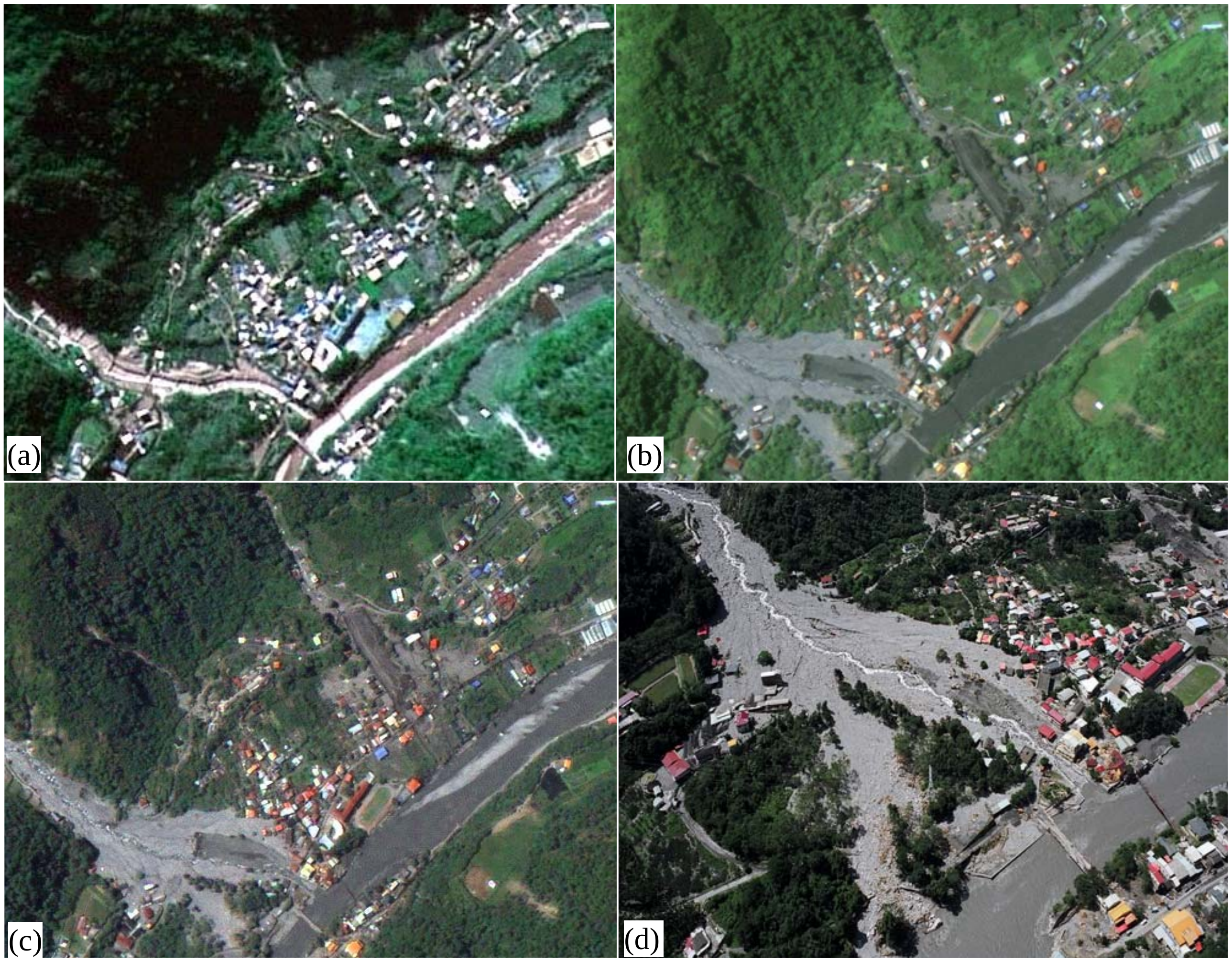

Fig. 4. Images of Song-He Community. (a) Simulated true color image with 2.5 m resolution taken by SPOT-5 in 2004. (b) HSI pan-sharpened image with 2 m resolution taken by FORMOSAT-2 in July, 2005. (c) SSIM pan-sharpened image with 2 m resolution taken by FORMOSAT-2 in July, 2005. (d) The high-spatial-resolution image taken by the unmanned helicopter flying at low altitude.

3) Quasi-orthorectification

With certain amount of ground controlled points (GCPs) and digital topography model (DTM) of the imaging area, a rigorous orthorectification can be made to generate the orthoimages from remote sensing. For most of the regions in the world, however, the information of GCPs and DTM are usually restricted or not available. Even in Taiwan area, the spatial resolution of DTM available is 40 m, which is not compatible to the high-spatial-resolution of FORMOSAT-2 imagery. In addition, the number and accuracy of existing GCPs are not sufficient for the requirement of rigorous orthorectification. Most of all, the rigorous processing of orthorectification is time-consuming. It would not be a practical approach for continuously monitoring a small site. For applications of the site surveillance, it is therefore necessary to seek an alternative approach for georeferencing the images.

Because the geometrics of ground feature are retained well in level-2 images and the generation of level-2 images from the FORMOSAT-2 terminal is completely automatic, this motivates us to use level-2 image to conduct the image-to-image or image-to-orthoimage registration. This approach is called quasi-orthorectification if an orthoimage is used as the base image. The accuracy of quasi-orthorectification for a small area with slow variation in topography would be sufficient, even though the detailed change of topography is not taken into account. This approach can be implemented automatically using the technique of FNCC. Therefore, it would be ideal for processing a time series of level-2 image for monitoring the dynamic phenomena in a small site. One example of the quasi-orthorectification will be given later in Fig. 5 to represent the cases of which the orthoimage in the study area is available.

4) Change Detection

As aforementioned, an ideal remote sensing system for site surveillance should enable us to monitor dynamic phenomena, especially the on/off events, at the highest temporal frequency and the similar viewing condition. The most straightforward approach is to compare the continuous observations and find out the subtle changes. This belongs to the category of change detection. A variety of change detection techniques have been summarized and reviewed by Lu *et al.* [17] recently. After comparing the main characteristics, advantages and disadvantages, and key factors affecting change detection results of a total of 31 methods, they recommended the single-band image differencing method for digital change detection of change/non-change information. They also concluded that one of the prerequisites of change detection is precise geometrical registration between multi-temporal images. The impact of misregistration on change detection has been emphasized in numerous studies as well [18] [19]. Townshend et al. [18] quantitatively evaluated the error caused by misregistration and concluded that the coregistration should be within one pixel for most of the purposes of change detection. After all of the procedures of processing described earlier have been applied, a set of coregistered and georeferenced images with both the high spectral fidelity at the high spatial resolution should be ready for the analysis of change detection. Although the sub-pixel level of misregistration still might cause some boundaries of land covers to be misinterpreted as changes, these false alarms can be easily filtered out. Only those change/non-change and on/off events would be left for further examination.

3. Results and discussions

As aforementioned, although FORMOSAT-2 is able to repeat the same orbit everyday, not many occasions or places actually enjoy the continuous acquisition of images. The first year's experience of archiving and processing FORMOSAT-2 imagery at DPRC shows that achieving the largest coverage area is still the major consideration of FORMOSAT-2 operation (Fig. 2). Here one case of sequential three-day images is presented and discussed as follows:

The set of FORMOSAT-2 sequential three-day images was taken near Hsin-Chu on July 2-4, 2005. The orthoimage in that area is available, therefore, the SSIM pan-sharpened and quasi-orthorectified images can be generated automatically following the procedures described in section 2 (Fig. 5). The accuracy of georeferencing can be examined by overlaying the digital map of road network onto the quasi-orthorectified image. Even though the detailed change of topography is not taken into account, the georeferencing information provided by the quasi-orthorectified image is accurate enough for locating the target area. For the consideration of site surveillance, what important most is the precise geometrical registration between multi-temporal images. Because all of these images were acquired under the same viewing conditions, the geometrical registration is indeed quite accurate. Consequently, this set of quasi-orthorectified images is very suitable for the analysis of change detection.

Fig 5(d) is the color composite of red (pan band of July 2), green (pan band of July 3) and blue (pan band of July 4). This is a common approach to highlight the changes among the images acquired at three different times. Generally speaking, the precise geometrical registration between multi-temporal images makes the color composite a monotone of grey level, except for those areas contaminated by clouds, hazes or shadows. Those areas can be easily recognized by the monotone of one prime color in comparatively large area. Even in those areas, the change/non-change and on/off events send clear alarms via three prime or complementary colors. The region denoted by red box in Fig. 5(d) is enlarged in Fig. 6(d) to illustrate the dynamic change of a fish port at the daily scale. No matter the arrival/departure of ships in the port or even the disappearance of vehicles in the parking lot or on the highway, all of these on/off events can be automatically identified from this set of FORMOSAT-2 sequential images. Thanks to the high quality of SSIM pan-sharpened and quasi-orthorectified images, the color composite of three pan images (Fig. 6d) gives the information of where and when the change is occurred. This information can guide us to locate the change in the corresponding SSIM pan-sharpened image, compare the spectral information of that object/phenomenon to the spectral library, and eventually identify what the change is.

For some phenomena that do not exhibit a significant change in only one day or two, such as the growth of vegetation, the level of changes would be lower than the threshold. Such a subtle change, therefore, cannot be identified clearly. Although the spatial resolution of FORMOSAT-2 is not as good as Quickbird or IKONOS, the larger swath as well as the unique capability of site surveillance makes FORMOSAT-2 an important complement to the existing imaging satellites. The example shown in Fig. 5 and Fig. 6 demonstrated the advantages of the daily revisit orbit and the approach of processing FORMOSAT-2 imagery for site surveillance.

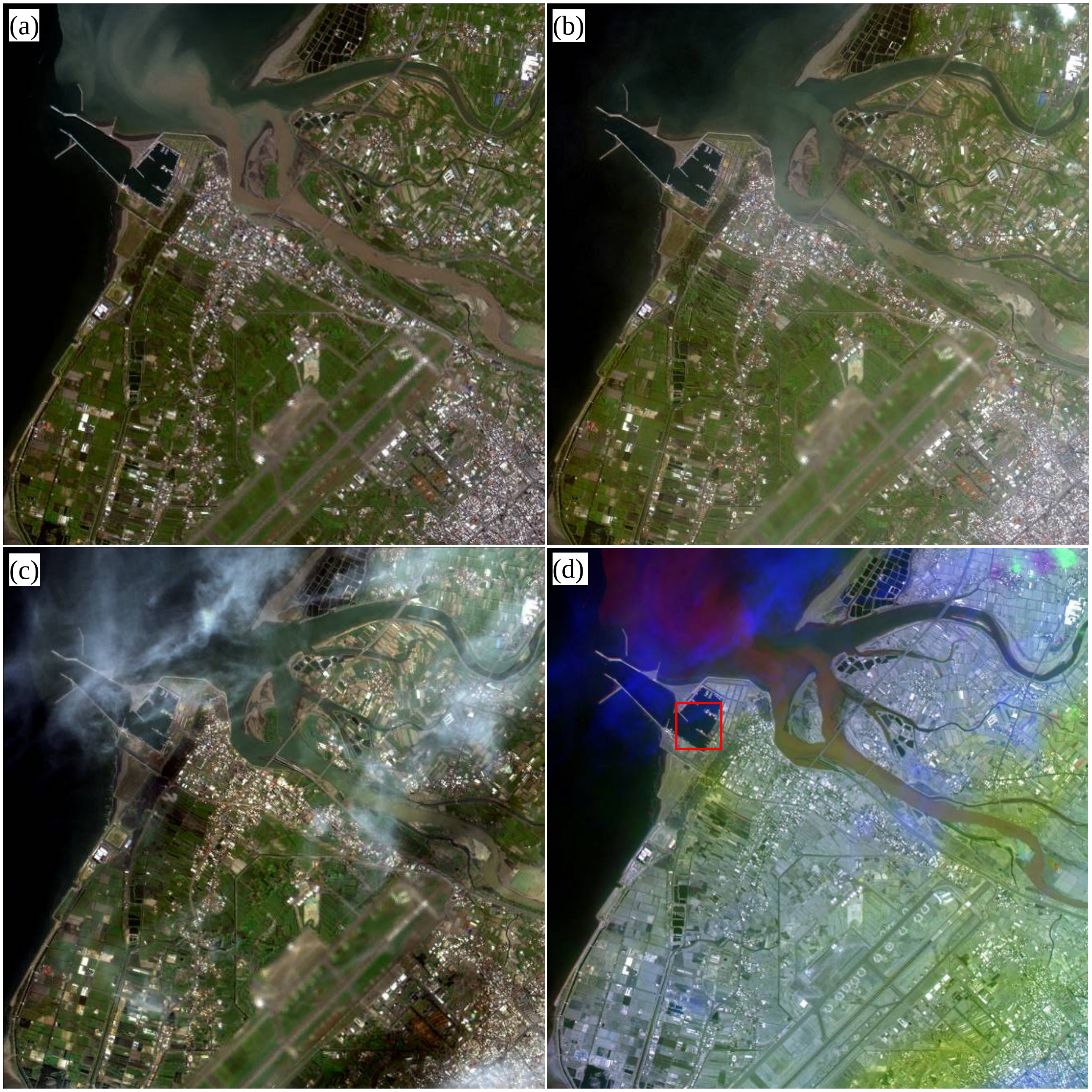

Fig. 5. The SSIM pan-sharpened and quasi-orthorectified images generated from the sequential three-day images of Hsin-Chu taken by FORMOSAT-2 on (a) July 2, (b) July 3, and (c) July 4, 2005. (d) is the color composite of red (pan band of July 2), green (pan band of July 3) and blue (pan band of July 4).

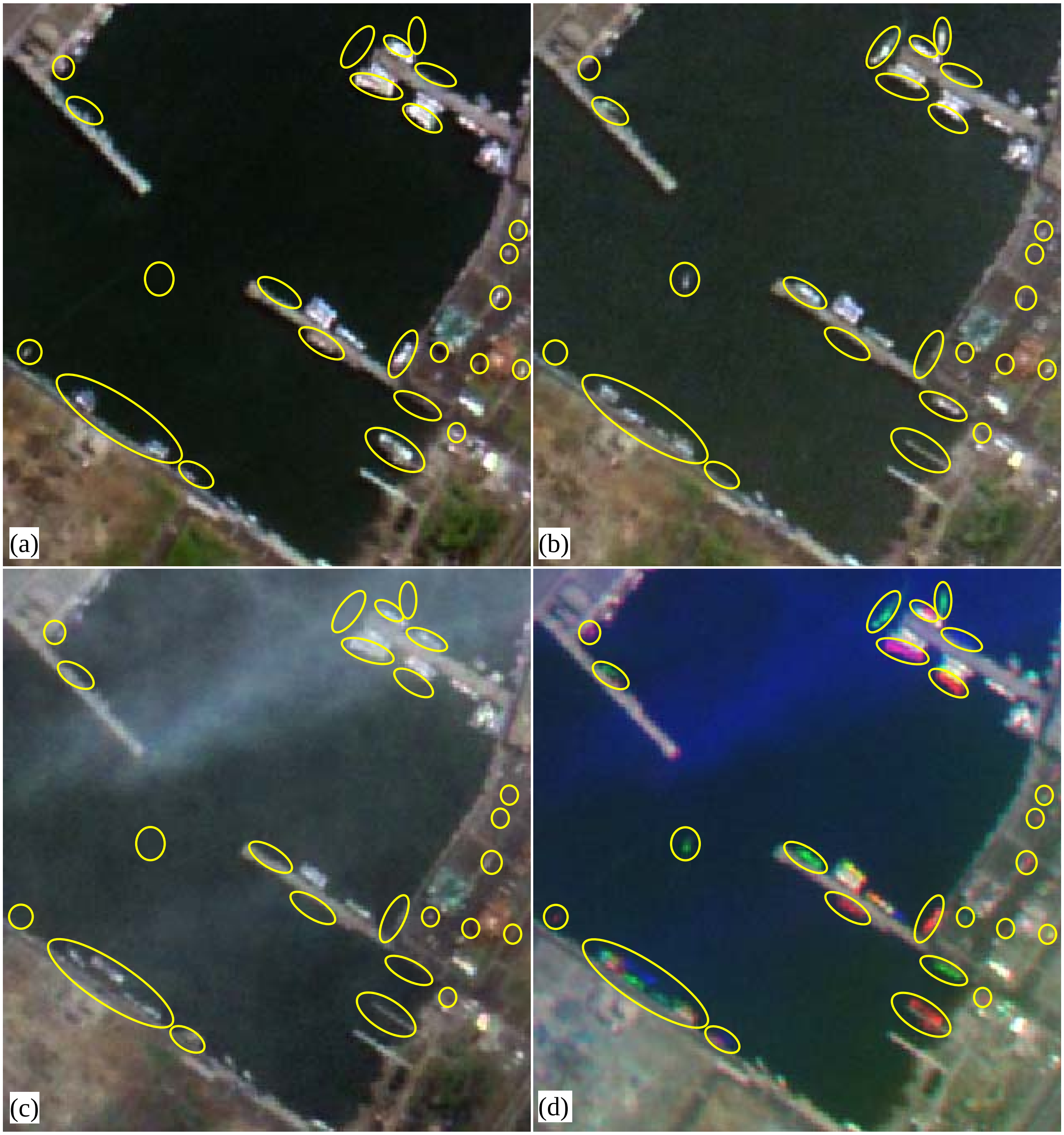

Fig. 6. Illustration of the dynamic change of a fish port at the daily scale. This figure is enlarged from the same region denoted by red box in Fig. 5(d). The SSIM pan-sharpened and quasi-orthorectified images generated from the sequential three-day images of Hsin-Chu taken by FORMOSAT-2 on (a) July 2, (b) July 3, and (c) July 4, 2005. The color composite of red (pan band of July 2), green (pan band of July 3) and blue (pan band of July 4) in (d).

4. Conclusions

The innovative characteristic of sun-synchronous and geo-synchronous orbit makes FORMOSAT-2 an ideal satellite for site surveillance. The arrangement of the CCD lines on-boarded FORMOSAT-2, however, has also raised new challenges in image processing. After more than a year of operation, DPRC has successfully applied FORMOSAT-2 imagery to disaster preparedness, rescue and environment monitoring. To meet the requirements of site surveillance, a fast and automatic approach has developed to process the daily FORMOSAT-2 images, including level-2 product generation, pan-sharpening and quasi-orthorectification. The sequential three-day images taken near Hsin-Chu on July 2-4, 2005 demonstrated the advantages of the daily revisit orbit and the approach of processing FORMOSAT-2 imagery for site surveillance. As both the spatial and temporal resolutions of the remote sensing systems are increasing, the approach developed for site surveillance is a practical way to automatically ingesting a large amount of data, processing the data for change detection, and screening the data for information. The high agility, high temporal resolution, and the innovative orbit of FORMOSAT-2 have been followed by the Pléiades HR, the next French earth observation system scheduled to be launched in 2008 [3]. Experience obtained from this work would benefit the system design and image processing of the future satellite missions.

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