Image Processing System of FORMOSAT-5

Li-Hsueh Chang [1,] , Yu-Lin Kuo [2], Shih-Chieh Chou [3], Kuo-Hsien Hsu [4], Sheng-Yun Yan [5] , Feng-Tai Hwang [6], and Cynthia Liu [7]

[1] National space Organization, National Applied Research Laboratories (NSPO, NARL),
8F, 9 Prosperity 1st Road, Hsinchu Science Park, Hsinchu, Taiwan,
Email: LHChang@nspo.narl.org.tw

[2] National space Organization, National Applied Research Laboratories (NSPO, NARL),
8F, 9 Prosperity 1st Road, Hsinchu Science Park, Hsinchu, Taiwan,
Email: kuoyl@nspo.narl.org.tw

[3] National space Organization, National Applied Research Laboratories (NSPO, NARL),
8F, 9 Prosperity 1st Road, Hsinchu Science Park, Hsinchu, Taiwan,
Email: jay@nspo.narl.org.tw

[4] National space Organization, National Applied Research Laboratories (NSPO, NARL),
8F, 9 Prosperity 1st Road, Hsinchu Science Park, Hsinchu, Taiwan,
Email: khhsu@nspo.narl.org.tw

[5] National space Organization, National Applied Research Laboratories (NSPO, NARL),
8F, 9 Prosperity 1st Road, Hsinchu Science Park, Hsinchu, Taiwan,
Email: ysyun@nspo.narl.org.tw

[6] National space Organization, National Applied Research Laboratories (NSPO, NARL),
8F, 9 Prosperity 1st Road, Hsinchu Science Park, Hsinchu, Taiwan,
Email: fthwang@nspo.narl.org.tw

[7] National space Organization, National Applied Research Laboratories (NSPO, NARL),
8F, 9 Prosperity 1st Road, Hsinchu Science Park, Hsinchu, Taiwan,
Email: Cynthia@nspo.narl.org.tw

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ABSTRACT: FORMOSAT-5 is a remote sensing satellite developed by National Space Organization (NSPO) in Taiwan which will be launched into space in the fourth quarter of 2016. As the owner of satellite, NSPO already setup the TT&C ground station, X-band antenna system, satellite operation and control center and image processing system for the remote-sensing data receiving and processing. The Image Processing System (IPS) of FORMOSAT-5 is inherited from FORMOSAT-2 IPS architecture. Compared to FORMOSAT-2 IPS, IPS development for FORMOSAT-5 has some advanced features. First, NSPO constructs a complete independent IPS to schedule the remote sensing opeartion by user's needs. After the images are taken, the data will be downloaded through X-band antenna, processed by the IPS such as de-compression, de-ciphering and de-packetization techniques, radiometric and geometric corrections and then filed and stored in the computers. Then these FORMOSAT-5 products will be delivered to the end users based on the clients' requests. The second advance feature of FS5 IPS shall take into consideration both FORMOSAT-5 and FORMOSAT-2 operations simultaneously so that the upgraded IPS is designed to be an integrated operational environment which can support multi imaging satellites operations.

In NSPO, IPS includes five subsystems: Planning and Scheduling Subsystem (PSS), Data Ingestion Subsystem (DIS), Data Management Subsystem (DMS), Data Processing Subsystem (DPS), and Image Quality Subsystem (IQS). The main functions of PSS are to generate a sequence of imaging parameters, such as attitude and timeline, as well as to send commands from ground stations. DIS is used to receive X-band signals in real time and to de-compress, de-cipher and de-format into raw remote sensing images. The DMS is in charge of data storage management and data-flow of IPS, also provide the services of query, quick-look, product order and product packing. The main functions of DPS are to process raw satellite image data to generate two different level products through radiometric correction and geometric correction. IQS is responsible for monitoring and tracking the quality of satellite image, such as relative and absolute radiometric and geometric calibration.

1. INTRODUCTION

FORMOAT-5 is the second remote sensing satellite developed by National space Organization, National Applied Research Laboratories (NSPO, NARL) in Taiwan, but it will be the first space program that NSPO takes fully responsibility for the complete satellite system engineering design including payloads. FORMOSAT-5 will to be operated in a sun synchronous orbit at 720-km altitude with a two-day revisit cycle and global coverage. A primary payload, optical Remote Sensing Instrument (RSI), will provide 2-m Panchromatic (PAN, black and white) and 4-m Multi-Spectral (MS, color) imagery. According to our schedule, FORMOSAT-5 will be delivered to the space in the end of 2016 by using the Falcon 9 vehicle provided by SpaceX to continue the global imaging services.

For the effective implementation of the remote sensing mission of FORMOSAT series satellites and thus enhance their overall application values for people's livelihood, NSPO decided to self-developed the image processing system (IPS). The first set of FORMOSAT image processing system were built for FORMOSAT-2 remote sensing satellite, the R&D project began from 2001, lasted 2 and half years of development, until 2003 for operation ready. The first FORMOSAT-2 image product was generated successfully for its first tasking event. The success of this project not only presented the Taiwan's self-development energy in high-tech field, but also led our country for a seat on an international leader in remote sensing satellite imaging applications.

However, due to the FORMOSAT-2 was produced by France, parts of the key technologies associated with the satellite body such as on-board compression algorithm which are belonged to the Intellectual Property Rights of France. NSPO couldn't get the permission for these technology transfers, so the first step of satellite downlinked data ingestion was designed by NSPO but implemented by France. Now thanks to the fully self-reliant development approach of FORMOSAT-5. NSPO maters the de-compression, de-ciphering and de-package techniques, so we will be able to construct a complete independent IPS. Meanwhile, the satellite may be having its life limited, but the data usages are unlimited. The image processing system of FORMOSAT-5 is designed as multi-satellite operation architecture, which can operate both FORMOSAT-2 and FROMOSAT-5, and also easy extend to other remote sensing satellites.

2. FORMOSAT-5 REMOTE SENSING MISSION

FORMOSAT-5 program consists of Space, Ground, and Launch segments. The Space segment is made up by Spacecraft Bus, Remote Sensing Instrument, and Scientific Instrument; Ground segment includes TT&C ground station, X-band antenna system, overseas TT&C station, satellite operation and control center, and image processing center; launch segment includes Falcon-9 launch vehicle. For the whole FRMOSAT-5 Remote Sensing mission chain, the IPS is the only elements that provides interface for the users.

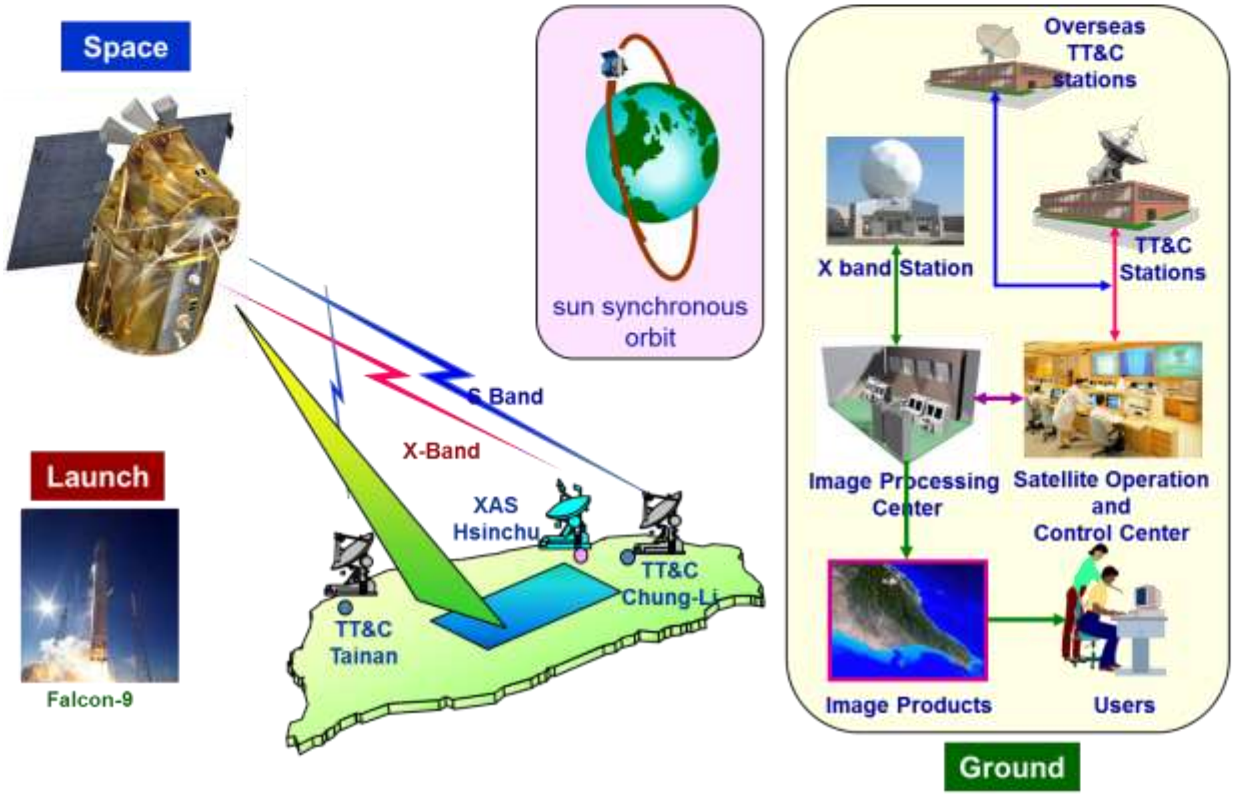

Figure 1 FORMOSAT-5 system architecture (NSPO, 2016)

3. Image Processing System

The image processing system has been implemented by NSPO to handle image scheduling, data ingestion, data processing, data management, and data quality invalidation (Wu, et al, 2004). Development of the IPS is highly relevant to satellite design. In order to build a viable development policy and setup the system specification, fundamental IPS research tasks including satellite and payload system performance analysis, image processing system requirement analysis and flow-down (Liu, 2011), system interface engineering trade-off (Chang, 2015), system software design trade-off (Tang, 2011), image tasking restriction study, and image quality study need to be completed before the arrival of a new system. Those research results will feedback to satellite development for the determination of certain design parameters. (Chang, 2011) After carefully analysis the IPS is divided into 4 daily operation subsystems and one supporting subsystem (NSPO, 2016):

1. Planning and Scheduling Subsystem (PSS): The main functions of PSS are to generate a sequence of imaging parameters, such as attitude and timeline, as well as to send commands from ground stations.
2. Data Ingestion Subsystem (DIS): The main functions of DIS are to receive X-band signals in real time and to de-compress, de-cipher and de-format into raw remote sensing image data for DPS.
3. Data Management Subsystem (DMS): The main functions of DMS are to manage all data storage and flow of IPS, and to provide the services of query, quick look, product order and product packing.
4. Data Processing Subsystem (DPS): The main functions of DPS are to process raw satellite image data to generate three different levels of image products, Level 1A or Level 2, through radiometric correction or radiometric/geometric corrections.
5. Image Quality Subsystem (IQS): The main functions of IQS are to monitor and track the qualities of satellite image, such as relative and absolute radiometric corrections, as well as geometric correction.

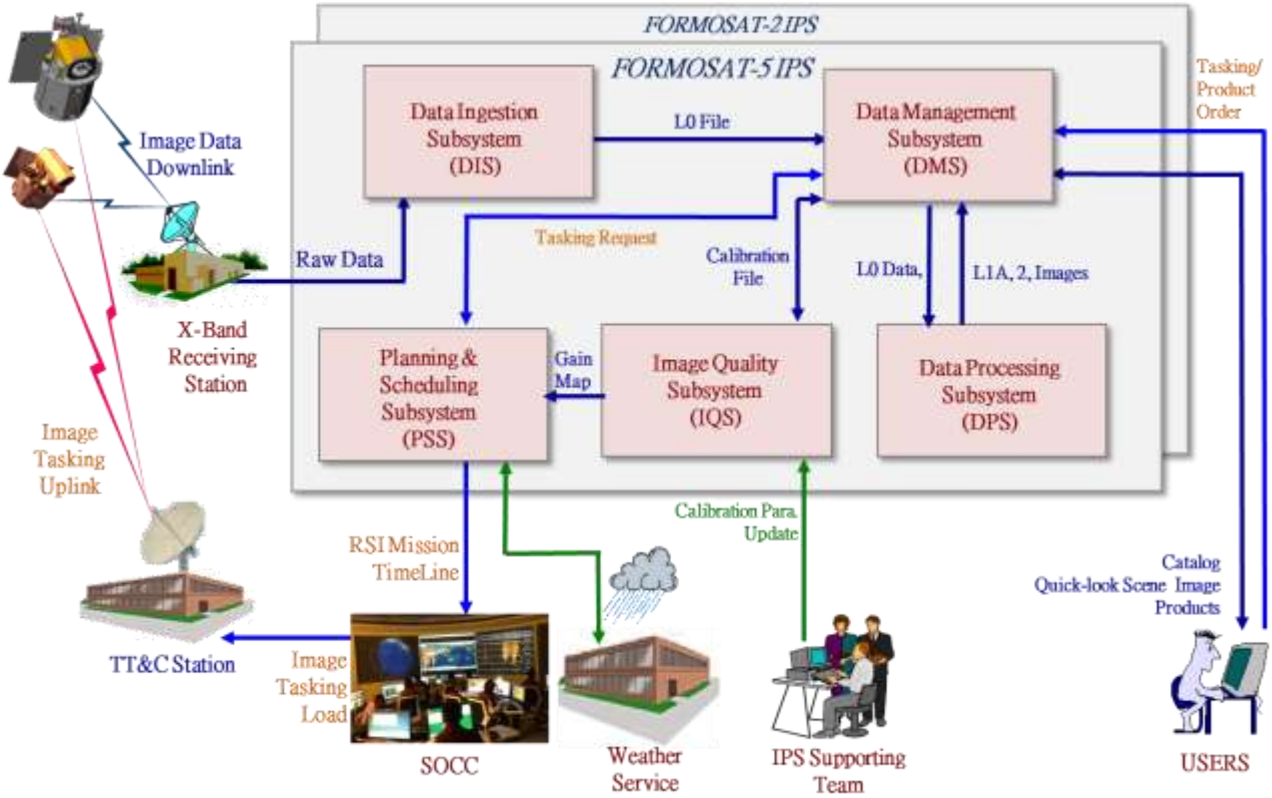

Figure 2 Overview of Image Processing System

To ensure that all the development phase of image processing system meet certain criteria and follow standard process, all the software and hardware architecture are under control by using Configuration Management (CM). NSPO setup a Product Assurance Program Plan (PAPP) which is consistent with ISO 9001 and ISO 9000-3 standards. The approach integrates the quality disciplines into the development and integration in PAPP, hence PAPP complement with and assist all areas of IPS developing, testing, integration, and operation. (Lee, 2009)

3.1 Planning and Scheduling Subsystem

Planning and Scheduling Subsystem is responsible for performing the feasibility study of user request and managing the satellite resources to initiate an imaging activity in the IPS data flow. The system design was inherited from FORMOSAT-2 PSS system and extends its function to manipulate multi-satellite operation. It provides the capacity to support both daily schedule and long-term mission planning capacity to assist operators to determine the sequence of satellite imaging parameters which satisfy user request.

The system was designed to perform feasibility study by considering the factors of user request such as the area of interest (AOI), requested viewing angle, temporal series and weather condition. Those factors, together with predicted satellite ephemeris, are able to be performed ground observation predictions for different overpass time of both single and multiple satellite combinations. It also determines the viewing angles in image which are related to the pointing of the instrument and the location of the ground site when the image was taken. This process was expected to minimize planning efforts and give the initial evaluate the chance of completion the task. Moreover, feasibility was also to characterize the AOI into the small portion of area (grid) according to the FORMOSAT-5 orbit characteristics if the AOI could not be acquired in one single image strip.

On the other hand, in order to manage the conflict of different imaging activity and accurate estimate the resources, the system has ability to calculate the satellite attitude whenever satellite acquire image data and seek suitable maneuver time between consecutive imaging attitudes. The satellite resources were estimated by taking into account the availability of receiving station and satellite duty cycle. Those planning results were provided in real time. The system also develop the visualization environment by utilize the well-known off-the shelf global map service such as Open Street Map to demonstrate the dynamic simulation such as satellite ground track, attitude variation, plan acquisition coverage and AOI. Since the time for the completion of the task is not known a priori for long term planning, the system also communicates with DMS on regular basis to notify that the task is completed.

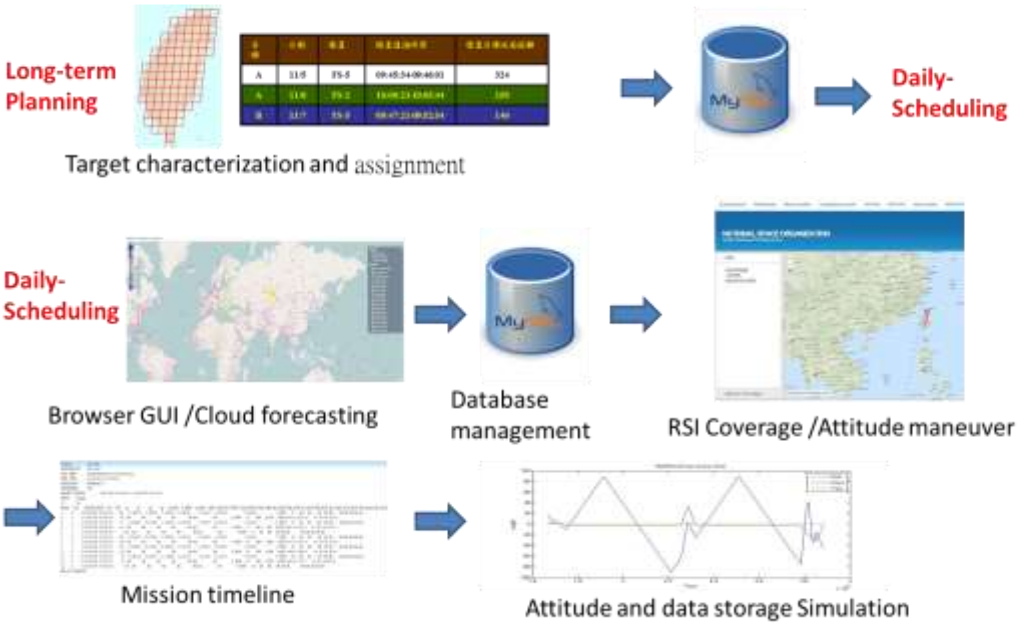

Figure 3 PSS operation concept

3.2 Data Ingestion Subsystem

Data Ingestion Subsystem play the important role of front-end image acquisition in Image Processing System (IPS), to real time acquire image signal and perform critical processing like frame synchronization, decompression and decryption etc. FORMOSAT-2 Data Ingestion Subsystem take the outsourcing approach, since satellite was designed and manufactured by Astrium Company, the key technology of on-board compression program cannot be acquired. NSPO has suffered from expense maintenance fee for central, backup and overseas stations in the past 11 years. In the niche of self-development for FORMOSAT-5, NSPO can acquire the core technology of decompression, decryption and source format decomposition, and successfully integrate the core application program with the mature front-end acquisition board by Norway Kongsberg company, we can claim the completion of system development by passing the satellite End-to-End test.

Compared to FORMOSAT-2 DIS, the DIS development for FORMOSAT-5 has some advanced features. First, NSPO adopts fully self-reliant development approach for FORMOSAT-5. The image signal processing kernel -- Remote Sensing Ground Processing Auxiliary Equipment (RSGPAE), developed by Data Ingestion Subsystem Team, which conduct the CCSDS De-packetization, Decryption (or Deciphering), Image Source Format reconstruction, Image Decompression, Image Moving Window Display and Level 0 file generation

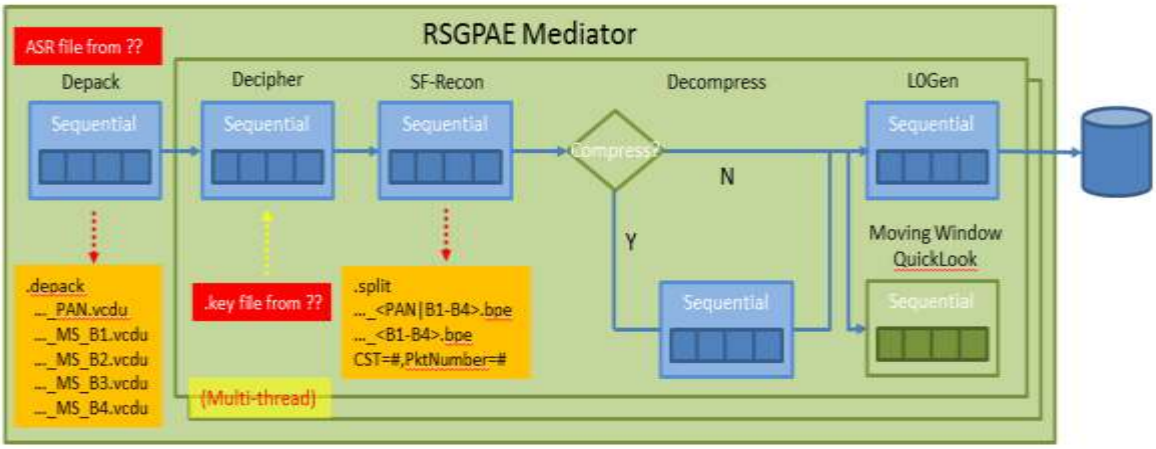

Figure 4 Functional diagram of Remote Sensing Ground Processing Auxiliary Equipment

Furthermore, to reduce development effort and take the advantage of maintenance flexibility, the RSPGAE is integrated into the COTS product -- Multi-mission Earth Observation System (MEOS), by 3rd-party API function, to achieve the automatic operations, and the Image Moving Window Display in real time frame. As the DIS framework, the MEOS can support complete hardware health check mechanism, which can help to offer abnormal status easily and avoid system error in operation.


Figure 5 DIS Multi-mission Earth Observation System

The front-end function of DIS is to capture real-time downlink data from X-band Antenna System (XAS), and to perform the frame synchronization, unscrambling, Reed-Solomon decoding and data storage for the image data received during the pass. The playback function from storage image raw data is also important in operation, the DIS should be capable to replay the image data on the disks or tape library offline, if necessary. For the playback front-end solution, the DIS adopts the open source--Real-time software telemetry processing system (RT-STPS, from NASA Garda Space Center) as the base technology for development. In 2015 July, the DIS has passed the satellite End-to-End test and proved the completion of system development.

3.3 Data Management Subsystem

Data Management Subsystem is capable of daily archiving, managing and pre-processing received imagery. DMS also serves as a central unit to connect other subsystems (e.g., IQS, DPS, PSS, and DIS) by exchanging the interactive work/task order in Image Processing System (IPS). As shown in Figure 6, based on the requirement of system engineering for DMS development, there are five configure software configuration (CSC) in DMS, including Image Frame Work (IFW), Image Data Management (IDM), Image Data Inventory (IDI), Man-machine Interface (MMI), and Web Customer Service (WCS).

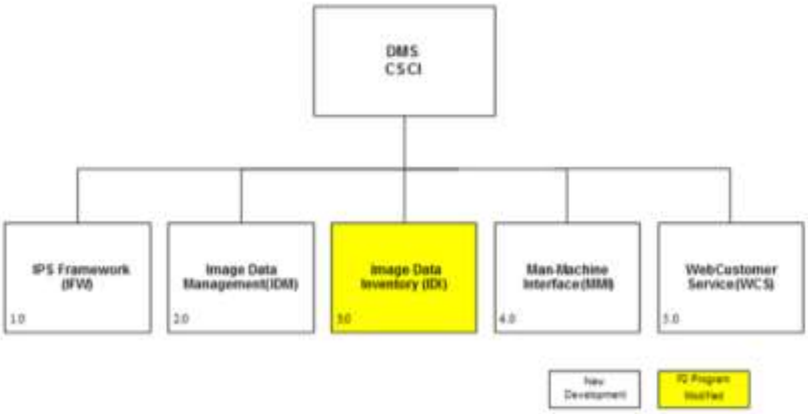

Figure 6: Five configure software configuration (CSC) of DMS, including Image Frame Work (IFW), Image Data Management (IDM), Image Data Inventory (IDI), Man-machine Interface (MMI), and Web Customer Service (WCS)

Specifically, IFW exchanges the work/task order among originator and destination subsystems. IDM manages the database of imagery catalog, archive/storage imagery, and programming/tasking information. IDI generates the quick-look imagery and related metadata in imagery catalog. MMI and WCS provides friendly system operational interface for internal operational team and users, respectively. As shown in Figure 7, MMI also has the capability of monitoring and remote controlling/operating ORS-DMS site where located oversea and in backup receiving station. Received imagery in and high-level product in ORS-DMS site can be transferred back to NSPO-DMS site via internet for central management and archive. User can search available imagery by WCS with specific requirements, such as locations, duration, cloud coverage, and …etc, please see the Figure 8.

Figure 7: MMI has the capability of monitoring and remote controlling/operating ORS-DMS site

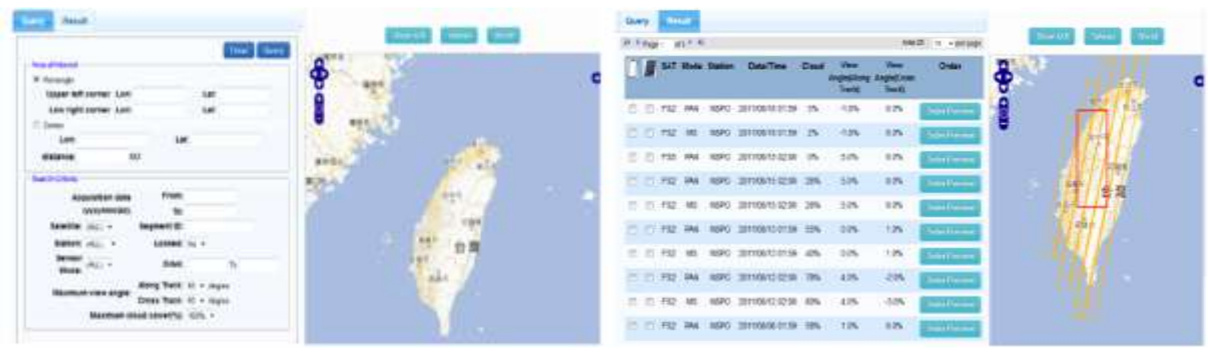

Figure 8: User query interface and query results

3.4 Data Processing Subsystem

In the architecture of IPS, the Data Processing Subsystem is responsible for providing systematic radiometric correction, systematic geometric correction on image data by using pre-processing procedures. Data will be processed up to the levels 1A and Level 2 depending on the product request from the DMS. The flow chart of DPS processing please refers to Figure 9.

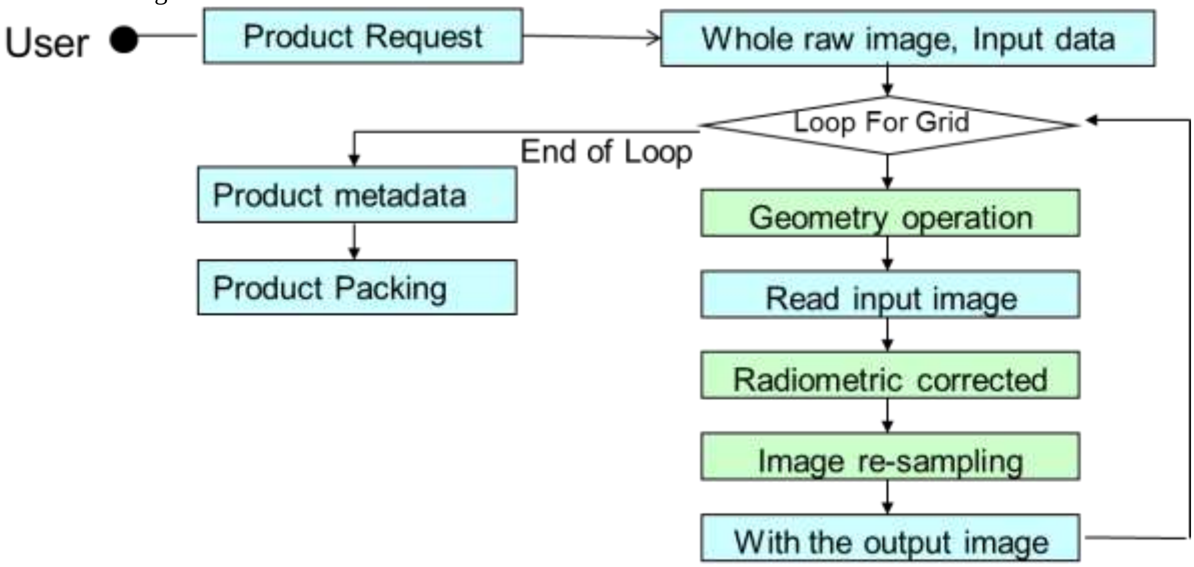

Figure 9 DPS processing operation procedure

The RSI observe the radiance, but the real data provide to the use is the digital number (DN). From the radiance to the DN value, there are some factors, such as atmospheric effects (scatting, absorption), illumination and topographic geometry, environment effects, transmission artifacts, RSI effects. But we only can use sensor equalization algorithm to compensate the difference of each individual.

Figure 10 (a) Level 1A without sensor equalization

Figure 10(b) Level 1A with sensor equalization

Level 2 products apply systematic radiometric and systematic geometric correction to generate a standard product for user application needs related to the map. There are many geometric distortion factors including image formation mechanism, spacecraft position, velocity and attitude, the ellipsoid of earth and satellite orbit, effects of earth rotation, elevation, curvature, the geometry of the instrument, the optical distortions, and so on. DPS need to consider these factors to develop appropriate algorithms to improve the geometry accuracy of level 2. Eventually, the main function for Level 2 is to locate an image pixel on the Earth surface with map coordinates by using the information provided from satellite.

There are two common ways to covert the image coordinates to map coordinates: (Chang, et al, 2016)

(1) Forward geo-locating: Given input image pixel, find map/geographic coordinates
(2) Backward geo-locating: Given map/geographic coordinate, find input image pixel

After the engineering analysis, DPS uses the backward-locating to reduce the processing time but also guarantee the geometric accuracy.

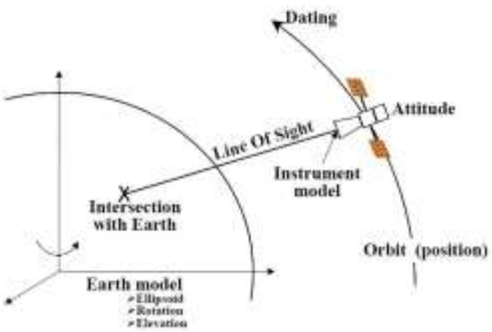

Figure 11 Geometric operation concept illustration

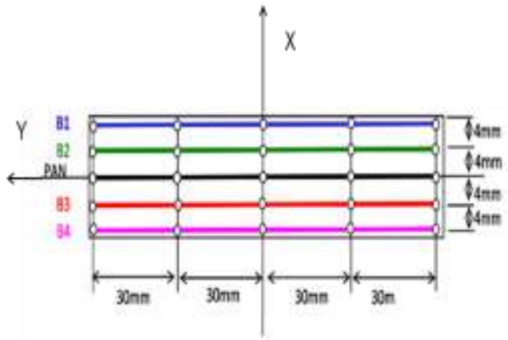

Figure 12 RSI sensor lines configuration in focal plane

According to FORMOSAT-5 RSI focal plane assembly (FPA) design, each band of multi-spectral images take different areas in the same time, which means DPS must to solve the shift values of each band and apply these values feedback to the product. From our experience of FORMOSAT-2, the geometric model constructed by satellite ephemeris can't describe the shift value very well in whole tasking segment. So DPS apple the normalized cross-correlation (NCC) algorithm to detect the mis-registration of MS each bands, then apply the values in Level 1A/Level 2 procedures.

3.5 Image Quality Subsystem

Image Quality Subsystem is capable of developing calibration plan, algorithm for pre-/post-launch satellite imagery quality assessment, and performing radiometric and geometric calibrations of RSI. These instruments performance and related radiometric/geometric parameters could be provided for users' purchase evaluation, and high-level products generation, respectively. Specifically, the radiometric calibration indicates that except measured SNR of Band 3(red) of multispectral band is about 0.9% less than its specification, the measured SNR (PAN: 99.3, B1:100.6, B2:125.2, B3:99.1, B4:121) of other bands are above their corresponding specifications(SNR Spec. for PAN:≧83,B1:≧95,B2:≧95,B3:≧100,B4:≧100).

Based on measured relative radiometric parameters, such as relative response and offset, relative radiometric calibration can properly adjust the uneven response behavior of sensor elements observed from raw imagery. Take G2 result for example, standard deviation of calibrated imageries can be dramatically decreased (PAN: 70 to 25.64, B1: 54.24 to 15.28, B2: 38.41 to14.85, B3: 38.42 to14.83, B4: 46.4 to 17.26). The resulting absolute radiometric coefficient of each band is independent of Compression Ratio (CR), electronic gain setting, and pixel, which is used for radiance conversion process (PAN: 12.809, B1: 12.289, B2: 13.93, B3: 11.438, B4: 14.14).

For geometric calibration, polynomial coefficients of light-of-sight vector of RSI sensor with three-order degree and three Euler angles between coordinates of RSI alignment and satellite master cube are derived as shown in Eq. 1

$$\Psi = C0 + C1 * p + C2 * p^2 + C3 * p^3, 1 \le p \le N_{sample} \qquad \text{Eq.1}$$

Where p denotes pixel number, ranges from 0~12000 for PAN and 0~6000 for MS. Based on our analysis, the magnitudes of 2nd and 3rd order polynomial coefficients are less than 10^{-12}. In other words, ground distance corresponding to the nonlinear distortion caused by the 2nd and 3rd order terms is as small as <0.15cm.

Figure 13 shows that the measured output signal is linearly proportional to given input radiance during radiance conversion process, Figure 14 shows Light-Of-Sight (LOS) vector of RSI.

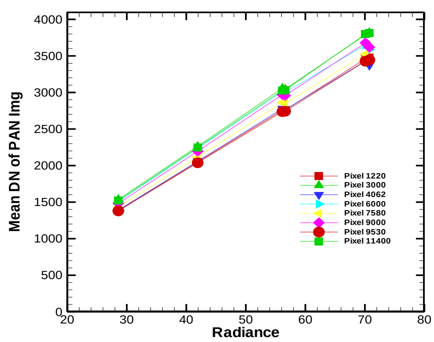

Figure 13 Radiometric linearity Check of PAN

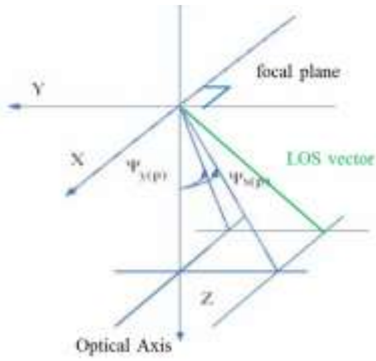

Figure 14 Light-Of-Sight (LOS) vector of RSI

For Contrast Transfer Function (CTF), Table 1 lists the comparison of measured CTF (Contrast Transfer Function) results and the specifications of panchromatic and multispectral bands in along ALT (Along-Track) and ACT (Across-Track) direction. Overall speaking, the measured along-track CTF of all bands are about 14~31% less than their corresponding specifications, but these performance are still within the potential users' acceptability. The measured across-track CTF of all bands are above their corresponding specifications.

Table 1. Comparison of measured CTF results with the specifications of PAN and MS in ALT and ACT directions

Spectral Band	Minimum Static CTF @ Nyquist Frequency	
	ALT CTF: Spec. (measurment)	ACT CTF: Spec. (measurment)
B1	0.44 (0.35)	0.29 (0.342)
B2	0.44 (0.34)	0.29 (0.374)
B3	0.44 (0.34)	0.29 (0.370)
B4	0.36 (0.31)	0.23 (0.311)
PAN	0.21(~0.145)	0.155 (0.172)

4. IPS End-to-End Test Result

System testing is the type of testing to check the behavior of a complete and fully integrated subsystem/software based on the software requirements specification documents. The SAT(System Acceptance Test) follows the successful completion of the Subsystem Formal Qualification Test (FQT) and Formal Acceptance Test (FAT). The SAT objective is to verify the function, performance, and validate the operational readiness of the end-to-end FORMOSAT-5 Image Processing System and the capability of external interface to support the FORMOSAT-5 mission.

All the test issues, results and records were be serious supervised under four quality control steps:

(1) Testing: Testing is one of the most important works to ensure software quality, it is necessary to arrange the testing for the various stages of the software development, including unit testing, system integration testing, formal qualification testing and system acceptance testing.

(2) Tracking：The quality assurance personnel is responsible for tracking items include bug, demand changes and program changes. When quality assurance personnel or test team supervisor find the test problem, and then notify the related software development manager to consult the problem recorded in problem-tracking system within non-compliance report (NCR).
In the IPS program, there is another way can track the issues called action item management .This mechanism is to ensure that the action items can be completed before the expiration date, and to achieve the desired objectives

(3) Monitoring: The main purpose of surveillance is to ensure that the entire IPS project can be in accordance with established procedures, standards and common specification to perform software development. To reminder program office personnel should pay attention the project progress and keep up with the pace of the entire project.

(4) Auditing: The main purpose of the audit is to ensure that the software can meet the specifications, standards and contractual requirements or other provisions of the guidelines. If found any missing, the auditor will assist the developers to corrective and preventive measures, in order to achieve continuous improvement goals.

Until the end of august 2016, the test team supervisor have done four important test phases: formal qualification test (FQT), formal acceptance test (FAT), system acceptance test (SAT) and end-to-end test (ETE). There are more than 200 test cases of all test phases were completed，and that makes FORMOSAT-5 IPS more efficient , feasibility and user-friendly.

Some of the test records of end-to-end test were captured as following pictures: (1) picture 15 and Figure 16 shows the simulated panchromatic image disappeared in moving window display; (2) picture 17 shows DMS can get the decoding key file and acquisition schedule file from the designation source, and can complete Level 0 File inventory successfully; (3) picture 18 show the image query and order function.

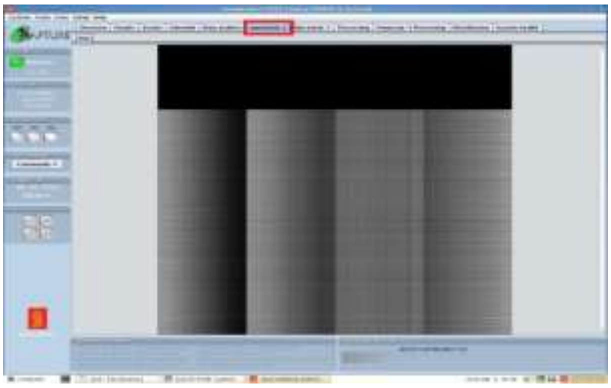

Figure 15 DIS Moving Windows Display (PAN)

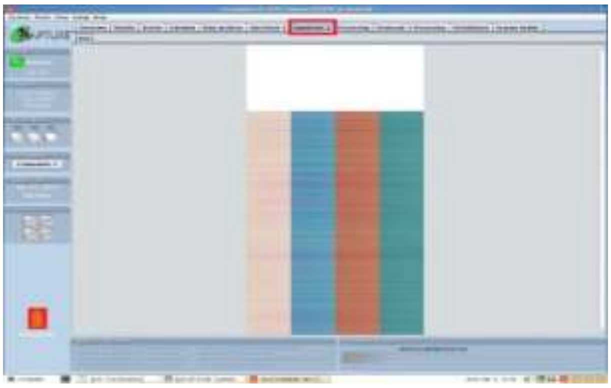

Figure 16 DIS Moving Windows Display (MS)

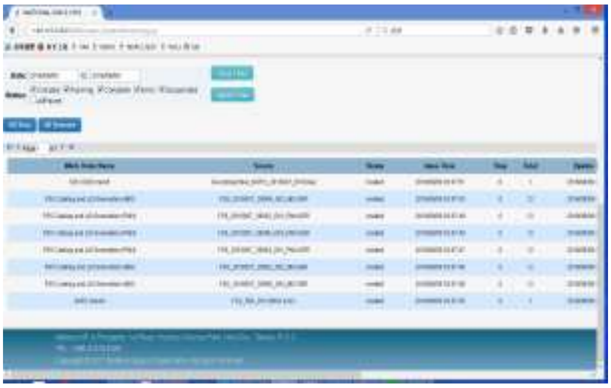

Figure 17 DMS Level 0 file inventory event log

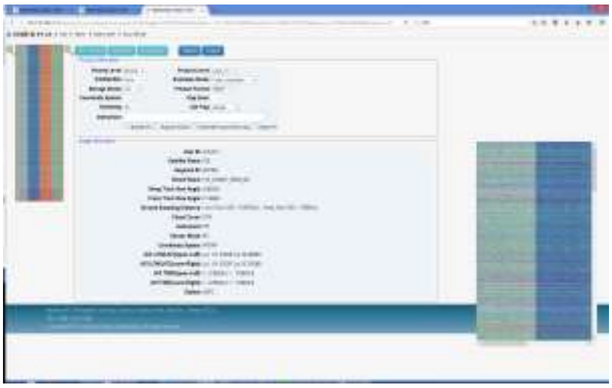

Figure 18 DMS Catalog query event log

5. CONCLUTIONS

Development of Image Processing System requires besides the precise system engineering analysis and well programming capability, most important is the depth understanding of satellite payload and satellite image formation mechanism. In the development phase, IPS development team participate the RSI trending research and feedback the results to the RSI engineering team. We also need to design the appropriate algorithms by RSI specification to build a system which meets the operational needs and performance criteria. Image Processing System of remote sensing satellite is a very successful self-development project in Taiwan, NSPO has already operated FORMOSAT-2 for more than 12 years, the coming FORMOSAT-5 RSI mission and its Image Processing System will continue to serve remote sensing user communities.

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