FLIGHT OPERATION AND IMAGE CALIBRATION OF FORMOSAT-5 REMOTE SENSING INSTRUMENT

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ABSTRACT: Taiwan's first self-reliant satellite, FORMOSAT-5, has been launched successfully on August 25th this year to resume the earth observation mission of the decommissioned FORMOSAT-2. There are many Taiwan-made key components in the Remote Sensing Instrument (RSI) including the Telescope, CMOS image sensors, Focal Panel Assembly, Electronic Units, and so on. The Image Processing System (IPS) on ground is also developed by National Space Organization (NSPO) itself.

In this paper, the flight operation for imaging and onboard image data handling are described. After images downlink, the processes for image commissioning and calibration are mentioned to show the image quality. The commissioning activity has been planned including verification of Ground Sampling Distance (GSD), Modular Transfer Function (MTF) and Signal-to-Noise Ratio (SNR). Meanwhile the in-flight calibration activity is aimed to generate the radiometric and geometric parameters for following image processing. The real downlink data will support the richness and completeness of this paper.

1. INTRODUCTION

FORMOSAT-5 was launched on August 25, 2017 at 2:51 a.m. Taiwan time from Vandenberg Air Force Base by SpaceX Falcon 9 rocket. The satellite was injected into mission orbit successfully. At 4:11 a.m. Taiwan Time, the ground station at Svalbard received the RF signal from FORMOSAT-5 as expected. On Sept. 7, the first image token by FORMOSAT-5 was downlinked.

FormoSat-5 is equipped with a domestically made high-resolution optical remote sensing instrument which can capture images on a Panchromatic spectral (PAN) band at a resolution level of two meters with 12,000 pixels, and four Multi-Spectral (MS) bands each at four meters with 6,000 pixels.

The RSI Electronic Units (RSI EU) is used for RSI operation control, image data compression and data storage. The image data compression is performed onboard to reduce mass memory volume and downlink data rate. The CCSDS Recommended Standard for Image Data Compression, CCSDS 122.0-B-1[1], is intended to be suitable for use on the spacecraft. The algorithm permits a memory efficient implementation which does not require large intermediate frames for buffering. The small memory in the FPGA is fit for this application.

The orbit altitude of the FORMOSAT-5 is planned to be 720 km with inclination of 98.28 degrees. The FORMOSAT-5 was put into earth orbit well by Falcon-9 launcher. The actual orbit altitudes are between 729.3~741.5km. The inclination angles are between 98.288~98.291 degrees. There is no need to adjust its orbit after separation from the launcher. To maintain the ground tracking pass the Taiwan, the cold gas propulsion will be used to adjust the orbit after 6 months.

In order to have 2m resolution for PAN image and 4m resolution for MS image, the image sensor integration time is 0.297ms for PAN image and 0.594ms for MS image individually. Each pixel signal is expressed by 12 bits digital number. The output data rate is up to 485Mbps for PAN image and MS images each. Hence the real-time downlink rate of both will be up to 970Mbps without compression. Thus the compression scheme is necessary in the Remote Sensing Instrument.

Image Processing System (IPS) is one of the essential elements for the FORMOSAT-5 program. For daily operations, the system collects imaging requests from users, receives and archives image data acquired by the FORMOSAT-5, and generates image products according to user's needs. Furthermore, the IPS is employed to support the FORMOSAT-5 commissioning phase activities, and to characterize system parameters needed for image product generation process. The major activities involved in the FORMOSAT-5 commissioning phase include the verifications of Ground Sampling Distance (GSD), Modulation Transfer Function (MTF), and Signal-to-Noise Ratio (SNR). The system parameters needed for image product generation include various coefficients modelling the radiometric and the geometric behaviors of the Remote Sensing Instrument (RSI) on board the FORMOSAT-5. A plan has been implemented to complete aforementioned operations. Throughout the mission life of the FORMOSAT-5, the plan will be carried out regularly to keep track the performance of the RSI, and to ensure the qualities of the image products.

2. ONBOARD IMAGE DATA HANDLING

The image flow of the Remote Sensing Instrument in the FORMOSAT-5 is as Figure 1. Behind the telescope, there is one CMOS sensor module inside the Focal Panel Assembly (FPA) to take the images. The CMOS sensor module can be accessed by two FPA electronics. The output data stream is sent to the Image Data Pre-processing (IDP) module in the RSI EU for data re-ordering. The difference between four PAN CMOS chips are compensated by IDP on board. Then the resultant data are sent to the Image Data Compression (IDC) module for data compression. The compressed data with header are stored in the Mass Memory (MM) modules under the control of the Memory Controller (MC) module. While the satellite is above the ground station, the image files can be retrieved and transmitted to the ground station.

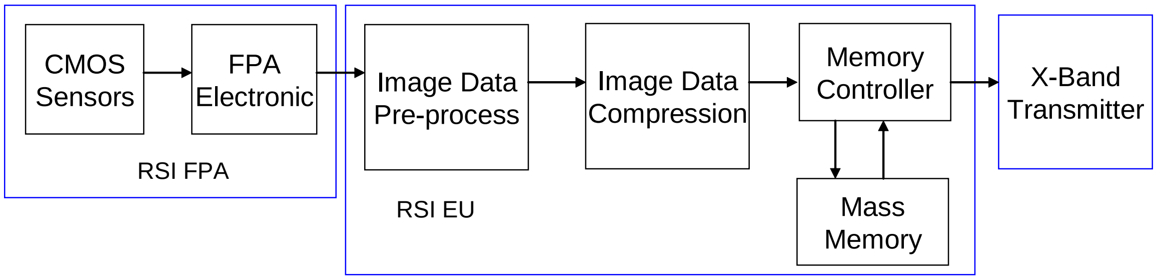

Figure 1. Image Flow of FORMOSAT-5 Remote Sensing Instrument.

The serial image data from FPA are re-ordered in the IDP to make the image data in right order. Then the image data are transferred to IDC in parallel with lower transmission clock rate. One channel of PAN data and four channels of MS data are compressed individually in the IDC. The strip-based compression architecture is used as defined in the CCSDS standard. For lossy compression, the Floating Point Discrete Wavelet Transform (FDWT) methodology is used; for lossless compression, the Integer Discrete Wavelet Transfer (IDWT) methodology is used. Then the PAN data and MS data are stored in individual files in the Mass Memory with 128Gbits storage volume.

3. RSI Flight Operation

It is important to keep the CMOS sensors in steady temperature to have good image quality. When the RSI is off on the orbit, the RSI temperature is monitored and maintained by the on-board computer, Command and Data Management Unit (CDMU). When the EU is powered on, it takes the role to monitor and maintain the RSI temperatures, including FPA. The EU can measure 48 thermistors, PT1000, and control 32 heaters which are allocated on various RSI locations, including FPA, EU and RSI telescope. There are two thermistors and two heaters near to the FPA CMOS sensors to maintain them on steady temperature. The accuracy of the temperature telemetry measured by Camera Controller is within +/-0.5 degC in 0~30 degC range. The on/off of the heaters on the Heater Controller are controlled every two seconds by the Camera Controller. The FPA CMOS sensors have been kept within 27~28degC well on orbit.

The output data rate from FPA is up to 485Mbps for PAN image and MS images each. The EU can perform image compression following CCSDS recommendation [CCSDS, 2005], with compression ratio 1.0, 1.5, 3.75 or 7.5, to reduce image data rate and volume. The compression ratio 1.0 is selected for lossless compression to keep original data. The higher compression ratio 7.5 is selected to allow transmit PAN and MS image data in real time via 150Mbps X-band downlink channel. The average PSNR (Peak Signal to Noise Ration) is higher than 55 dB while handling the sample images provided by the associated CCSDS official website.

There are two major modules in the IDC: Discrete Wavelet Transform (DWT) module and Bit Plane Encoder (BPE) module. The processing flow is shown in Figure 5. The space grade Xilinx FPGA, XQR5VFX130, is used for image compression processing. The major characteristics of the XQR5VFX130 are 130,000 logic cells, 288 blocks of 36K bits RAM, 300Krad total dose, and etc. The PROM part for FPGA programming is XQR17V16, which has

16Mbits memory size with 50krad total dose capability. One XQR5VFX130 FPGA is used for PAN data compression. Two XQR5VFX130 FPGAs are used for four MS data compression. The external memories, 24 chips of 256K x 32 SRAM, are used as data buffer. The compression functions work well on orbit so far.

There are one Memory Controller module and two Mass Memory modules in the EU for image data formatting and storage. The MC includes one FPGA (Xilinx XQR4VFX60) with embedded PowerPC micro-processor to handle UART communication, time tag management, data formatting, file management, internal bus communication of MC and MM, data encryption and channel coding, and QPSK I/Q/CLK generator. The MC can decode the CC command to turn on or off MMs, IDP and IDC, and monitor their housekeeping status. Each Mass Memory module has two memory banks. The capacity of each memory bank is 32 Gbits with extra 8 Gbits EDAC (Error Detection and Correction) memory. The file allocation can be reconfigured to various memory sector quantity and the bad memory sector can be isolated. The file can be set to linear or circular type. The circular files can support the near real time PAN and MS image data downlink. While retrieving the image data from the mass memory, the CCSDS telemetry format is implemented on the data. The output data rate is 150Mbps in QPSK format.

4. IMAGE PROCESSING SYSTEM

To fulfill the FORMOSAT-5 remote sensing mission objectives, NSPO has developed its own ground Image Processing System (IPS) for daily operations. The system is one of the essential elements of the FORMOSAT-5 program, which provides end users the only interface to utilize the FORMOSAT-5 imaging capabilities and to access the remotely sensed data it acquired. Besides supporting daily operations, the system is developed with routine image quality assessment capabilities in mind. Furthermore, to ensure the continuous services for the FORMOSAT-2 end users, the system is designed to manage both requests for FORMOSAT-2 and FORMOSAT-5 remotely sensed data.

The IPS consists of five subsystems, namely, the Planning and Scheduling Subsystem (PSS), the Data Ingesting Subsystem (DIS), the Data Management Subsystem (DMS), the Data Processing Subsystem (DPS), and the Image Quality Subsystem (IQS). The major functions of each subsystem will be briefed in the following paragraphs. Figure 2 illustrates the baseline architecture and the major data flows of the IPS.

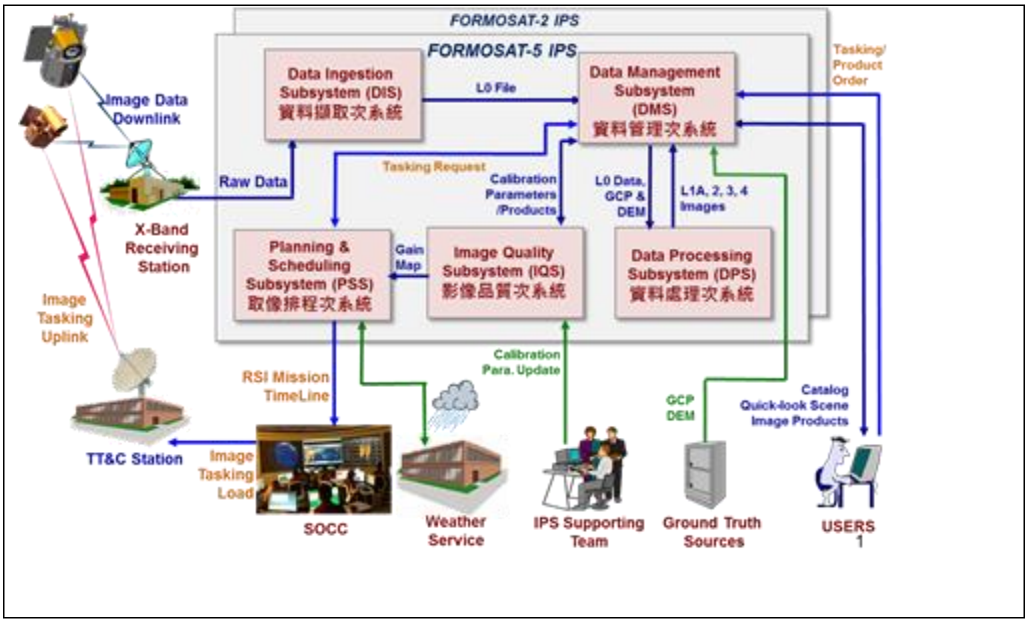

Figure 2. Overview of the Image Processing System

The PSS plans long term and schedules near term image acquisition activities for the FORMOSAT-5. The subsystem collects user's imaging requests, analyzes the feasibility of each request, resolves conflicts between user's requests, and optimizes the use of satellite resources. A RSI Mission Time Line file (MTL file) detailing image acquisition related activities for the FORMOSAT-5 is compiled and sent to Satellite Operations Control Center (SOCC) for upcoming command upload operation. To minimize the chance of acquiring cloudy images, an external weather service is introduced in daily scheduling activities.

The DIS captures and ingests differential ECL data stream dispatched from X-band Antenna System (XAS) and readies Level-0 product for further processing. To facilitate subsequent processing, the Level-0 product contains raw image data as well as the auxiliary and ancillary data associated with the image segment and image acquisition activity. The major functions of the subsystem include CCSDS depacketization, data deciphering, source format reconstruction, image decompression, and Level-0 product generation. To examine firsthand the image acquisition status, the subsystem generates on the fly also the quick-look image which could be inspected with the equipped moving window display facility.

The DMS maintains an archive of FORMOSAT-2 and FORMOSAT-5 remotely sensed data, manages data flows as well as information exchanges between different IPS subsystems, and provides interfaces for users to monitor IPS overall status, or to place IPS work orders. Upon receiving a newly generated Level-0 product from the DIS, the subsystem generates the corresponding quick-look scene, performs automatic cloud cover assessment, edits the associated metadata and attribute data, and updates database and catalog information accordingly. With web-based services, end users are allowed to query or to retrieve the datasets available in the archive and to place IPS work orders according to their interests.

The DPS performs image pre-processing and generates Level-1A and/or Level-2 image products for end users. A Level-1A product is a radiometric corrected product. The system radiometric correction applied equalizes the sensitivities of different detectors. A Level-2 product is a radiometric and geometric corrected product. The system geometric correction takes the effects from the Earth’s rotation, the Earth’s curvature, the satellite orbital motion, and the satellite attitude variation into account, and re-project product image according to the user specified map projection system. The subsystem calculates also the auxiliary data needed for different applications, which include but not limited to the radiometric calibration parameters, the geographic related information, the image acquisition time, the sun/viewing/incident angles, and the converted ancillary data in ECEF coordinate system.

The IQS performs in orbit image quality assessment for the IPS with a set of standalone tools and analysis procedures developed based on the field proven algorithms (Hsu, et al., 2011). The subsystem evaluates the in orbit performance of the RSI, and updates the system Calibration Parameter File (CPF) for the IPS. In addition, the subsystem validates the Ground Sampling Distance (GSD) for the FORMOSAT-5 program and maintains a world-wide gain map to be referenced in image acquisition planning operations. To evaluate and to keep track of the RSI in orbit performance, the subsystem derives the Modulation Transfer Function (MTF) value at the Nyquist frequency and deduces the tendency of the Signal-to-Noise Ratio (SNR) variation from the image data acquired by the FORMOSAT-5. The CPF file comprises parameters characterizing the radiometric and the geometric properties of the RSI. The radiometric parameters include the average read-out values in response to a dark and a given constant illumination inputs for each detector. A Line Of Sight (LOS) coordinate system is introduced in the IPS to describe the line of sight vector for each detector. The geometric parameters contained in the CPF file include the coefficients modeling the line of sight vectors in the LOS coordinates and the rotation angles between the LOS and the body coordinate systems.

A software engineering process adopted from NSPO’s Program Review Handbook s is strictly followed for the development of the IPS. Various test works have been performed at different development stages to check if the system meets all requirement specifications and to ensure the integrity of the system. In addition, a series of end-to-end testing works have been conducted to examine the readiness of the IPS (Chang, et al., 2016). The pre-launch measurement data, the simulated FORMOSAT-5 data, and the FORMOSAT-2 imageries are used in these testing works. Test cases mimicking various daily operation scenarios and different user’s requests are introduced. All the H/W and S/W components behave as expected, various operation sequences go smoothly, excellent system performance is observed. Overall speaking, the satisfactory test results signal that the IPS is ready to support FORMOSAT-5 remote sensing mission objectives.

5. IN-ORBIT CALIBRATION PLAN

An in-orbit calibration plan has been set up for the FORMOSAT-5 remote sensing mission. Tasks proposed in this plan include GSD measurement, MTF characterization, SNR tendency analysis, and adjustments of system radiometric and geometric parameters. The plan is designed to support FORMOSAT-5 commissioning activities, to keep track of the performance of the RSI, and to update the system calibration parameters. The major activities involved in the FORMOSAT-5 commissioning phase include the verification of the GSD, the measurement of the

MTF, and the setup of measurement references for the SNR assessment. Aside from commissioning phases, initial orbital and regular maintenance phases are defined according to this plan. The initial orbital phase is proposed to profile the RSI performance stabilization process in detail during the early orbit stage. The initial orbital phase lasts for no less than 6 months. For the regular maintenance phase which lasts throughout the mission life of the FORMOSAT-5, tasks proposed in this plan will be carried out regularly to monitor the performance of the RSI, and to ensure the qualities of the IPS image products.

The GSD measurement will be conducted during the commissioning phase to validate the FORMOSAT-5 system requirement specification. The along track and the across track GSDs can be found by comparing the distances between known ground targets and the corresponding measurements obtained from the image acquired. Six pairs of ground targets located world-wide have been chosen for this validation task.

The MTF describes the sharpness of the outcomes from an imaging system. A 60m x 60m MTF site painted with given specific pattern has been set up in Peng-Hu County for the FORMOSAT-5 MTF characterization work. Figure 3 shows the picture taken from this MTF site.

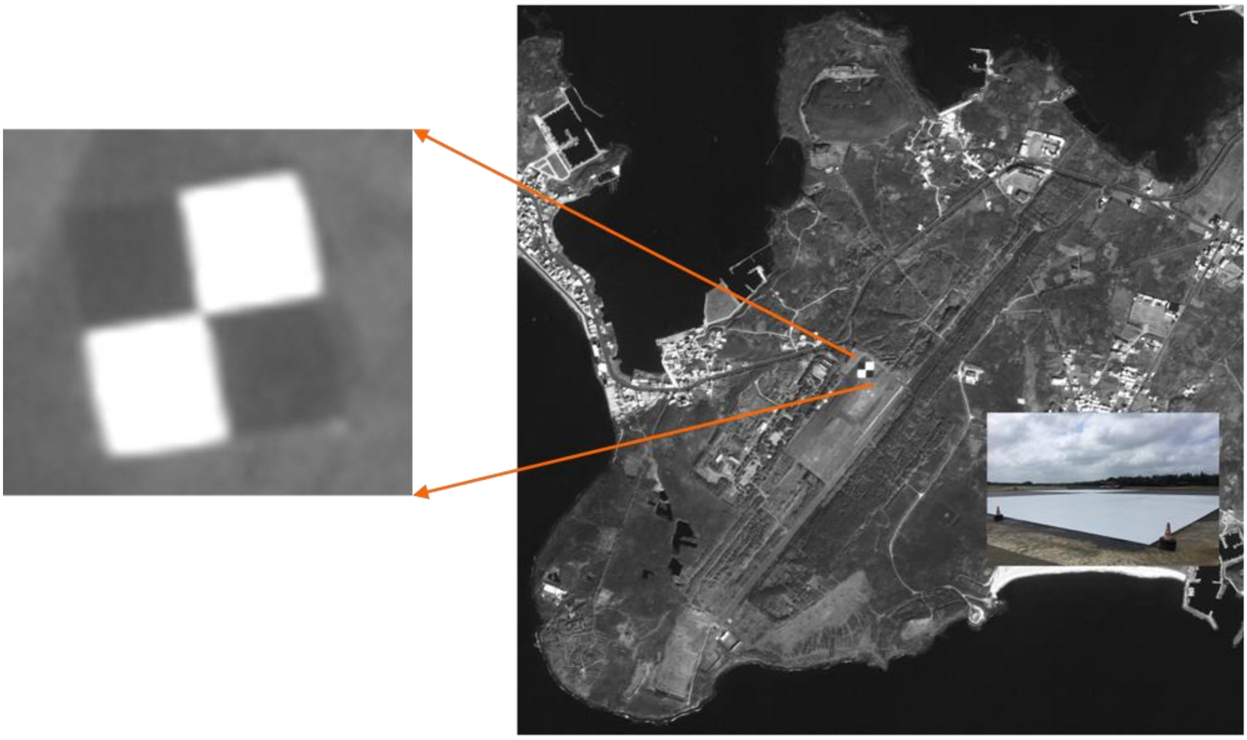

Figure 3. The MTF Site Located in Peng-Hu County

With the image taken over this site, the 2-D Knife Edge Function (KEF) is extracted, the Point Spread Function (PSF) is derived, followed by a Fourier transform, the Modulation Transfer Function value (MTF value) at the Nyquist frequency is calculated with an adjustment needed to compensate the viewing angle effects. According to the in-orbit calibration plan, the MTF site will be maintained periodically to support the MTF characterization activities throughout the mission life of the FORMOSAT-5.

The time-varying behavior of the SNR implies the variation of the RSI performance. Without a featureless target, estimating the SNR based solely on the images acquired is impractical. To overcome the restriction imposed on nature images, images acquired over desert areas are used. An image is divided into patches with reasonable size. Save some exceptions, the patches obtained represent near-featureless targets. After removing those outliers, the system SNR is estimated by averaging the SNR obtained from the remaining patches. To minimize the side-effects resulted from residual ground feature variations, the pre-flight measurement is referenced to determinate the patch size. The parameters used for the SNR estimation are derived during the commissioning phase, and are applied afterward to ensure a common reference for tracking the SNR tendency.

The system radiometric parameters are employed to derive the relative and the absolute radiometric calibration coefficients. The relative coefficients containing the dark current and the relative response of each detector are utilized to equalize the detector sensitivities for the image product generation process, the absolute coefficients are referenced for end users to find the TOA (Top-Of-Atmosphere) radiance from the digital count for their applications. For that the FORMOSAT-5 is not equipped with an on-board calibrator, vacarious and cross- calibration approaches are introduced to deduce the system radiometric parameters. The LANDSAT data as well as other data sources will be utilized for the cross-calibration analyses. The clear sky moonless night images taken over the Pacific Ocean will be used to estimate the dark currents. To deduce the relative responses behavior of detectors, six sites located world-wide characterized with smooth ground features have been chosen for this operation. By taking out the averaged low-pass figures of the images taken over these areas, the relative responses could be deduced. Vacarious calibration is employed to invert the absolute coefficients as well as to validate the linearity of the CMOS detectors. A domestic site equipped with a number of radiometric measurement instruments and various atmospheric radiative transfer models has been set up to carry out the vacarious calibration for the FORMOSAT-5 program. The international cooperation for the vacarious calibration is also planned.

The system geometric parameters are employed to perform geometric correction operations in the product generation process. The data are also used to derive the geometric related auxiliary data for end users. The initial geometric parameters are set according to the pre-launch measurement data. A coarse adjustment removing possible offsets and the first-order effects will be performed during the FORMOSAT-5 commission phase. These parameters will then be fine-tuned during the initial orbital phase and updated periodically afterward to ensure the geometric quality of the image products.

The first ground image was taken by FORMOSAT-5 on Sept 7, 2017. The four MS bands were merged to one color photo as the left one in Figure 4. It is the farm area near San Francisco, USA. The Panchromatic image was shown on the right photo in Figure 4. The patterns can be used for quick estimation for system MTF. There were some “light spots” spread on the original images. It may be caused by focusing problem on the FORMOSAT-5 telescope. The image quality can be improved by the refocusing processing on ground.

Figure 4. Images taken by FORMOSAT-5 in Early Orbits

8. SUMMARY

NSPO has developed its own remote sensing satellite system from end to end, including remote sensing instrument, spacecraft, ground station operation system, and ground Image Processing System (IPS). FORMOSAT-5 is in good health and can take the images daily. The IPS consists of five subsystems, namely, the PSS, the DIS, the DMS, the DPS, and the IQS. The daily operation shows that the system performs well and can provide services for the FORMOSAT-5 remote sensing data users. Moreover, an in-orbit calibration plan has been set up to support the activities during the FORMOSAT-5 commissioning phase, and will be carried out throughout the FORMOSAT-5 mission life. According this plan, the system radiometric and geometric parameters needed for the image pre-processing will be updated periodically to ensure consistent quality of the image products.

9. REFERENCES

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