

## Innovative Design Concepts for the Low-Cost Remote Sensing Satellites

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### ABSTRACT

This paper presents some innovative design concepts for the low-cost remote sensing satellites, including: designing the special low-altitude orbit; implementing the in-flight fine refocusing to increase image quality; applying the radiation-hard FPGA (field-programmable gate array) for advanced data compression processors; using the time delay integration (TDI) sensor concept for reducing the camera aperture size. By implementing the calculated perturbation, the selected low-altitude orbit is capable to achieve daily revisit of Taiwan area and near-global coverage. By using commercial FPGA and technologies such as TDI and the refocusing, the smaller telescope aperture and the smaller satellite and thus cheaper cost can be met. The key advantages associated with these design concepts are introduced. The simulations of the mission performance for different approaches are demonstrated. The limitations of those concepts have also been discussed.

### I. Introduction

THE concept of low cost doesn't mean the sacrifice of performance. It shall mean the more efficient ways of system design. Therefore, the innovative design concepts shall be seriously investigated. Especially, one major study objective is to reduce the acquisition difficulties, such as the export license control of the vendor's country.

National Space Organization (NSPO), Taiwan, successfully launched the two-meter resolution remote sensing satellite, Formosat-2, in year 2004. Formosat-2 has the unique feature of mission capability of daily revisit and daily repeat. The satellite can continuously image the same target with the same viewing angle condition for consecutive days, excellent for monitoring changes of intended target. Figure 5, as an example, shows the successive three images of Levee breaks, USA, from Formosat-2 right after the Hurricane Katrina



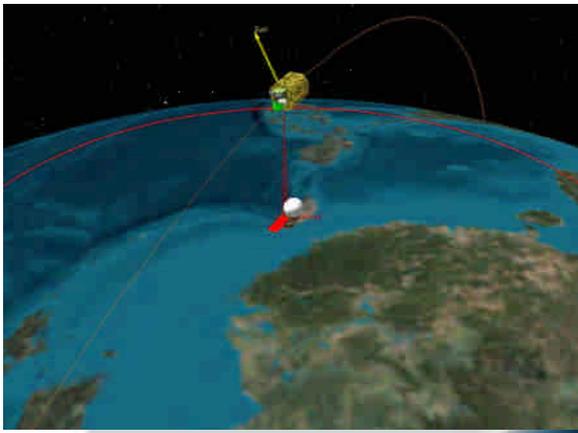
**Figure 1. Continuously Daily Monitoring by Formosat-2 on Levee Break, USA**

in year 2005. However, its orbit altitude of 891 km is relatively too high to be inserted by small launch vehicles, becoming a cost issue. NSPO is developing the next generation remote sensing satellite. The mission orbit is re-selected for the consideration of compliance of small vehicles. The satellite platform has the objectives of achieving promising system performance with the most cost efficient ways. It is motivated, during the system conceptual design phase, to explore design concepts to achieve these objectives. Many concepts have been investigated with the expected performance simulated. Figure 2 shows the conceptual satellite in-flight.

This paper presents some innovative design concepts, including: designing the special low-altitude mission orbit; applying the radiation-hard FPGA (field-programmable gate array) for advanced data compression processors; using the time delay integration (TDI) sensor concept for reducing the camera aperture size; implementing the in-flight fine refocusing to increase image quality. By implementing the calculated perturbation, the selected orbit is capable to achieve daily revisit of Taiwan and near-global coverage. The smaller aperture, the smaller satellite and cheaper cost can be met. The key advantages associated with these design concepts are introduced. The simulations of the mission performance for different approaches are demonstrated. The limitations of those concepts have also been discussed.

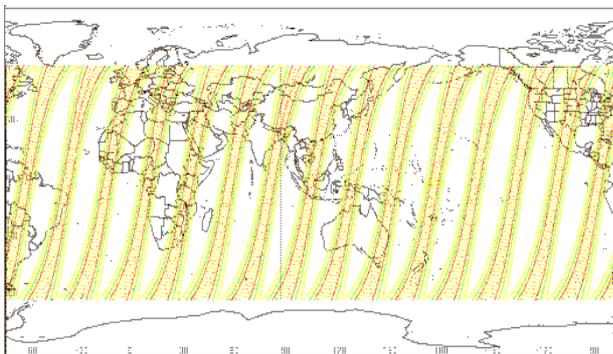
## II. Orbit Design -- Daily Revisit Orbit with Perturbation

The first and the most important study topic of the mission analysis for a remote sensing satellite program is the selection of mission orbit. The orbit selected will have impacts on the program budget, the mission performance and mission operation scenario, required technologies for development of the satellite, the space environment, and the satellite lifetime. In order to achieve the low cost aspect, the budget for the satellite design, which includes the spacecraft bus and the remote sensing camera, the launch service are of concerns. It is assumed that the cold gas propulsion subsystem is used for the satellite orbit control. The cold gas propulsion subsystem is low cost and easy of



**Figure 2. Simulation of the Satellite in-flight**

availability. The consideration of more small launchers to be feasible is also demanding for lowering the program cost. Among the candidate launchers, Falcon-1 has the least capability; however, it is cost effective.



**Figure 3. The Global Coverage of 561km Sun Synchronous Orbit (50%)**

The sun synchronous orbit is selected, thus the topic is to decide the altitude of the sun synchronous orbit. The criteria of the orbit selection for remote sensing satellites will be the following points:

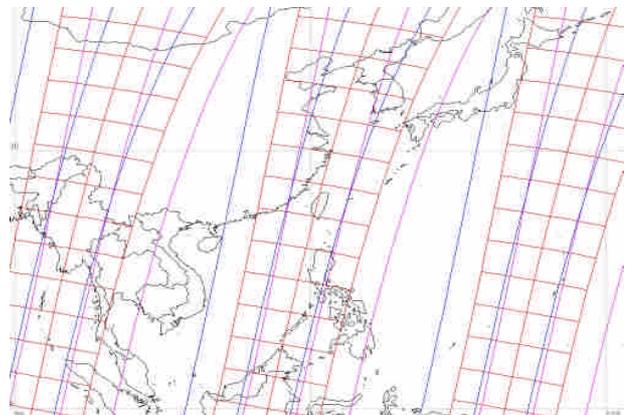
1. Short revisit cycle
2. Large global coverage area
3. Minimum required orbit maintenance efforts
4. More available launch vehicles
5. Remote sensing camera technology and budget constraints

The larger global coverage can stand for higher value of needs. The satellite with short revisit cycle can provide timely image and monitoring operation, which are especially needed for the disaster assessment. The satellite flying at the lower orbit, the camera aperture size and the focal length can be smaller to achieve the same resolution requirement, thus implying less budget and simpler technologies.

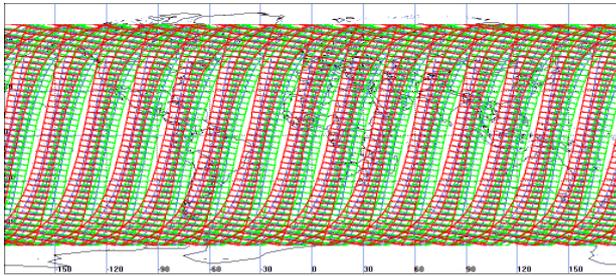
Table 1 shows several candidates of the orbit. Considering the revisit cycle, the altitude of 561km is the best, of which the satellite will revolute the earth exactly fifteen times a day. This low altitude is good for launch budget and the small camera. However, as shown in Figure 3, this orbit can not provide global coverage even for the Field-of-Regard of 45 degrees. The coverage is 40% earth.

Table 1 Characteristics of Sun Sync Orbits of Different Altitude

Altitude	Revolutions per day	Repeat Cycle of Ground Track
561 km	15	Daily
666 km	14 <sup>2</sup> / <sub>3</sub>	Every 3 days
720 km	14 <sup>1</sup> / <sub>2</sub>	Every 2 days
891 km	14	Daily



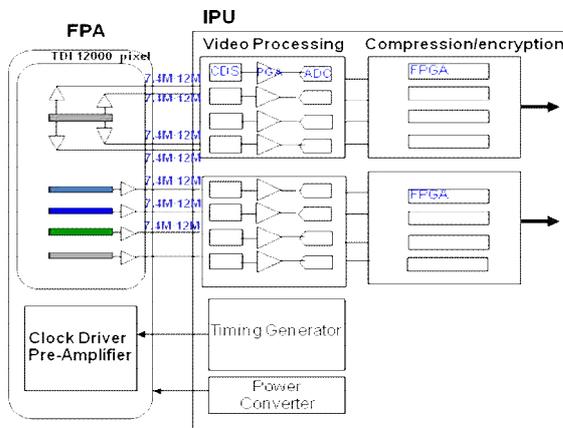
**Figure 4. Perturbation of the 561 km Orbit**



**Figure 5. Global Coverage of 561km with Perturbation (WP) Orbit**

The way to have a larger global coverage and the small revisit time is by adding a perturbation to the orbit. If the satellite is inserted in a slight higher orbit than 561km, the satellite ground track will drift westward day by day. Moreover, with the larger perturbation, the drift rate will be faster. On the other hand, if the satellite is inserted in a slight lower orbit than 561km, the satellite ground track will drift eastward day by day. One merit thing is that we can take some advantage of orbit decay by drag, especially during the solar maximum period round year 2011. Referred to Figure 4, while inserting into the slight higher orbit, the satellite ground track drift westward. As orbit decay, it touch the west limit, then drift eastward till the east limit.

During the perturbation, the satellite can cover more area. Figure 4 shows the coverage of the perturbation 561km orbit. As we put Taiwan in the middle, Taiwan area can be also visited daily. The disadvantage is the looking angle and thus the resolution will be changed during this perturbation cycle.



**Figure 6. Data Channel Architecture**

### III. FPGA Based High Speed Data Compression Processor

The Image Processing Unit (IPU) of the Remote Sensing Instrument has the functions: to acquire the data from CCD sensors, data compression, data encryption, and packetization. Among those functions, the data compression requires the most computing power. The function block diagram of the IPU is shown in Figure 6. The IPU has to provide sufficient computing power, mission specific radiation tolerance, low consumption of power, volume and mass, and adequate reliability at moderate unit costs. For high-resolution, high-speed imaging instruments, especially acquisition sequence control and image processing impose strong real-time requirements on the system design to handle the high sensor data rates in the order of up to some hundred Mbits per second for advanced sensors.

The key part of the IPU is the high speed data compression processor. The processor PC board will be developed in a parallel effort with the processor. The FPGA ICs will be directly plug in at the late stage. Considering the computation power, the panchromatic CCD output is the driver. There will be four channels for one CCD IC. The data channel requirement is summarized in Table 2.

Table 2 Data Channel Throughput Requirement

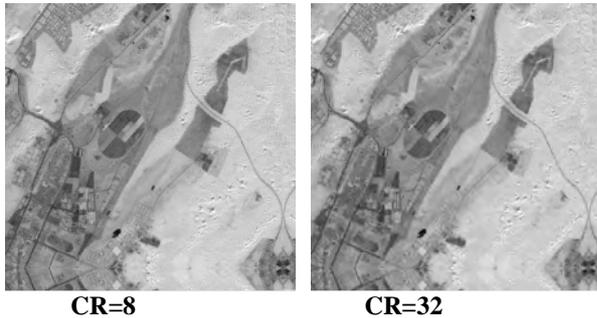
Calculation item	Value
Line rate	3300 lines per second
Pixel per channel	3000 pixels
Bits per pixel	12 bits
Bits per second	~ 120Mbits /sec

The throughput is close to 120 Mbps. It is assumed that the computation cycle is the time for 64 lines, which is 20 msec. The development of such as high speed processor is as follows:

- Step 1: Make decision of the compression algorithm
- Step 2: Development of C-code program
- Step 3: Translate C-code to FPGA-code
- Step 4: Port the FPGA code and simulation
- Step 5: Optimize the efficient of the FPGA code
- Step 6: Port the code to Hard-hard IC

There three different implementations of the high-speed data compression processors:

1. Digital Signal Processor (DSP)
2. Application-Specific Integrated Circuits (ASIC)
3. Field Programmable Gate Arrays (FPGA)



**Figure 7. CCSDS Image Data Compression**

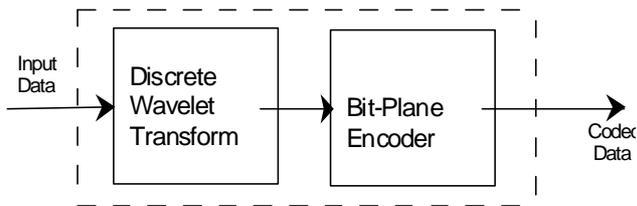
The FPGA based approach is considered for the following reasons:

1. The rad-hard ASIC is very expensive and export license controlled.
2. With FPGA, the most advanced algorithm can be considered.
3. The FPGA is an open system, therefore, the performance can improved with better FPGA IC available

There three image data compression algorithms have been considered for studies:

1. JPEG
2. JPEG 2000
3. CCSDS Recommended Standard

The JPEG2000 and CCSDS Recommended Standard are both based on the Discrete Wavelet Transform (DWT) and Bit-Plane Encoder (BPE). Figure 7 shows the performance of the CCSDS image data compression.



The CCSDS Image Data Compression is considered for the following reasons:

1. Highly advanced wavelet-tree-based algorithm, tailored to space imaging requirements
2. Performance & image quality equal to JPEG 2000
3. Lower implementation complexity and budgets
4. Optimized to line by line input data (pushbroom data)
5. No image buffer required in front of the DWT
6. The Integer arithmetic-based 9-7 DWT provides lossless compression performance

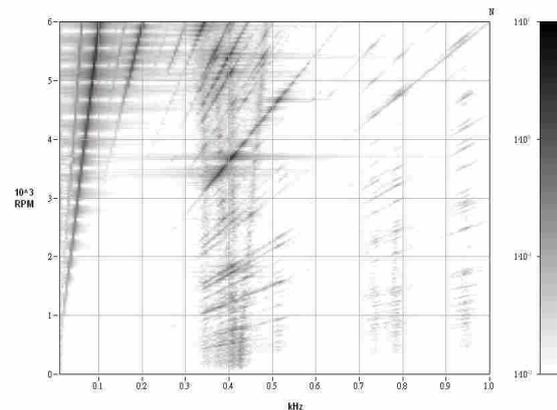
7. The Bit-plane Encoding (BPE) process provides lossy compression at user defined constant data rates or image quality

The availability of the radiation tolerant Virtex SRAM-based FPGA by Xilinx Inc., which provides up to one million configurable gates on a single chip, provides a good opportunity to develop the high-speed data compression processor. We consider the lower end product of Virtex-II 3000 IC (XQR2V3000) for cost reason. The IC has the following characteristics:

- BRAM: 1728K bits
- Configurable bits: 10248K
- On-chip DLL system clock > 150 MHz
- Max. IO: 512
- Radiation tolerant: 200K dose
- High energy particle: SEL >200 MeV cm<sup>2</sup>/mg

#### IV. Time Delay Integration (TDI)

The TDI imager is a current trend for future small remote sensing satellites. One major advantage of the TDI imager is that it can operate at extremely low light levels, thus relaxing the requirement for the larger size of aperture for camera. Signal level increases as the number of TDI stages increases. Considering jitter effect on TDI images, when TDI stages increases, the image quality like MTF decreases in some range of trembling frequency. Different stages of TDI image with different trembling frequencies were simulated. Analyses on the image quality of simulated images can help finding out the jitter requirement for satellite control design, also finding out the system dynamic



**Figure 8. Dynamics of the reaction wheels**

Modulation Transfer Function (MTF) in optimum TDI stages. MTF is a measure of spatial resolution. MTF is the normalized spatial frequency response of an

imaging system which is defined as the normalized magnitude of the fast Fourier transform of the point spread function (PSF).

The major disturbance to the satellite platform is from the reaction wheels. Figure 8 shows the measurement of the disturbance of a typically selected reaction wheel (the horizontal axis is the disturbance frequency, the vertical axis is the wheel speed, and the gray scale of the plot is the disturbance magnitude). The disturbance has two major modes of 100Hz and 330 Hz. The results of the jitter effect on the TDI performance for different number of TDI steps has been given in Figure 9.

### V. Refocusing

The development of the remote sensing instrument faces a difficult problem to achieve the good alignment of telescope. The tiny error of some microns (one millionth a meter) of the alignment will destroy the

camera performance. Usually the error in the focal length shall be less than 20 microns totally from all effects. Moreover, the alignment of the telescope will be perturbed by effects, such as the vibration during the launch phase, the release of the gravity in space, and the vacuum effect on the composite material of the telescope structure. Those effects are referred to micro setting. The way to overcome the micro setting is by refocusing. The refocusing is the capability of the satellite in-flight for very fine tuning of the focal length by ground commanding. The refocusing mechanism shall be ground controllable.

The refocusing approaches include the three major categories:

- 1) Thermal temperature actuation
- 2) Step motors
- 3) Smart materials

Figure 10 shows a conceptual design of the telescope structure, based on the Cassegrain type optics.

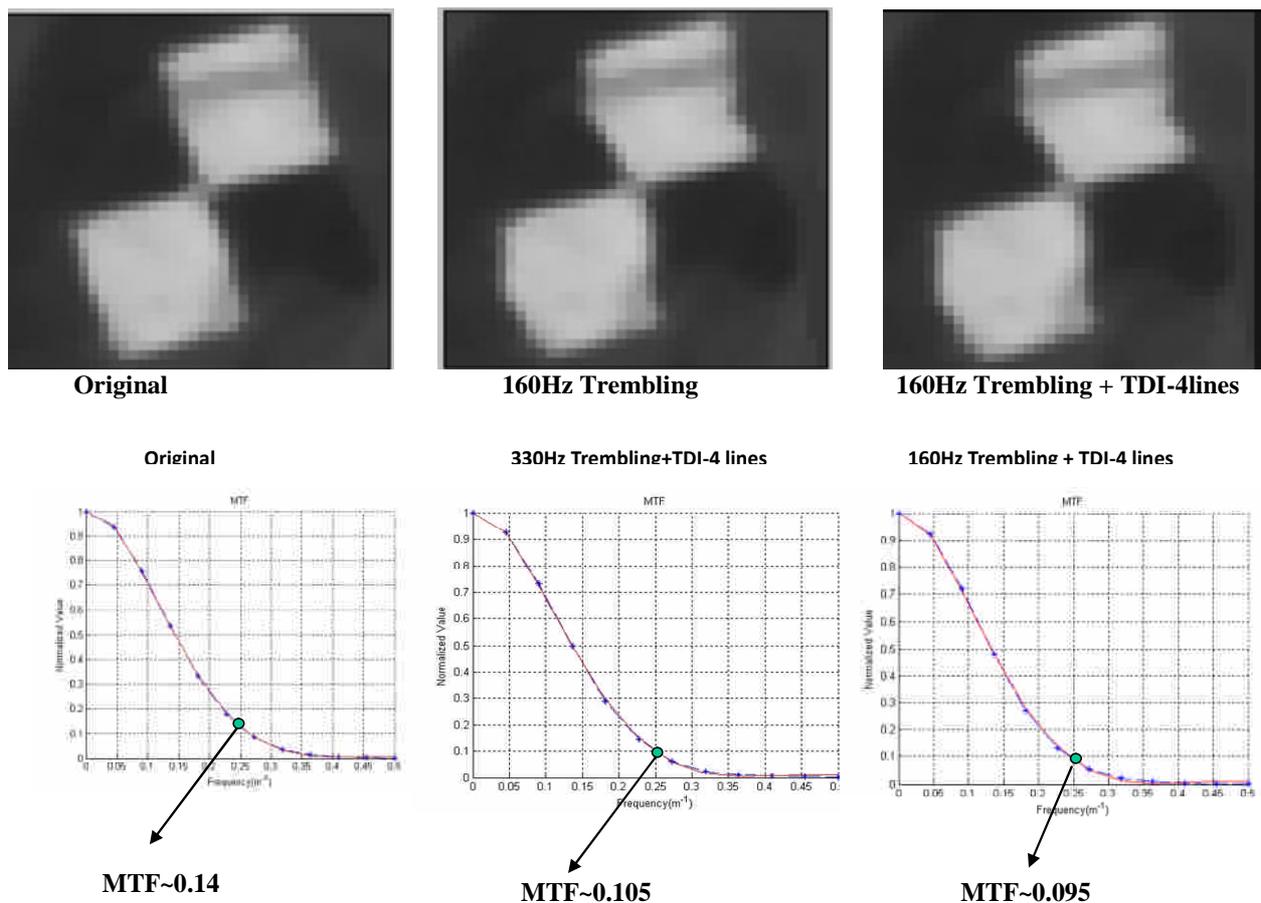
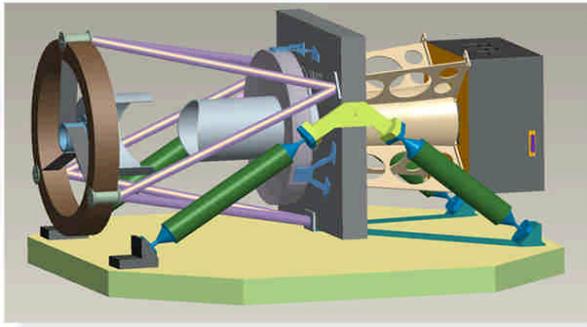


Figure 9. Simulation of the Jitter Effect on TDI



### Structure Design w/o Cover

**Figure 10. The telescope structure of the remote sensing instrument**

With our studies on the above three approaches of refocusing on the telescope, the thermal refocusing is the most simple to implement; however it has the drawbacks, such as the temperature is difficult to control for high resolution and high accuracy, and it takes long time for the thermal settling so it is not possible to make try-and-error adjusting operations of refocusing during a ground-contact pass. The step motors has the difficulties of manufacturing for qualification of the launch environment and the space environment. The smart material approach is preferred. We have done the design and applied for pattern for the refocusing by smart material.

## VI. Conclusion

The concept of low cost doesn't mean the sacrifice of performance. It shall mean the more efficient ways of system design. Especially, one major study objective is to reduce the acquisition difficulties, such as the export license control of the vendors' countries. The innovative design concepts shall be seriously investigated in our system conceptual design. Herein we have present some works of our system engineering design studies, with our experience and lessons learned. We appreciate and think it will be very fruitful to take the opportunity to exchange experience with all experts.

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