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Invited Paper

Orbital resonances of Taiwan's FORMOSAT-2 remote sensing satellite

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A B S T R A C T

Unlike a typical remote sensing satellite that has a global coverage and non-integral orbital revolutions per day, Taiwan's FORMOSAT-2 (FS-2) satellite has a non-global coverage due to the mission requirements of one-day repeat cycle and daily visit around Taiwan. These orbital characteristics result in an integer number of revolutions a day and orbital resonances caused by certain components of the Earth's gravity field. Orbital flight data indicated amplified variations in the amplitudes of FS-2's Keplerian elements. We use twelve years of orbital observations and maneuver data to analyze the cause of the resonances and explain the differences between the simulated (at the pre-launch stage) and real orbits of FS-2. The differences are quantified using orbital perturbation theories that describe secular and long-period orbital evolutions caused by resonances. The resonance-induced orbital rising rate of FS-2 reaches +1.425 m/day, due to the combined (modeled) effect of resonances and atmospheric drags (the relative modeling errors < 10%). The concave shapes in the time-evolution of the longitude of descending node (LonDN) coincide with the positive rates of daily semi-major axis (SMA) change, also caused by resonances. The non-zonal geopotential coefficients causing the resonance effects contributed up to 45% of FS-2's inclination decline. Our retrospective analysis of FS-2's resonant orbit can provide lessons for a remote sensing mission similar to FS-2, especially in the early mission design and planning phase.

1. Introduction

FORMOSAT-2 (FS-2) is a remote sensing satellite of Taiwan. It is the second space mission of Taiwan and was decommissioned in late June 2016 due to the permanent double failures of the reaction wheels. Since its launch on 21 May 2004, FS-2 had been operating on orbit for more than twelve years, collecting enormous amounts of satellite images and flight data that can be explored in the fields of remote sensing and orbit science.

Located in the East-Asia subtropical area, Taiwan is prone to natural hazards such as earthquakes, hurricanes, and floods that can cause great property damages or loss of life. Early warning and post-disaster data from sensors on remote sensing satellites such as FS-2 are crucial to hazard mitigations in Taiwan. To satisfy this particular need, FS-2 was designed to pass through Taiwan with a shortest possible repeat period to provide day-to-day satellite images. This mission requirement results in unique ground tracks of FS-2, compared to other remote sensing satellites such as the SPOT or Landsat series of satellites.

In addition to an imaging camera, FS-2 was also equipped with a scientific payload for space research. In order to meet both needs of hazard mitigation and space research, FS-2's orbit was so designed that its data can fulfill two objectives. The primary one was to acquire daily images over Taiwan and other parts of the world during day times with its remote sensing instrument (RSI). The second objective was to observe global transient luminous events (TLEs) during night times using an instrument called imager of sprites on the upper atmospheric lightning (ISUAL). These two payloads (i.e., instruments) were operated exclusive to each other. Fig. 1 (a) shows the multi-tasking capability of FS-2 for collecting remote sensing images in one pass with different combinations of pitch/roll maneuvers. The blue-shaded area is the imaging area with $\pm 45°$ of roll maneuvers. In addition, Fig. 1 (b) shows the nominal descending ground track (the long line in the center) of FS-2 passing over Taiwan in day time. In this case, the entire Taiwan can be imaged using different combinations of pitch/roll maneuvers in one orbit pass and 4 strips [1-5].

Since the scientific payload was operated in eclipse time without special orbit requirements, the primary consideration on FS-2's orbit design was to satisfy the need of RSI operations. To achieve the unique remote sensing mission characteristic, the orbit of FS-2 was so designed that it was a near-polar, circular, sun-synchronous, low-Earth-orbiting (LEO) satellite. Again, the repeat cycle was one day, and the revisited ground tracks were over Taiwan daily at the same time of a day. It is

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known that a lower orbit for FS-2 could benefit RSI's spatial resolution and a higher orbit could lead to a reduced atmospheric drag to prolong its life time. A trade-off study on FS-2's orbital heights had been conducted and it was decided that the final altitude should be slightly higher than those of typical remote sensing satellites such as SPOT (822 km) and Landsat (705 km), so that the atmospheric drags on FS-2 can be reduced without sacrificing spatial resolution [6]. In summary, the mission orbit of FS-2 was a phased sun-synchronous orbit at an altitude of 888 km and an inclination of 99.133°. As such, FS-2 encircled the Earth 14 times a day along the same ground tracks.

Because of the various perturbations on orbit, the orbit of FS-2 was maintained and controlled periodically to ensure the repetition of ground track and to acquire the favorable sunlight condition for imaging. Accordingly, there were two maintenance requirements in order for FS-2 to fly over Taiwan in an adequate manner: the first one was to maintain the drift of the ground track to be within a ± 200 km window with respect to the reference ground track near Taiwan, and the second one was to keep the local time of descending node (LTDN) to be within a ± 15 min window from the nominal local mean solar time of 09h40. To carry out the orbit maintenances (OMs) efficiently and to save onboard propellant, a thorough analysis on FS-2's orbit perturbations and tracking strategy was performed in the feasibility study phase before FS-2's launch [7-8].

In comparison to other remote sensing satellites that have non-integer orbital revolutions per day, the 14:1 commensurability of FS-2 is expected to create orbital resonances that are well documented in the literature [9-13]. Unfortunately, the mission team of FS-2 was either unaware of or ignored the impact of such resonance effects in the early mission design and planning phase. As a result, FS-2's 12 years of orbital data have shown many conflicts between the predicted (pre-launch) and the real flight orbits (see Section 2). Such conflicts have been noticed but not analyzed. Therefore, the objective of this paper is twofold. First, we will compare FS-2's predicted orbits with those from the real flight data and show the conflicts. Second, we will determine the contribution of FS-2's orbital resonances to the conflicts using the analytical orbit theories [10, 14], along with theories that predict the changing rates of certain orbital parameters of FS-2 caused by the Sun and atmospheres.

2. Discrepancies between FS-2's predicted and real orbits

2.1. predicted decreasing vs. real increasing semi-major axis (SMA)

In this section, we will show the differences in semi-major axis (SMA), the longitude of descending node (LonDN) and inclination between the results from FS-2's prelaunch simulations and real flight data. From Section 3 onward, we will explain the differences in terms of orbit dynamics and in particular resonances induced by the Earth's gravity field. The pre-launch simulations were to predict the declines of mean SMA due to atmospheric drags. The atmospheric density model plays a key role in the simulation results. In this paper, we cited the predicted results, which used the MSIS-86 density model for the simulations [7]. The density for the simulations in a year was the mean value over the year. Atmospheric density variations are related to the solar flux (F10.7 cm), the planetary geomagnetic index (Ap), and the exospheric temperature. The solar flux in Table 1 is in solar flux unit (s.f.u.). The predicted solar activities were based on the information from the Marshall Space Flight Center, NASA. Table 1 shows the atmospheric parameters for the predictions and the resulting rates of SMA change over 2004–2007 [7].

Using the rates of SMA change in Table 1, we show the predicted SMAs in Fig. 2 (green line) before FS-2's launch in the first 3.5 years. Fig. 2 also shows the SMAs from the flight data (blue line) over FS-2's entire period. In the first 3.5 years, the predicted mean SMAs had decayed by 505.2 m, from 7266.5665 to 7266.0613 km. The average decaying rate from the predictions was about 0.395 m/day. In contrast, the SMAs from the flight data did not decrease monotonically. Most of the time, the real SMAs increased steadily. There were SMA oscillations

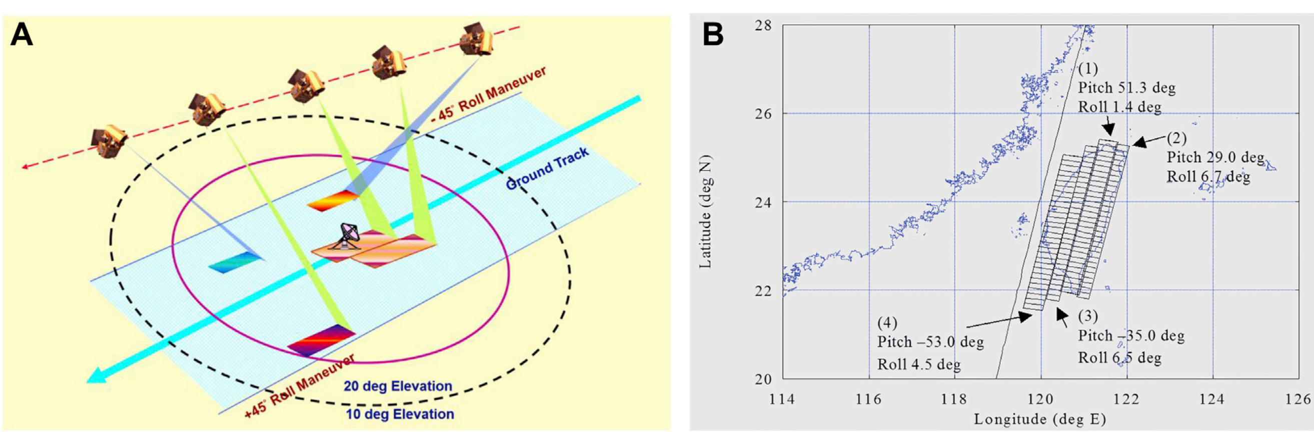

Fig. 1. (a) The multi-tasking capability of FS-2 to carry out the remote sensing images in one pass with different combinations of pitch/roll maneuvers, the blue-shaded area is the imaging boundary with ± 45° of roll maneuvers. An elevation is the vertical angle of the antenna beam measured at the earth station from ground to satellite position. The circles of 10°- and 20°- elevations show the effective communication regions of the S-band and X-band antennae, respectively. (b) RSI imaging areas around Taiwan in sunlight time (courtesy of NSPO, Taiwan). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Atmospheric parameters for the pre-launch simulations and the resulting mean SMA decreasing rates of FS-2

Parameter	2004	2005	2006	2007
Average Ap (2 nT)	23	25	20	18
Average F10.7 (s.f.u.)	150	125	100	85
Average atmospheric density (kg/m^3)	8.00E-15	5.19E-15	3.32E-15	2.59E-15
Average SMA rate (m/day)	−0.706	−0.456	−0.292	−0.228