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Ten-year transient luminous events and Earth observations of FORMOSAT-2 ☆

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The purpose of this paper is to summarize the enormous contributions of FS2 (FORMOSAT-2 or Formosa satellite 2) in both Earth and transient luminous events (TLEs) observations in 10 years. As a small satellite operated for 10 years (20 May 2004 to 20 May 2014) in orbit, FS2 keeps its two unique characteristics: (1) to orbit 14 revolutions around the Earth per day with daily revisit capability, and (2) to provide the capabilities of Earth observation in sunlight time and TLEs observation in eclipsed time every day. It carries two payloads: the remote sensing instrument (RSI) for Earth imaging in satellite's day time and the imager of sprites and upper atmospheric lightning instrument (ISUAL) for scientific observations in satellite's night time, respectively. Daily revisit capability provides changes of events on Earth in either short time (several days) or long term (several years). Examples include: Indian Ocean earthquake and tsunami (December 2004), disintegration of Wilkins Ice Shelf in Antarctica region (2006–2014, long term), Sichuan earthquake (May 2008), Tohoku earthquake and tsunami (March 2011), polar regions (2006–2014, long term), etc. In the TLEs observation, ISUAL had recorded more than 35,000 events in 10 years with 73.93% elves, 6.54% red sprites, 5.81% halos, 13.42% blue jets and 0.30% gigantic jets. Major contributions of FS2 in this specific scientific area are presented. In particular, current and future research topics on TLEs are discussed. Also, major contributions of FS2's RSI to the United Nations Institute for Training and Research (UNITAR) Operational Satellite Applications Programme (UNOSAT) and Group of Earth Observation System of Systems (GEOSS) are summarized. This paper also addresses briefly the health status of FS2 after working 10 years in orbit.

Abbreviations: AEP, associated electronics package; AIP-2, Phase 2 Architecture Implementation Pilot; AP, array photometers; CCD, charged-couple device; CERN, European Organization of High Energy Physics; +CG, positive cloud to ground lightning; −CG, negative cloud to ground lightning; COSMIC, constellation observing system for meteorology, ionosphere and climate; DMWG, Disaster Management Working Group; DOTCam, dual-band optical transient camera; DPU, data processing unit; ELF, extremely low frequency; ELVES, (elves) emission of light and VLF due to EMP sources; EMP, electromagnetic pulse; FS2, FORMOSAT-2, Formosa satellite 2; GEOSS, Group of Earth Observation System of Systems; GIS, geospatial information system; GOX, GPS radio occultation experiment; GPS, global positioning system; ISUAL, imager of sprites and upper atmospheric lightening; KM, Kinmen; MET, mission elapsed time; MS, multi-spectral; NCKU, National Cheng Kung University; NSPO, National Space Organization; PAN, panchromatic; PH, Penghu; RISESAT, rapid international scientific experiment satellite (Hodoyoshi-2); RSI, remote sensing instrument; SDDC, Science Data Distribution Center; SOH, state-of-health; SP, spectrophotometer; SSR, solid-state recorder; TLE, transient luminous event; ULF, ultra low frequency; UN, United Nations; UNITAR, United Nations Institute for Training and Research; UNESCO, United Nations Educational, Scientific and Cultural Organization; UNOPS, UN Office for Project Services; UNOSAT, UNITAR Operational Satellite Applications Programme; UT, universal time; VLF, very low frequency; WWLLN, World Wide Lightning Location Network

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1. Introduction

FS2 (FORMOSAT-2 or Formosa satellite 2), the first remote sensing satellite of Taiwan, has been working on orbit for 10 years since its launch on 20 May 2004 [1–11]. Two payloads, one scientific imager of sprites and upper atmospheric lightning instrument (ISUAL) and one remote sensing instrument (RSI), operate in elapsed and sunlight times alternatively. Therefore, FS2 uses its onboard as well as ground resources efficiently. Other system engineering characteristics include the circular Sun synchronous orbit at 891 km altitude, orbiting around the Earth 14 revolutions per day with daily revisit capability, and 8 min duty cycle per orbit. Local time at the descending node (LTDN) was specified at 9 a.m. during the mission design. There are four parts in the ISUAL system: a charged-couple device (CCD) imager, a six-channel spectrophotometer (SP), two array photometers (AP), and a central control unit called associated electronics package (AEP). The RSI consists of one panchromatic (PAN) band with 2 m resolution and 4 multi-spectral (MS) bands with 8 m resolution [1–11].

The discharge from thundercloud to the ionosphere forms a natural phenomenon of upward lightning called the transient luminous event (TLE) in the upper atmospheric layer [12–13]. It has been observed and recorded from ground, aircraft, and space shuttle [14–16]. The ISUAL onboard FS2 had observed the phenomenon globally from space for 10 years since 4 July 2004. There is no atmospheric attenuation so that the properties of upward lightning can be measured more definitely. Furthermore, some unobserved or unexpected features have been discovered. Based on the observations before and after ISUAL and according to its appearances, scientists used to classify it into five categories: elves, red sprite, halo, blue jet and gigantic jet. Up to 31 May 2014, a total of 35,165 TLEs had been observed and recorded by ISUAL. Major contributions of FS2 in this specific scientific area are presented in Section 2 with global distribution and current researches on TLEs discussed [10,17].

Examples of major observations of RSI include Indian Ocean earthquake and tsunami (December 2004), disintegration of Wilkins Ice Shelf in Antarctica region (2006–2014), Sichuan earthquake (May 2008), Tohoku earthquake and tsunami (March 2011), polar regions (2006–2014, long term), etc. Major contributions of FS2 in Earth observation are summarized and presented in Section 3, especially the long term observation results with evidences to show pronounced changes on Earth in the 10 years [4–9].

In order to meet both mission objectives of the two payloads simultaneously, the mission operations plan of FS2 is more complicated. To maximize the usage of the on-board resources, the satellite attitude maneuver activities and power charge/discharge cycles have been scheduled cautiously in every detail. Under such fully engaged operations scenario and with a design life of 5 years, it is inevitable that the satellite encountered many anomalies, either permanent or temporary. In particular, one attitude gyro (totally four) and one reaction wheel (totally four) have been failed. Many iterations and trade-offs had been made to minimize the effect of the anomalies. It still can provide about 80% of the designed functions and capabilities. The state-of-health (SOH) and future prospects of FS2 after working 10 years in orbit is addressed briefly in Section 4 [4,11]. Finally Section 5 gives the conclusions.

2. ISUAL Observations in ten years

2.1. ISUAL instruments

The ISUAL system has a data processing unit (DPU) and a solid-state recorder (SSR). Its interfaces with FS2 spacecraft include SOH, command, power and data transfer. One or two channels of SP are used to provide trigger signal for imager and other photometers. The DPU executes onboard processing based on the priority of observation missions determined from ground. The number of triggers is counted to establish the global distribution of TLEs statistically. Since the brightness of TLEs is very different, a filter is employed for discrimination [10,17].

The ISUAL is mounted on the payload interface platform in a direction for cross-track limb-view. To avoid the possibility of direct sun-view and to have better night-time observation, a right-hand side-direction along the orbit is selected. The CCD camera of sprite imager takes 100 frames per second with 512×80 pixels resolution and $20^\circ \times 3.125^\circ$ field of view. Therefore, the viewing area is 1217 km wide and 190.2 km high. The observation altitude extends from ground to mesosphere and ionosphere. Three modes have been designed for ISUAL operation: continuous, burst, and aurora and airglow. In continuous mode, imager, AP and SP operate continuously at 100 Hz, 20 kHz and 10 kHz, respectively. The burst mode is the same as continuous mode except that the imager operates at 650 Hz. Finally in aurora and airglow modes, the imager and SP operate at 1 Hz while AP operates at 200 Hz [10,17].

There were four purposes defined for the scientific mission of ISUAL: (1) to obtain the global distribution of TLEs, (2) to study the spatial-temporal dynamics of TLEs, (3) to explore the UV band content of TLEs, and (4) to investigate the degree of ionization in the TLEs emission regions.

2.2. Statistics of observations in ten years

After the launch of FS2 on 20 May 2004 and the completion of instrument check on-orbit, ISUAL caught its first image on 4 July 2004. Tables 1 and 2 show the annual observation time and number of TLEs observed by ISUAL from 4 July 2004 to 31 May 2014, respectively. A total of 35,165 events have been recorded in 12,943.32 h. On average, there are only 2.72 events per hour. Global distribution of the 35,165 TLEs is shown in Fig. 1 [17]. Since there are unobserved gap between each two orbits due to the orbital characteristics of FS2, the globalization extension of TLEs based on FS2's observation had been studied in [10,18]. It is seen from Table 1 that there are no enormous changes in the percentages of elves, sprites and gigantic jets from 2004–2014. Rather significant percentage variations found in halos and blue jets with the former decreased from about 9% to near 4% and the latter increased from near 6% to about 17%, respectively.