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Global survey of upper atmospheric transient luminous events on the ROCSAT-2 satellite

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Abstract

Upper atmospheric transient luminous events (TLEs; sprite, elves, blue jet, etc.) are recently discovered thunderstorm-induced phenomena. Imager of sprites/upper atmospheric lightning (ISUAL) is a scientific payload on the Taiwan's ROCSAT-2 satellite that aims primarily to provide crucial observation data on these TLEs from space. The ISUAL payload includes an intensified CCD imager, a six-channel spectrophotometer, and two array photometers. All the instruments are mounted on a common platform and boresighted in the same direction. The imager is equipped with six selectable filters, which have bandpasses covering the visible spectrum. The spectrophotometer contains six photometers, and each photometer is fitted with a special bandpass filter ranging from ultraviolet to red regions. The two array photometers are identical in every aspect, except one is fitted with a blue band filter and another one is equipped with a red band filter. With this set of well-chosen instrument, this project seeks to determine the location and timing of upper atmospheric transient events above thunderclouds, to investigate their spatial, temporal and spectral properties, to obtain a global survey of them, and to perform a global study of aurora and airglow.

ISUAL project is an international collaboration supported by the National Space Program Office in Taiwan, with additional contributions from the National Cheng Kung University, Taiwan, the Space Science Laboratory of the University of California at Berkeley, and Tohoku University, Japan. ROCSAT-2, the platform of ISUAL, is scheduled to launch around October 2003.

Keywords: Transient luminous events (TLEs); ISUAL payload; ROCSAT-2; Satelitte observation

1. Introduction

Upward lightning discharges into clear air have been reported by pilots world wide for over a century (e.g., Everett, 1903; Boys, 1926; Vaughan and Vonnegut, 1989). However, scientific investigations of these phenomena did not begin until early 1990s. The first science recording of upward electrical discharge events was on the night of 22 September 1989 (Franz et al., 1990). Since then, night-time lightning-induced transient luminous events have been recorded by low-light-level television cameras on space shuttles (Boeck et al., 1995), on aircrafts (Sentman et al., 1995; Wescott et al., 1995), and on the ground (Rairden and Mende, 1995; Lyons, 1996; Winckler et al., 1996; Stanley et al., 1999; Gerken et al., 2000; Barrington-Leigh et al., 2001; Su et al., 2002). Recently, there are some observations indicate that other new types of TLEs may exist (Lyons et al., 2001; Pasko et al., 2002). However, so far, no satellite observations of these phenomena have ever been performed.

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Based on ground, aircraft, and space shuttle observations in the past 10 years, transient luminous events above thundercloud are found to fall into at least three categories including sprites (Sentman et al., 1995), blue jets (Wescott et al., 1995), and elves (Fukunishi et al., 1996). A brief introduction to the characteristics of these transient luminous events is given below.

1.1. Sprites

Sprites are luminous discharges that occur between cloud and ionosphere. Sentman et al. (1995) described the sprites as luminous structures with a reddish main body that typically spans the altitude range 50–90 km, and possessing lateral dimensions of 5–30 km. Sprites may occur singly, but more typically occur in clusters of two or more. Clusters may be tightly packed together into large structures of 40 km or more across or loosely spread out into distended structures of spatially separated sprites. Onset of luminance occurs almost simultaneously across the cluster as a whole, coincident with the occurrence of cloud-to-ground lightning below. Time scale for the persistence of red sprites is about a few tens of milliseconds (e.g., Sentman, et al., 1995; Rairden and Mende, 1995). The recorded radio noise coinciding with the sprite flashes makes a distinct “pop” when playing back through a speaker, a sound that differs from normal lightning discharge signals. Both ground and aircraft observations indicated that the red color emissions of sprites are mostly due to the first positive band of N_2 but not to the Meinel bands of N_2^+ (Mende et al., 1995; Hampton et al., 1996). The bluish tendrils in the lower part of the sprite usually cannot be seen from ground observations. The atmospheric scattering and absorption effect may make these blue emissions nearly impossible to see from ground. Sprites are observed primarily to associate with positive cloud-to-ground lightning (e.g., Sentman et al., 1995). Most of the sprites are observed above large mesoscale convection systems with horizontal extension of several hundreds of kilometers (e.g., Vaughan et al., 1992; Lyons, 1996; Boccippio et al., 1995; Boeck et al., 1995). However, the team of scientists from University of Alaska Fairbanks also observed sprites in southern America above a small mesoscale, thermal convection system with horizontal size of only a few tens of kilometers.

1.2. Blue jets

Blue jets are cloud-to-stratosphere electrical discharge events. Wescott et al. (1995) described the observed blue jet to be a narrowly collimated beam of blue light that appear to propagate upwards from the tops of thunderstorms, with speed approximately at 100 km/s and reach terminal altitudes of 40–50 km, which is about the altitude of stratopause. From the black/white recording of the video tape, the beam of light seems diverge at top when it reaches to the stratopause. Time scale for blue jet is about 200 ms (Wescott et al., 1995). The spectrum of blue jet has yet to be determined. The color of blue jet is mostly blue with some green emissions. The blue jets appear to be much brighter in the black and white images than in the color video images. This could be due to the color camera has negligible response at 391.4 nm band of the first negative bands of N_2^+, while the black and white camera has 40% response to the maximum. A blue jet extended from the cloud top to the lower ionosphere has recently been recorded in a ground campaign (Pasko et al., 2002). However, atmospheric scattering and absorption usually render these blue emissions harder to observe from ground. Thus, a photometer at wavelength less than 400 nm on broad an aircraft, a space shuttle, or a satellite will provide useful information on the blue emissions of the blue jet and the bluish tendrils of sprites.

1.3. Elves

Elves are lightning-induced transient luminous events in the lower ionosphere. Fukunishi et al. (1996) described the elves to be diffused optical flashes with a duration less than 1 ms and horizontal scale of 100–300 km. This type of TLEs usually occur at 75–105 km altitude in the lower ionosphere just after the onset of cloud-to-ground lightning discharges, but proceeding the sprites. They also suggested that the most likely source of elves is heating of the lower ionospheric electrons by electromagnetic pulse (EMP) generated by the intense lightning discharge: This suggestion was made previously by Inan et al. (1991) and Taranenko et al. (1992, 1993). Later, Inan et al. (1997) use a low-light-level camera together with an array of horizontally spaced photometers with time resolution of 30 μs and spatial resolution of 200 km to observe the rapid lateral expansion of luminosity in elves.

Recent ground-based optical and search coil magnetometer observations by Fukunishi et al. (1997) indicated that ULF transients have different waveforms for sprites without preceding elves and the sprites with preceding elves. Their results also indicated that sprites without elves always occur singly with a carrot-like shape. Sprites occurred after elves are usually in a column-shaped cluster distribution.

1.4. Theoretical modeling of TLEs

Among the current theoretical models on the cause of transient luminous events include electromagnetic pulse (EMP) (Taranenko et al., 1993; Rowland et al., 1995; Inan et al., 1996; Fukunishi et al., 1996; Glukhov and Inan, 1996; Sukhorukov et al., 1996b; Fernsler and Rowland, 1996; Inan et al., 1997; Sukhorukov and Stubbe, 1997a), runaway electrons (Bell et al., 1995), and quasi-electrostatic thundercloud electric field (Pasko et al., 1995, 1996a, b; Sukhorukov et al., 1996a; Fernsler and Rowland, 1996). EMPs are generally believed to be the cause of elves (Fukunishi et al., 1996; Glukhov and Inan, 1996; Sukhorukov et al., 1996b; Fernsler and Rowland, 1996; Inan et al., 1997;

Sukhorukov and Stubbe, 1997a). Runaway electrons and/or quasi-electrostatic thundercloud electric fields are believed to be the cause of blue jet (Pasko et al., 1995, 1996a; Sukhorukov et al., 1996a) and red sprites (Bell et al., 1995; Pasko et al., 1995, 1996b; Fernsler and Rowland, 1996). In addition, gravity waves (Pasko et al., 1997), ELF pulses (Sukhorukov and Stubbe, 1997b), and the spider lightning in the cloud by return stroke (Lyons, 1996; Valdivia et al., 1997) have also been used to explain the spatial structures or triggering of sprite clusters.

For quasi-electrostatic electric field model, the ambient conductivity, density, and temperature distributions may also play an important role on the electron accelerations. A large temperature gradient can be found in the summer hemisphere, where temperature increases toward the stratopause but decreases toward the mesopause. The implication is that sound speed will increase toward the stratopause but decrease toward the mesopause. Thus, in summer hemisphere, a compressible wave can easily turn into a shock wave in the mesosphere but not in the stratosphere.

Roble and Tzur (1986) obtained and published a vertical profile of daytime electrical conductivity distribution. The night time ionospheric conductivity should be lower, but EMP and runaway electrons can both provide additional ionizations that can increase the local conductivities and affect electric field distributions above the thundercloud. The ionization density associated with the upward electrical discharges may be determined by measuring the spectra of N_2^+ ions and N_2 molecules.

From the result of Roble and Tzur, one can see that to produce a radiative transition of N_2^+ 1N (391.4 nm, blue) the energy of the energetic electrons must be greater than 19 eV. To produce a radiative transition of N_2^+ Meinel (785.2 nm, red) the energy of the energetic electrons must be greater than 16.73 eV. Also to produce a radiative transition of N_2 2P (337.0 nm, blue) the energy of the energetic electrons must be greater than 11eV. To produce a radiative transition of N_2 1P (650–900 nm, red) the energy of the energetic electrons must be greater than 7.35 eV. Thus, by measuring the spectra of N_2^+ ions and N_2 molecules, we can obtain not only the ionization density and the modified electric conductivity, but also the energy distribution of energetic electrons associated with the upward electrical discharge events.

The ISUAL science payload on ROCSAT-2 will measure the spectra, ionization densities, occurrence, distribution, and possible vertical dynamics of the lightning-induced TLEs, especially the red sprites. This science payload project will provide a global and long-term observation of sprites and other TLEs, which could provide valuable information for the theoretical modeling of global electrical circuit (Roble and Tzur, 1986; Hale, 1994) in the future. The spectrophotometer and the photometer arrays may provide information on ionization density and energy distribution of energetic electrons associated with upper atmospheric transient luminous events. These observations could provide important information for determining the physical mechanism in generating sprites or other TLEs.

2. ROCSAT-2 satellite and the ISUAL instrument

Studies of upper atmospheric TLEs events from a satellite have its special advantages. The most notable one it could facilitate an unbiased and global survey of the upper atmospheric luminous events. Also, the emissions produced by the TLEs are much less attenuated if observed from the space. This point is well taken by referring to a MODTRAN code calculation performed by Chang (1998) on the transmittance of a range of emission wavelength. When computing these transmittances, the source is assumed to occur at an elevation of 50 km above ground. As shown in Fig. 1, the upper transmittance curve is for observing from a 300-km elevation. The middle and the bottom curves are for observing from locations at a 10-km elevation and ground, respectively. Obviously, observation from satellite offers a far superior transmittance, especially for ultraviolet emission. Naturally, the properties of the TLEs could be measured more definitively. Moreover, satellite observations may also be able to uncover new types of TLEs or unexpected features of the known luminous events.

To perform the observations from space, the ISUAL instrument consists of a CCD imager, a six-channel spectrophotometer and two array photometers. In this section, the salient characteristics of the platform of the ISUAL payload, the ROCSAT-2, and the most critical parameters of the ISUAL instrument will be presented.

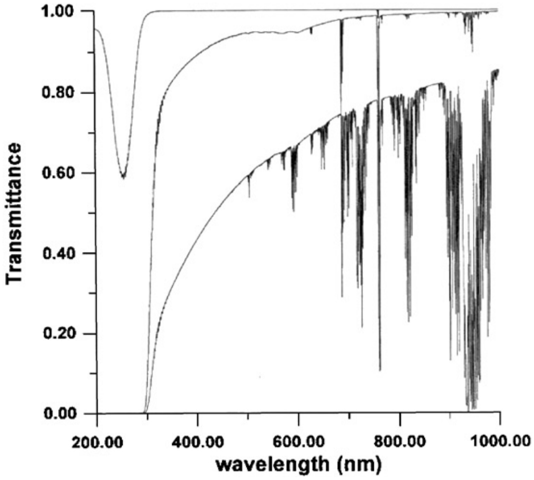


Fig. 1. The calculated transmittance of atmosphere based on a MODTRAN code for three different observation elevations, assuming the luminous source located at 50 km above ground. The top curve is for an observing elevation of 300 km or higher; the middle curve is for 10 km and the bottom one is for observing from ground.

Fig. 2. The exterior view of the ROCSAT-2 and the layout of the ISUAL instrument. The hexagonal object on the top of the spacecraft is the telescope of the remote sensing imager, and the three instruments of the ISUAL payload is located at the left of the upper deck. From left to right, the instruments are a CCD imager, two array photometers and a 6-channel spectrophotometer.

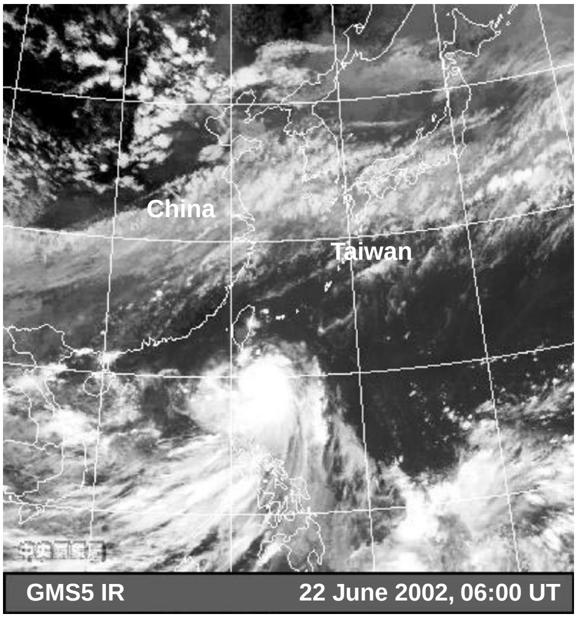


Fig. 3. Typical weather pattern in the vicinity of Taiwan during the summer season. The local weather is heavily influenced by convective systems, tropical depressions and typhoons.

2.1. The ROCSAT-2 satellite

The carrier of the ISUAL instrument, ROCSAT-2, is a small-class satellite from Taiwan with mission goals of remote sensing and scientific experiments, see Fig. 2. The satellite is now under constructing at the Astrium's facility at France and will be shipped to Taiwan for final system integration and testing conducted by National Space Program Office (NSPO) around June 2002. The remote sensing experiment is needed because Taiwan is experiencing rapid economic growth with dynamic changes in land use. Taiwan also is an island prone to natural disasters brought on by typhoons during the summer months, e.g. see Fig. 3. Timely availability of remote sensing data is essential and critical for Taiwan in the aftermath recovery from these natural disasters.

The ROCSAT-2 mission will focus mainly on satisfying Taiwan's user needs. Therefore, frequent revisits of Taiwan and timely availability of the data for Taiwan are unique characteristics that distinguish the ROCSAT-2 from other commercial satellites. The Remote Sensing Instrument (RSI) will be operated mainly over the region of Taiwan Island, Taiwan Strait and the remote offshore islands. The satellite pass time for operation is in the period between 9:30 am and 10:30 am Taiwan Local Time. Other relevant information on the ROCSAT-2 are as followings:

- Weight: around 700 kg
- Orbit: polar-orbit and sun-synchronized with altitude of 891 km, daily revisit Taiwan
- Orbital plane: 98.99°
- Period: 14 revolutions per day (repeating orbit)
- Agility: body rotation with ±45° roll and pitch
- Pointing accuracy < 0.7 km
- Pointing knowledge < 450 m
- Position knowledge < 70 m
- Mission life: 5 years,
- Launch date: October 2003.

2.2. The ISUAL CCD imager

Sprites, elves and other luminous phenomena have been observed on ground and airborne high sensitivity video cameras. However, so far the only space-based observation of these phenomena was reported by Boeck et al. (1995), who examined video recordings taken by the space shuttle's cargo bay cameras. Although they were able to extract useful information out of these footages, their results also showed that it is desirable to discriminate against the parental lightning. The parent cloud to ground flash often precedes the sprite events only by a few msec (Rairden and Mende, 1995), and its illumination of the thunderstorm cloud can overlap with TLE events. The flash intensity of the parental lightning can be so high that a camera, which is not designed specifically for the purpose, would be blinded.

To identify the upper atmospheric luminous events, we will employ a limb-viewing observation scheme. Hence the CCD camera is also called the Limb and Optical Flash Transient Imager (LOFTI, see Fig. 4). The ISUAL imager

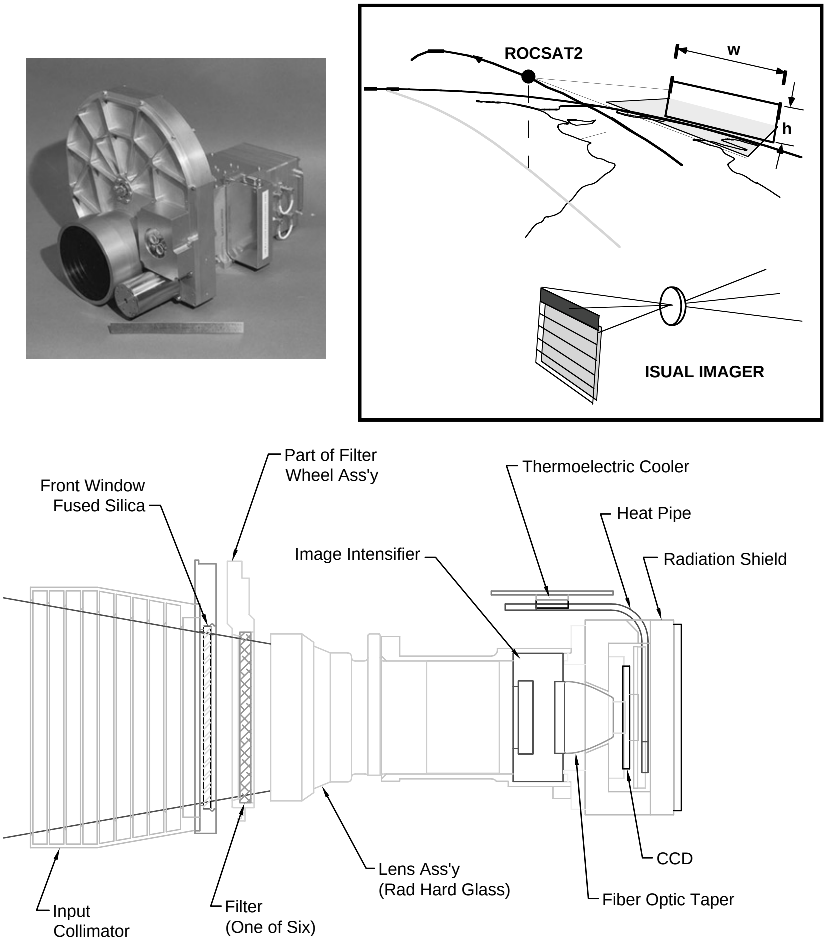


Fig. 4. The ISUAL CCD imager and its operational concept.

uses four separate techniques to improve the sprite to parent lightning intensity ratios:

(1) By observing the flashes near the limb or on the limb it is possible to get spatial separation between the two sources of intensity.
(2) By using appropriate spectral filtering it is possible to maximize the sprite-induced spectral bands and cut down on the spectral bands produced by cloud to ground lightning.
(3) By using a trigger photometer and only turning on LOFTI imager at the appropriate time, it is possible to remove some of the parent lightning intensity.
(4) Using a CCD type, which has anti-blooming gate to minimize the contamination of adjacent areas near a flash.

The ISUAL imager is a versatile instrument capable of multiple functions. It is a survey instrument to determine the statistical properties of sprites and other the high altitude flashes, such as latitude, longitude and local distributions as well as their altitude distributions. It is an instrument, which enables the studying of individual flashes including their altitude/time development and spectral spatial properties. With the inclusion of a filter wheel, LOFTI can select specific airglow wavelength and can be used to study the altitude distributions of the airglow luminosity. The relevant information of the ISUAL imager is tabulated in Table 1 and presented in Fig. 5.

The need to analyze the time response of these fast discharge events imposes an important requirement, i.e., the ability to take extremely fast snap shots. The ISUAL imager uses the technique derived from the observations of Rairden and Mende (1995). Rairden and Mende used the charge sweeping capability of the CCD to produce the submilisecond time resolution required. The ISUAL imager will be designed specifically to have a fast vertical sweep with a specially masked CCD allowing several images to be stored

Table 1
Relevant parameters of the ISUAL imager

Field of view	20° (horizontal) ×5° (vertical)
Number of active pixels	512 × 160
Time resolution/frame rate	Programmable (1 ms to 1 s)
Number of frame stored	6
Spatial resolution	∼ 2 km/pixel at limb
Filter number	Bandpass and remarks
1	623–750 nm N_2 first positive band filter for observing sprites, removing the lightning induced 777.4 nm line and minimizing the Contribution of the airglow 760 nm O_2 band
2	762 nm O_2 (0,0) atmospheric band for observing airglow and aurora
3	427.8 nm Energetic electron induced emissions of sprites and aurora
4	630 nm Aurora and airglow emissions
5	557.7 nm Aurora and airglow emissions
6	Blank With IR blocking by the camera lens

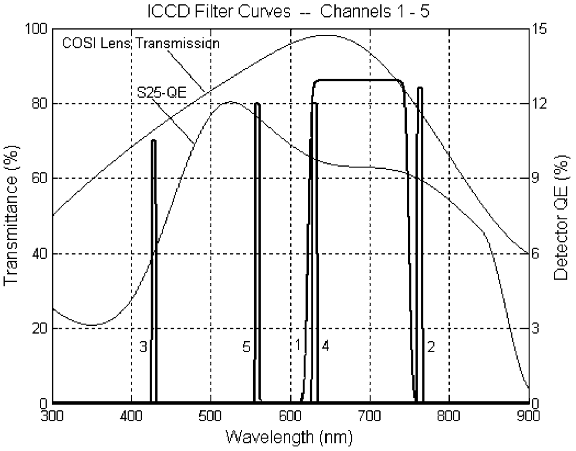


Fig. 5. Transmittance curves for the CCD lens and the bandpass for the CCD filters.

under the masked area. In this way images can be taken in quick succession providing a sequence of images depicting the time history of the phenomena.

One of the bore-sighted photometer channels is used to detect optical flashes. When a flash is detected the photometer signal is used to command the image intensifier to gate on after some delay. After the first exposure is completed the CCD shifts the image up and a second exposure is commenced. After a suitable delay the CCD stops the exposure sequence and reads out the last six images. This way the camera can record a number of frames for each flash event and the duration and repetition rate of the exposures are programmable. It should be noted that if the image intensifier is gated on permanently this technique permits the capture of images, which are taken prior to the occurrence of the trigger photometer pulse. This method of operation can obtain images with high temporal resolution.

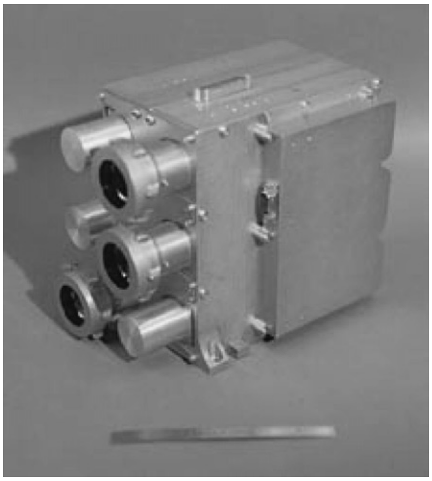
During taking an image, light enters the imager through the lens. There is a filter wheel to select the pass band of the observation. A single stage MCP intensifier precedes the CCD. The photo cathode of the tube can be back biased so that the instrument is gated off. The photometer can be programmed to control this gating function. Behind the intensifier is the CCD. The CCD has a metal mask, which covers most of the CCD except the lower region corresponding to a narrow strip of 1/4th of the image. This is exposed to the incoming light. When the exposure time is finished the image (images) is (are) transferred upward into the upper part of the CCD where the storage area is metalized and therefore not light sensitive. This way a sequence of images is collected on the CCD. Whenever the photometers detect a flash a programmable delay will start, at the end of which the intensifier is gated on exposures are taken and the upward transfers are initiated until five exposures are taken. The CCD will have to be shielded so that trapped protons in the < 50 MeV range are excluded.

With the ROCSAT-2 satellite operating at an 891 km orbit, the limb is about 3467 km (20°) from the satellite. In the vertical dimension the field of view is relatively small (5°) covering an altitude range on the limb of only about 180 km. During the satellite operation period, we may occasionally dip the imager down to reduce the observational range. With this type of maneuvering, we could obtain images with higher spatial resolution.

2.3. The spectrophotometer

The 6-channel spectrophotometers use high time resolution burst mode data recording. All the photometers are bore-sighted in the same direction as the CCD imager, see Fig. 6. The wavelength band selection for these photometers is given in Table 2 and illustrated in Fig. 7. With the channel 1 of the spectrophotometer, we may obtain a clear UV signature of sprites/elves and will not be blinded by a parent lightning. If this can indeed be confirmed, this channel can be used as a trigger for the ISUAL imager. Channels 2, 3 and 5 would provide information on electron energy distribution of the TLE events. The purpose of channel 6 is to detect the 777.4 OI emission which is strongly emitted in lightning discharges in comparison with $N_2$1P. While channel 4 is a primary trigger to detect the well-established $N_2$1P emission.

Channel number 4 is the baseline channel because this feature is best understood from numerous ground based measurements at this wavelength. Some of the other lines are interesting because they provide clues regarding the energet-



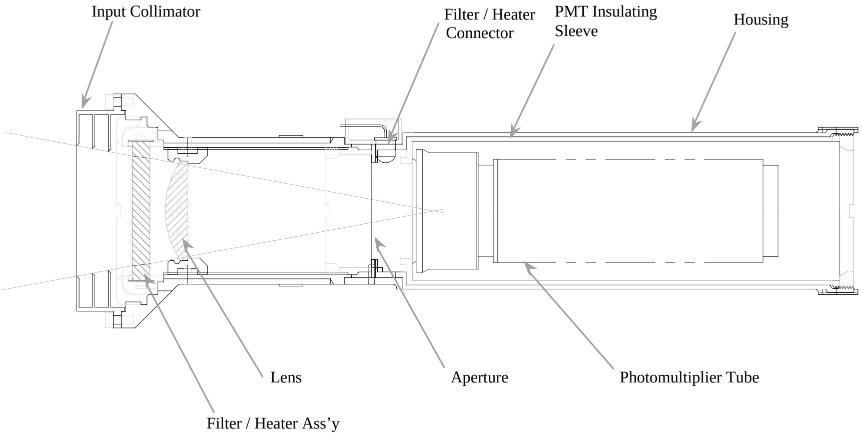


Fig. 6. The ISUAL spectrophotometer and the components of a photometer.

ics of the high altitude discharges causing the optical emissions. The LBH lines are observed because it is thought that they might provide additionally a clear sprite signature because the lower atmospheric lightning is less likely to penetrate the dense O_2 region in this wavelength range. The baseline design assumes that triggering of the imager will be from channel 4. However, other wavelengths can also be programmed to act as triggers.

Each photometer consists of a filter and an objective lens, which images the sky on an aperture mask, see Fig. 6. The mask limits and defines the field of view of a photometer. Behind the aperture, a Fabry-lens projects the image on the photomultiplier. With this design, a uniform response from the photometer can be assured regardless of where the flash appears in the field of view.

2.4. The array photometers

The ISUAL array photometers (AP) are designed to measure the temporal and spatial (vertical) structures of luminous phenomena induced by cloud to ground lightning. As reported in the literature (Takahashi et al., 1996; Stanley, 1999; Watanabe, 1999; Miyasato et al., 2003), the vertical development of sprite and sprite halo emission is closely related to the characteristics of spatial structures of sprites. It was found that columniform sprites are often accompanies by sprite halo, which propagates downward from an altitude of ~ 90 km, at the initial phase of optical emission within a few ms after the causative CG. While for the carrot sprites, the optical emission propagates upward and downward from the middle of sprite's head region in the first stage. From the resulted obtained by Watanabe (1999), the carrot sprites could be categorized further into two groups. One whose peak emission occurs within 20 ms after the causative CG and another one peaks after 20 ms. To examine the vertical development of sprites, a spatial resolution of ~15 km and a temporal resolution of ~100 μs are required.

The ISUAL instrument includes two array photometers, see Fig. 8. Each array photometer consists of a bandpass filter, an objective lens and a multi-anode U5900-01-L16

Table 2
Relevant parameters of the ISUAL spectrophotomter

Field of view	20° (horizontal) ×5° (vertical)
Number of photometers	6
Sampling rate	Programmable (2 or 20 kHz)
Channel number	Bandpass and remarks
1	150–280 nm Looking at N_2 LBH long wavelength bands. Upper state lifetime is 0.14 ms resulting in some quenching at lower altitudes. The altitude of unit optical depth is about 40 km in this range perhaps possible to see sprites while attenuating lightning.
2	250–390 nm It might be possible to see sprites and much attenuated lightning
3	337 nm N_2 second positive band requires higher electron energies therefore provides a particle energy “spectrometer”
4	427.8 nm Energetic electron detector in sprites and aurora
5	623–750 nm N_2 first positive emission “bread and butter” sprite measurement
6	777.4 nm O lightning—a possible triggering source for imager

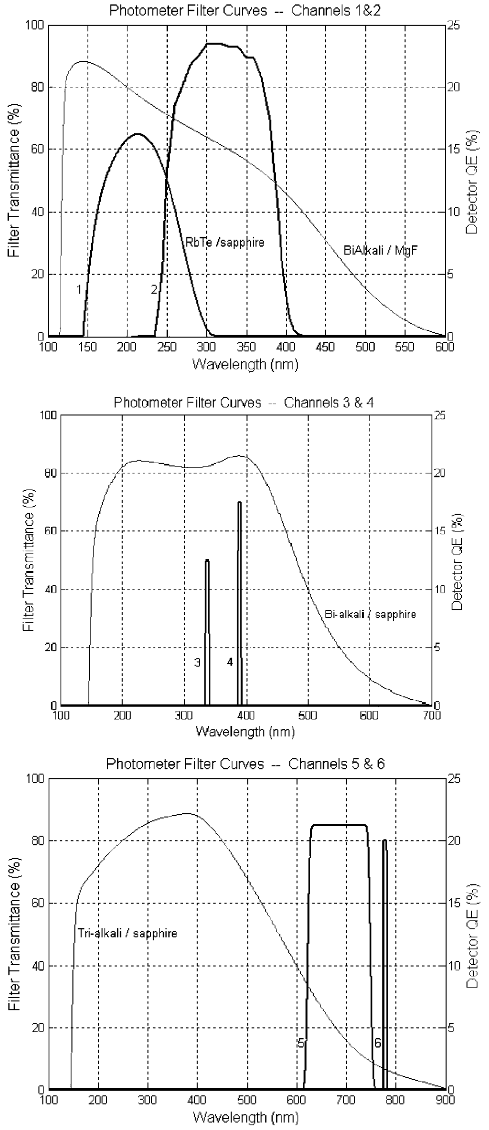


Fig. 7. Transmittance curves for the windows of the photometer and the selected bandpasses.

Hamamatsu photomultiplier. One AP has a bandpass filter of 330–470 nm and another AP is equipped with a filter of 510–800 nm. The photomultiplier has 16 anodes all aligned in one direction. The total anode area of the PMT is approximately a square with sides of 16 mm in length. Hence, an objective lens is needed to map the collected light into the squared anode area of the PMT. To achieve a wide field of view in the horizontal direction and without degrading the vertical resolution, two cylindrical lenses with different focal lengths are used. The resulting FOV of the array photometer is 22° (horizontal) and 3.6° (vertical). Therefore, the FOV for each anode is 22° × 0.23°, corresponding to ∼14 km in height at a range of 3500 km. The two array photometers are boresighted in the same direction such that the ratio of the measured luminosity can be computed, and the electron energy distribution of the sprites, elves or blue jet-initializing discharge can be estimated (Takahashi et al., 1998; Miyasato et al., 2003; Sera et al., 2003).

To achieve a definitive identification of the different types of sprites, each channel of the AP is sampled at 20 kHz for the first 20 ms after the onset of the causative CG. After that the data is sampled at a lower rate at 2 kHz until ∼ 100 ms after the CG. In the electronic circuitry of the AP, a low pass filter (LPF) with a cut-off frequency of 10 kHz is employed for the faster sampling rate at 20 kHz. While a LPF with a cut-off frequency of 1 kHz is used for the slower sampling rate of 2 kHz. It is known that elves also show an apparent downward propagation due to its geometrical evolution (Inan et al., 1996). This particular property of elves allows us to distinguish elves from the scattered CG flashes, which show no time difference of peaks at any elevation (Fukunishi et al., 1999). A sampling rate of 20 kHz with a 10 kHz LPF is sufficient for measuring the apparent vertical development of elves.

The operation of array photometers in the sprite burst mode (see Section 4) is triggered by a signal issued by the spectrophotometer. AP enables to run in pre-triggering or in immediate trigger ring modes according to the channel

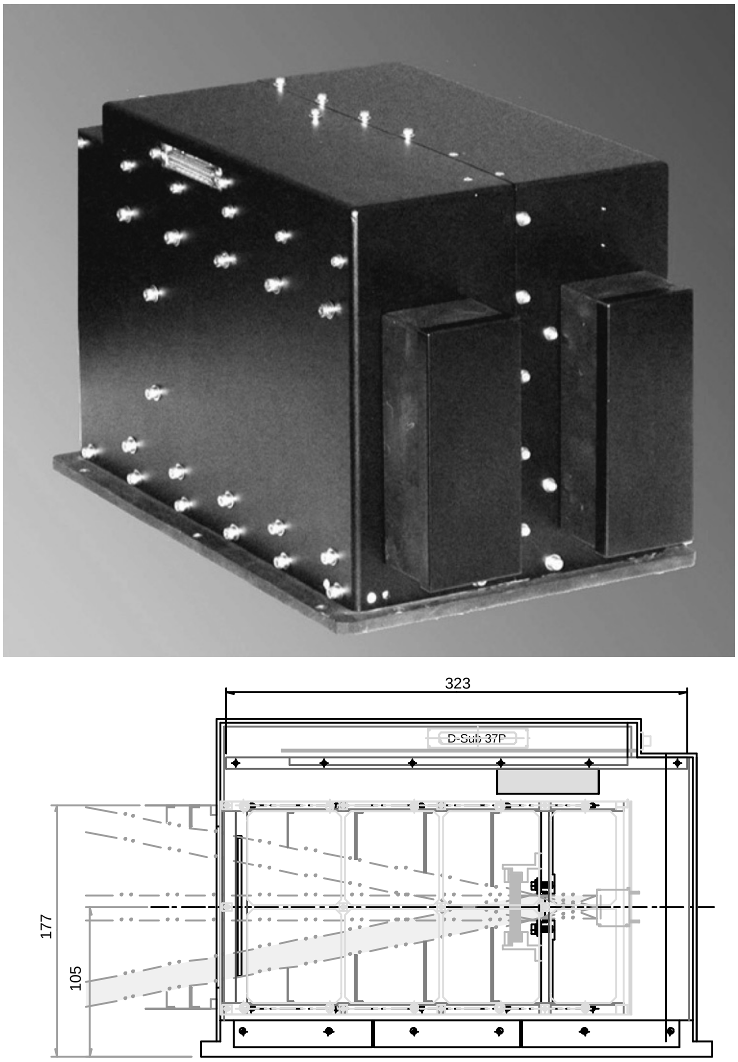


Fig. 8. A bird-eye view and an optical layout (side view) of the ISUAL AP.

of the spectrophotometer used for initializing the triggering signal. Observations of blue jets, aurora and airglow could also be conducted by AP at a sampling rate of 200 Hz with a 100 Hz low pass filter. One of the unique targets of auroral phenomena that could be studies by AP is the flickering aurora, which is blinking at a rate of up to 100 Hz. The data will be recorded continuously without a triggering signal. The sensitivities of photometers could be adjusted by varying the high voltage input to PMTs, so that it can measure luminous emissions with a large dynamic range, covering faint airglow to intense filaments of sprite head.

3. The scientific objectives

The ISUAL project has three primary scientific goals and two secondary scientific goals. The primary scientific goals are to understand the spectral characteristics, to quantify the intensity, occurring frequency, and global distribution, and to investigate the possible generation mechanisms of the lightning-induced upper atmospheric TLEs from the satellite measurement. Also from the satellite study, we hope to uncover other new transient TLEs. The secondary scientific goals include assessing the implications of the upward lightning in atmosphere to earth's electrical environment and comparing the conditions for the occurrence of red sprite and other luminous phenomena, and distinguishing their physical origins.

From the ISUAL measurement, we have the opportunity to study red sprites and other TLEs globally. The investigation will help to quantify the intensity and occurring frequency at various locations on the earth. The global distribution of TLE events will be investigated statistically. Its correlation with the global thunderstorm distribution can be studied. The occurrence TLEs at major thunderstorm areas will be compared, with an emphasize on their occurring frequency and intensity.

With the proposed multi-channel spectrophotometer, we can obtain the absolute intensity and relative ratio of various emission lines from the simultaneous measurements of multiple spectral bandwidth. From the proposed CCD imager, the spectral structure of red sprites and other TLEs can be recorded. Because this measurement will be made from satellite, it offers some advantages, especially for shorter wavelength emissions at ultraviolet region. The time evolution of red sprite events and other TLEs will be monitored by the ISUAL instrument with time resolution much shorter than the luminous duration of these events.

Light emission from the TLE events is often closed related to the gas/plasma condition of the local atmosphere at where the emission originates. For example, from the intensity of emission at 391.4 nm wavelength, measured by the designated photometer, we can estimate the population of N_2^+ if sufficient amount of N_2 are ionized during upper atmospheric discharges. Since the density of N_2 can be estimated from other photometer bands, we can obtain the information of the ionization fraction (e.g., N_2^+/N_2). From that, we can estimate the local temperature during the upward lightning event. Beside the dynamics of gas/plasma condition can provide the clue to resolve the generation mechanism for red sprite event and other TLEs, the temporal and spatial evolution of transient luminous events can test the validity of the existing models.

Assisted by the satellite observation data, we hope to give a definitive answer to the possible generation mechanism of the discharge events in upper atmosphere, especially for red sprite. Currently, there are several existing models to explain the process in producing the red sprites. Based on the driven sources, the models can be classified to two categories, by electromagnetic fields or by energetic electrons. These models predict different evolutionary path of the red sprite and different consequences such as emission spectral lines. The ISUAL satellite measurements may be able to prove one of these models. In addition to investigate the existing physics models, we hope to explore the possibilities of new generation mechanisms. The understanding of the generation mechanism is not only important in science, but also critical for the assessment of the impact to earth's electrical environment due to the occurrence of upward lightning discharges.

4. Operation scenarios

To fulfill the scientific objectives of the ISUAL project, the payload instrument is designed to operate at various modes. For clarity, the operation modes are itemized as follows:

TLE continuous mode

- Imager is continuously taking images at 100 frame/s rate
- Array photometer is continuously sampled at a 2 or 20 kHz rate
- Spectrophotometer is continuously sampled at a 10 kHz rate
- All data are written into a series of circular memory buffers
- Upon meeting trigger criteria by one or more Spectrophotometer channels, a selected block of data are saved in the mass memory for compression and transfer to the satellite T/M for downlink
- Selectable parameters include trigger channel, level, rise time and the size of the pre-trigger and post-trigger blocks.

TLE burst mode

- Same as the continuous mode except for the imager is operating at a 650 Hz rate for a limited period
- Price of high sampling rate is ~ 80% dead time for the imager after consecutive bursts.

Auroral and airglow mode

- All the ISUAL instruments, except for the array photometers, operate at a constant rate of 1 sample/s
- Array photometers are continuously sampled at a 200 Hz rate
- All data saved, compressed, and transfer to spacecraft for downlink.

With the ISUAL instrument operate in these modes, we expect to study sprite (TLEs), aurora, and airglow. The main influence of aurora and airglow on the photometry observations is on the following wavelength: 557.7, 630, 427.8, and 391.4 nm. However, the optical brightness of these three different optical activities is very different. The optical emission of red sprite is estimated as 100 kR–1 MR, while for aurora and airglow their optical activities are 1–100 kR, and 100 R–1 kR, respectively. (R: Rayleigh, $10^6/4\pi$ photons/cm^2/strd/s.) The time evolution of sprites is in sudden pulse form. In contrast, the aurora and airglow are with a rather smooth and continuous form of activity.

Sprites appear predominately in association with positive cloud-to-ground lightning (Lyons, 1996; Reising et al., 1996). Moreover, the sprites are generally observed within the nocturnal mesoscale convective systems (MCS). A common type of MCS occurring in the US Midwest plain is the mesoscale convective complex (MCC). The sprite occurrence rate varies among the MCCs over a wide range, and the ground-based observation of the sprite production rate for two Midwest MCCs is around 0.2–1/min over 3 h period (Lyons, 1996; Reising et al., 1996). Su et al. (2002) defined a slightly different sprite production rate for the sprite-producing thunderstorms they observed in Asia. Their

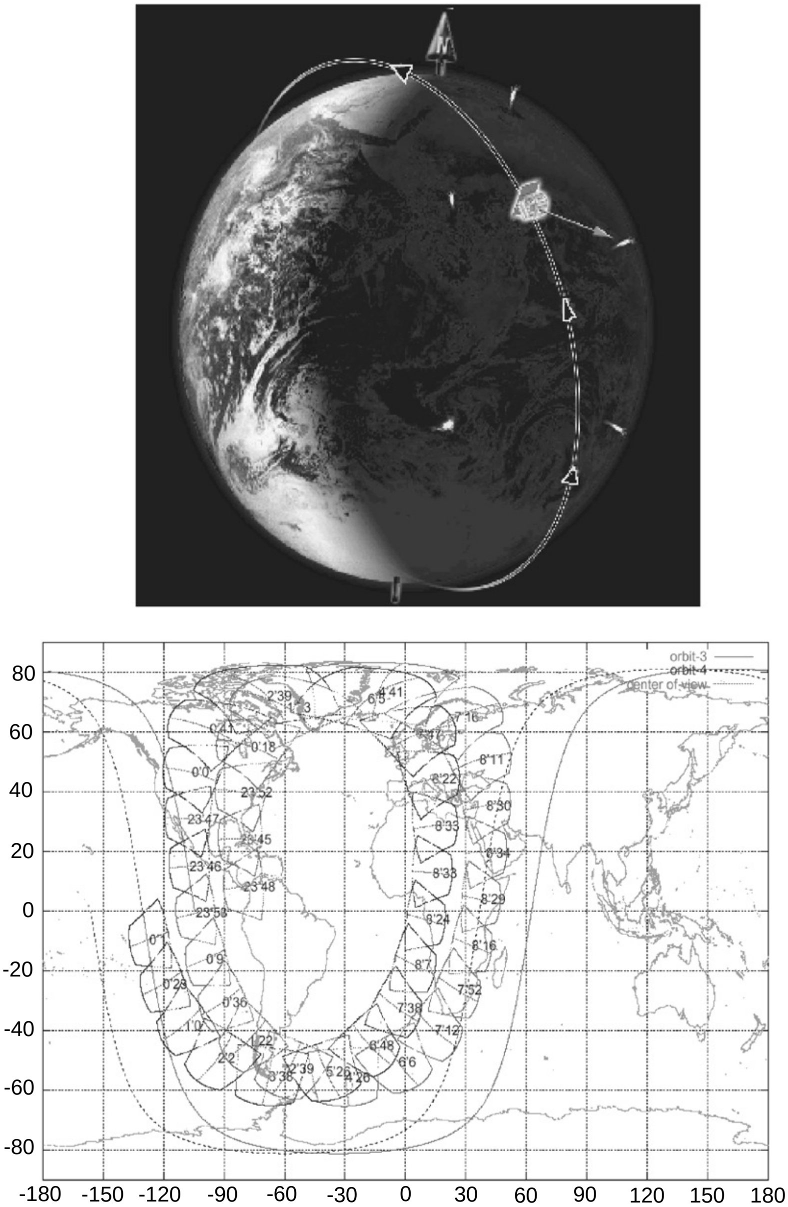


Fig. 9. The operation scenarios and the ground coverage of the ISUAL instrument.

sprite production rate is normalized to the observed area of the storm, and the calculated sprite production rate for the Asian thunderstorms are $\sim 5 \times 10^{-4}$ events/h/km^2. Assuming the cold cloud shield area of the storm is $\sim 4 \times 10^4$ km^2, the computed rate is $\sim$ 0.3 events/min during the active sprite generating period. Therefore, the sprite production rates for the thunderstorms in the American plain and in the Asia are comparable. The true production rate is probably higher since the cloud generally obscured parts of the MCC for the ground-based observations.

Globally, about 400 MCC systems occur for each year primarily over land (Laing and Fritsch, 1996). These nocturnal MCCS typically have cold cloud shield area $\sim 4 \times 10^5$ km^2 and last for 10 h. Since the area is four times of the mentioned US Midwest samples, it is expected that the sprite production rate will be $\sim$ 0.8–4/min. Normally during the night, the overfly of the ROCSAT-2 is $\sim$10 p.m. local time and with the imager points sideways, the region observed by the imager is around midnight. Because of the large scanning area of the ISUAL and the long duration of the MCC, the probability that the ISUAL will observe a typical MCC during the night is better than 50%. Thus, on average, ISUAL will observe more than 200 MCCs per year. With the imager points sideways and the field-of-view of 1024 km, it will, on average, take the Imager ∼ 2.5 min to over fly a MCC and to observe ∼ 2–10 sprites per over fly. Hence the equivalent sprite observation rate is ∼ 400–2000/year or ∼ 40–180/month.

The designed operation life of ROCSAT-2 and the ISUAL instrument are both 5 years, which may allow the ISUAL instrument to pursuit other scientific researches. The ROCSAT-2 will operate on a polar orbit along a dawn–dusk meridian. The ISUAL imager camera will usually point across the track to the midnight regions. For the ISUAL operation, the spacecraft is allowed to roll 45° in either direction. This feature will be extremely useful when conducting space–ground coordinated campaigns on transient luminous events. With the prior selection view angle and the ground-covering track, the observation from the ISUAL and the ground instruments can be synchronized to look at the same thunderstorm, see Fig. 9. The space–ground coordinated observations could shed some new light on the characteristics of the TLEs, airglow and aurora. At the conclusion of the ISUAL project, we hope that this project has contributed substantially in the field of TLE study and facilitated a better understanding of the terrestrial environment.

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