SPACECRAFT BASED STUDIES OF TRANSIENT LUMINOUS EVENTS

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Abstract The Imager of Sprites and Upper Atmospheric Lightning (ISUAL) is a scientific payload on Taiwan's FORMOSAT-2 (previously known as ROCSAT-2) that provides new observations of transient luminous events (TLEs) from space. The ISUAL project is an international collaboration between the National Cheng Kung University, Taiwan, Tohoku University, Japan and the instrument development team from the University of California, Berkeley. The project was supported by the National Space Program Office in Taiwan. The ISUAL payload includes a visible wavelength intensified CCD imager, a boresighted six wavelength spectrophotometer, and a two channel Array Photometer (AP) with 16 vertically spaced horizontally wide sensitive regions. The imager is equipped with 5 selectable filters on a filter wheel and a 6^{th} open position. The spectrophotometer contains six filter photometer channels, their bandpasses ranging from the far ultraviolet to the near infrared regions. The two channel AP is fitted with broadband blue and red filters. The orbiting platform with this set of instruments will provide the first comprehensive global latitude and longitude survey of TLEs near the midnight local time region. One of the great advantages of spaceborne observations is the lack of the intervening atmosphere between the TLEs and the observer. Ground based observations are often adversely affected by clouds, atmospheric extinction or scattering whereas the space-borne ISUAL instrument measurements provide true emission ratios unobstructed by the variable atmospheric extinction. The channels of the spectrophotometer channels cover the far and mid ultraviolet in addition to channels that respond to various excitation levels of the neutral and ionized nitrogen molecule atmosphere and to emissions from oxygen. The preliminary data shows that the ratio of the emissions is highly variable during the lightning and the associated TLEs. The data is qualitatively consistent with harder characteristic energy electron production

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in lightning less hard in sprites and even less in elves. The focus of the data analysis will be to solidify these conclusions and to put them on firmer statistical and quantitative basis.

6.1 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 90s. Franz et al. (1990) were the first to record upward electrical discharge events during a storm associated with hurricane Hugo on the night of 22 September 1989 using a low-light-level television camera.

Since then, night-time lightning-induced transient luminous events have been recorded using low-light-level television cameras on the space shuttle (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). Since then there were observations that indicate other types of TLEs (Lyons et al., 2001; Pasko and George, 2001). Based on ground, aircraft, and space shuttle observations in the past 10 years, TLEs have been classified into several categories including sprites (Sentman et al., 1995), blue jets (Wescott et al., 1995), elves (Fukunishi et al., 1996) and halos (Barrington-Leigh et al., 2001). Systematic observations of TLEs from a free flying spacecraft is expected to produce a much better understanding of TLE processes.

6.2 FORMOSAT-2 Satellite and the ISUAL Instrument

Satellite based studies of upper atmospheric TLE events have several advantages. The most notable one is that global latitude longitude surveys of TLEs can be conducted from satellite orbit. The lack of atmospheric attenuation also provides many advantages such as UV viewing and quantitative interpretation of the measurements regardless of atmospheric conditions or viewing angles. Since TLEs are thunderstorm related phenomena they tend to occur when ground based viewing conditions are relatively unstable. The Imager of Sprites and Upper Atmospheric Lightning (ISUAL) is a scientific instrument package on the Taiwanese FORMOSAT-2 satellite that was launched on May 20, 2004. ISUAL is the first multi-wavelength, quantitative observatory on a free flying satellite primarily dedicated to observing TLEs. The ISUAL payload includes an intensified CCD visible imager with a six position filter wheel, a boresighted six wavelength channel spectrophotometer (SP), and a two channel array photometer (AP) with 16 vertically spaced, parallel, horizontal strip photomultiplier anodes. The imager is equipped with 5 selectable filters on a filter wheel and the 6^{th} filter position is open. The SP six filter channel wavelength band passes range from the far ultraviolet to the near infrared regions (Table 2 in Section 6.2.3). The two AP channels are fitted with broad band filters, one blue and one red. Thus the ISUAL instrument complement provides calibrated emission intensities of sprites and elves, such measurements have been problematic to obtain from the ground.

The high time resolution requirement for TLE studies, produce very high data volumes that is beyond the allocated capacity of most satellite data storage and down link transmission systems. To overcome this difficulty the ISUAL data system operates essentially in a type of burst mode. Data are gathered continuously during the night pass but they are saved only if the on-board hardware control system determines that a significant “trigger” event had occurred. The instrument hardware has several programmable discriminators that produce a trigger when selected SP channel signals exceed a certain threshold. Most triggers are caused by lightning. Without trigger the data is discarded. It is difficult to distinguish the bright lightning from TLEs in real time even with the aid of the SP UV channels that are optimized for TLE detection. In addition, energetic particle events from penetrating space radiation can provide false signals in the phototubes that are indistinguishable from optically induced events. The satellite has a flexible programmable logic system that can be programmed and which will accommodate various “trigger algorithms” and execute them in “real time”. The fine tuning of the system is an on going process. At the time of writing of this work we have been able to capture 67 sprites, 580 elves, and 47 halos.

6.2.1 The FORMOSAT-2 Satellite

The ISUAL instrument operates on FORMOSAT-2 (previously known as ROCSAT-2), which is a small-class Taiwanese satellite carrying another instrument, the Remote Sensing Instrument (RSI), that takes high resolution images of the Earth surface under sunlit conditions. The satellite was constructed at the Astrium facility in France and was shipped to Taiwan for system integration and testing, conducted by National Space Program Office (NSPO). It was launched by a Taurus launch vehicle on May 20th, 2004 from the Vandenberg Air Force Base in California.

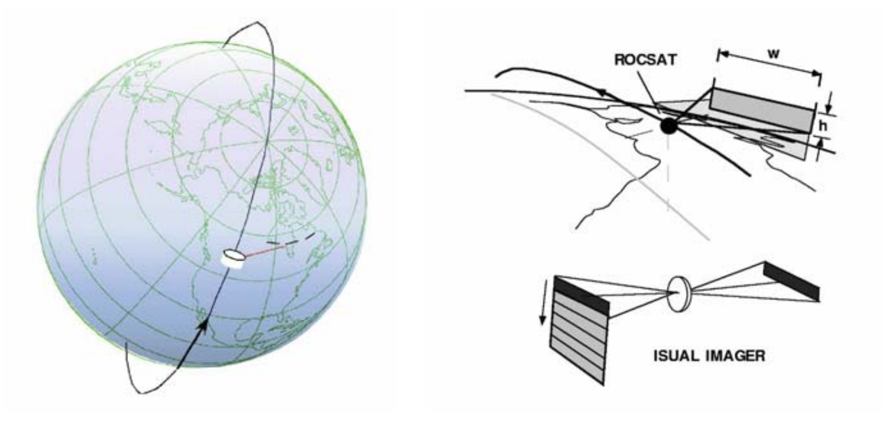
The primary mission goal of the FORMOSAT-2 program is the RSI observation over the region of Taiwan Island, Taiwan Straits and the remote offshore islands. Therefore frequent revisits of Taiwan and timely availability of the data in Taiwan are a high priority. A sun-synchronous repeating orbit was chosen with overpass at 9:30 and 21:30 local time. The orbit is also a repeating orbit and it traces the same geographic footprint every 24-hour day.

Other relevant information on the FORMOSAT-2 satellite is as follows:

- Weight: approximately 700 kg

- Orbit: polar-orbit and sun-synchronized with altitude of 891 km, repeating orbit i.e. the geographic ground track is constant (centered on Taiwan).
- Orbital plane: 98.99°
- Period: Exactly 14 revolutions per day
- Agility: body rotation ±45° roll, pitch and yaw
- Pointing accuracy <0.7 km
- Pointing knowledge <450 m
- Position knowledge <70 m
- Mission life: 5 years

The ISUAL observing scenario is illustrated in Figure 1a and b. The ISUAL imager is looking essentially horizontally in the direction perpendicular to the orbit plane in the starboard direction as the satellite proceeds northward. Its field of view (FOV) is approximately 20° (1024 pixels) in the horizontal direction (w) and 5 (256 pixels) in the vertical (h). The 4 to 1 aspect ratio of the



(a) (b)

Figure 1. (a) An artist impression of the satellite traveling north while ISUAL is viewing North America. (b) FORMOSAT-2 (shown as ROCSAT) observing scenario showing the satellite orbit track and the approximate view angle. The imager observes a region near the Earth limb perpendicular to the orbit track. The imager takes several horizontally wide images which can be stacked on the CCD.

image allows the storing of 8 images on the 1024×2048 frame transfer CCD. All but one of the image 1024×256 pixel segments are behind an opaque mask. Following each exposure image on the active part of the CCD is transferred down one step as shown by the arrow in the bottom illustration (1b). This technique permits the taking of up to 8 exposures in a quick sequence on the CCD.

The satellite altitude of 891 km defines the straight line viewing distance (range) to the 60 km altitude limb tangent point as 3373 km. The instrument view angle to observe the solid Earth limb is 28.68° below the local horizon at the satellite. The great circle distance along the 60 km altitude layer from the satellite foot point to the tangent point is 3106 km.

The ISUAL instrument block diagram is shown in Figure 2. The instrument consists of 4 packages, the Imager, Spectrophotometer (SP), Array Photometer (AP) and the Associated Electronics Package (AEP). The imager subsystems are the filter wheel, the CCD control electronics, the image intensifier gating and high voltage power supplies (HV). They are all controlled by the digital processing unit (DPU) housed in the AEP. A daylight sensor is included which detects excessive brightness in the field of view of the ISUAL instruments and can shut down the high voltage (HV) supplies by hardware control to protect the instrument from over exposure. The spectrophotometer SP consists of 6 individual photomultiplier units with pre-amplifiers and individually controllable HV supplies each. The Array Photometer is a two-wavelength channel instrument with two 16-channel multi anode photomultipliers and corresponding high voltage supplies. Each sensing instrument has an assigned section of the instrument mass memory and the data is collected at that location. The entire instrument and the data processing sequences are controlled by the DPU. This microprocessor executes the flight software and controls the entire ISUAL instrument operation. In burst mode suitable for TLE observations a lightning flash or a TLE generates photometer signals that are combined by the hardware event detect circuit according to the trigger detection algorithm. This algorithm determines what combination of signals from several photometer channels satisfies the trigger criterion. When the signals satisfy the trigger criteria the hardware processor in the AEP activates the mass memory controller to execute an operating cycle and store the resulting data for downlink transmission. There is a Digital Signal Processor (DSP) attached to the mass memory and it is capable of compressing and repackaging the data for the telemetry format.

6.2.2 The ISUAL Imager

The ISUAL camera is schematically illustrated in Figure 3. There is a light baffle to exclude scattered stray light. Preceding the filters the light goes through a fused silica window, which is used to minimize the radiation exposure of the filters and the following optics. The filters are mounted on a filter wheel driven by a stepper motor under direct control of the DPU.

The imager optics consists of a 62.5 mm focal length F/1.5 lens specially designed for the ISUAL imager by Coastal Optical Incorporated. The lens elements are constructed entirely of space radiation resistant glasses. The image is produced with a vertical dimension 5° by 20° covering a limb region of about 250 km in the vertical and 1000 km in the horizontal direction. The instrument's nominal pointing is 27.5° down from the local horizontal. With this pointing configuration the lower boundary of the field of view intercepts the 60 km altitude region at 2000 km distance from the spacecraft. This view covers a horizontal region of the atmosphere starting at 2000 km from the satellite and extending all the way to the limb at 3106 km perpendicular to the orbit

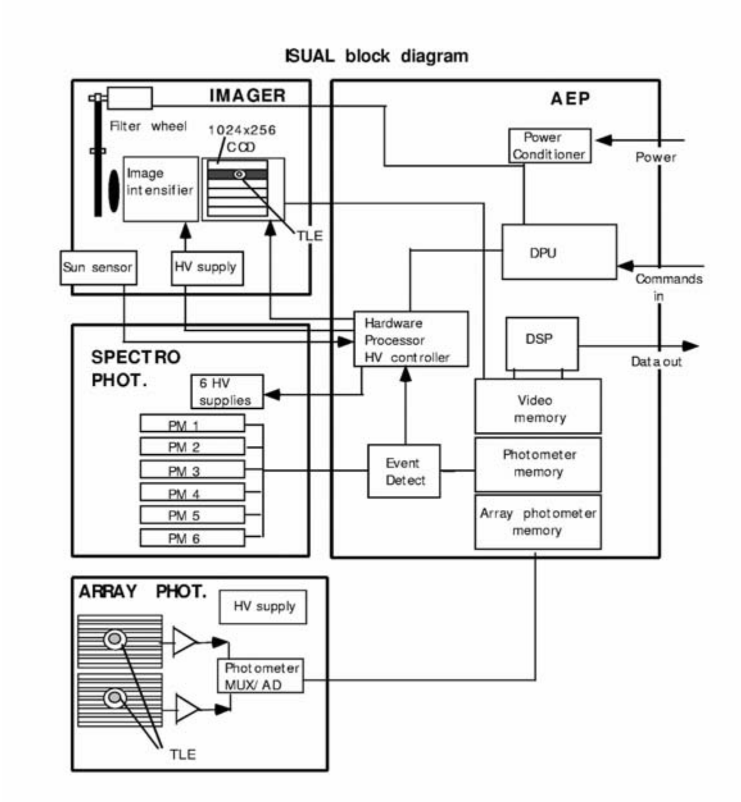


Figure 2. The ISUAL instrument block diagram.

plane. Since the width of the coverage is 1090 km the approximate area of horizontal coverage is $1000\times(3106\text{-}2000) = 10^6$ km^2.

The detector is an intensified frame transfer CCD of 2048×1024 pixels. The image intensifier (made by Delft Electronic Products) is a proximity focused tube with a red enhanced, so-called S25 photocathode on the input window (Figure 3). The intensifier tube can be operated in a gated configuration by reversing the voltage between the photocathode and the micro-channel plate (MCP). To set the gain of the intensifier, the MCP high voltage is adjusted by the DPU. The electrons from the microchannel plate are accelerated and they impact on the phosphor in the image tube. The image tube phosphor has a separate high voltage supply. A tapered fiber optics (Figure 3) is used to relay the image intensifier output image on to the CCD. The ISUAL imager CCD is used mostly in a 2×2 binned pixel configuration, where each pixel is 12×12 μm and the maximum charge that can be stored on each pixel is 105,000 electrons. One half of the area, (1024×1024 pixels) 512×512 resolution elements, was masked during the manufacturing process and the other half was left open and is light sensitive. In ISUAL there is an additional mask to restrict the light sensitive region to only the top 128×512 resolution element region. The images therefore have 4 to 1 aspect ratio and it is possible to stack eight pictures on the CCD containing 128×512 resolution elements each. The stacking is illustrated at the bottom of Figure 1b. The limb image is focused on the top, unmasked area of the detector. A combination of masks covers the rest of the CCD and this area represents the image storage region for the fast exposure sequences. After an image exposure is completed the entire stack of images is shifted down and the read out electronics picks up the last row of the storage register. The image stacking permits taking a fast sequence of eight exposures containing a sequence of short duration (>1 msec) images. In the standard operating mode, while the system is idle, the detectors take data but only minimal data is recorded. When a flash is detected by the trigger detection hardware driven by pre-selected SP channels, the data capture mode is initiated and a preprogrammed sequence of images is recorded in memory. After each exposure sequence is completed, the CCD storage area is full and no more images are taken until all the images have been completely read out. The duration and repetition rate of the exposures are all programmable. It should be noted that this technique permits the capture of images, which are taken prior to the occurrence of the triggering event. The imager filter chamber can be temperature controlled by regulating heaters located in the filter wheel housing. The filters are of the low temperature coefficient variety with minimal wavelength change due to temperature and the heaters would not be used under normal circumstances. The CCD builds up signal at a slow rate even while it is not exposed to light. This building up is called “dark current”. The CCD has a thermoelectric cooler system that can be used to suppress dark current in the long exposure low light level operations that are desirable for airglow and auroral observations. This was also a pre-cautionary design feature that would be important if the spacecraft were to run warmer. The ISUAL instrument can be operated in sprite burst mode to study fast spatial/temporal profiles of TLEs in high time resolution (up to 1000 frame rate i.e. 1 msec exposure time). This was described above and in this mode the photometer trigger algorithm commands the instrument to take up to 8 consecutive exposures and store them on the CCD. After that the instrument data system reads the CCD, which can take up to 100 msec while there is a dead time and the CCD would be unable to take another image even if another trigger were to occur. If continuous trigger readiness and data taking is desirable then the exposure times have to be lengthened to about 20-30 msec. For continuous data taking such as observing aurora and airglow, the ISUAL DPU can be made to issue periodic artificial triggers. There is also a continuous "aurora mode" in which the instrument takes 1 second duration integrations in a continuous sequence.

Examination of the video recordings taken by the space shuttle video cameras (e.g., Vaughan et al., 1992) showed that it could be quite difficult to distinguish TLEs from the accompanying lightning flashes. An intense cloud-to-ground flash usually precedes the sprite event illuminating the thunderstorm cloud above the flash with very high intensity light. A camera viewing from a spacecraft includes both the flash as well as the TLE in the field of view. The

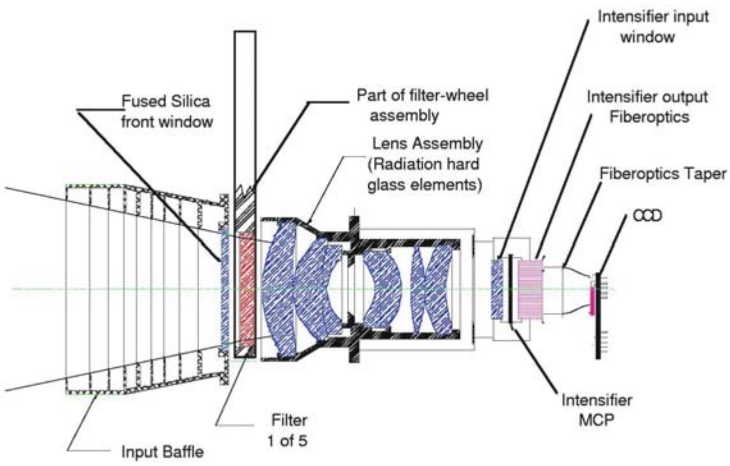


Figure 3. Imager cross sectional view.

intensity of the flash can be so large that a camera that was not designed specifically for the purpose, could be blinded. The ISUAL imager design uses several techniques to minimize the contamination from the parent lightning. ISUAL field of view is directed towards the Earth's limb and flashes near limb have large (altitude) separation between the TLE and the lightning. In some cases the lightning can be completely hidden by the solid Earth's Limb. Appropriate spectral filtering was also used to select specific spectral features (see Table 2 in Section 6.2.3) to maximize the detection of the TLE induced luminosity and reduce the broad continuum signature of lightning. By taking fast exposures it is also possible to maximize the intensity of the short duration TLE compared to the relatively long duration lightning.

A photograph of the ISUAL imager is included as Figure 4. The imager filter properties are shown in Table 1 and Figure 5.

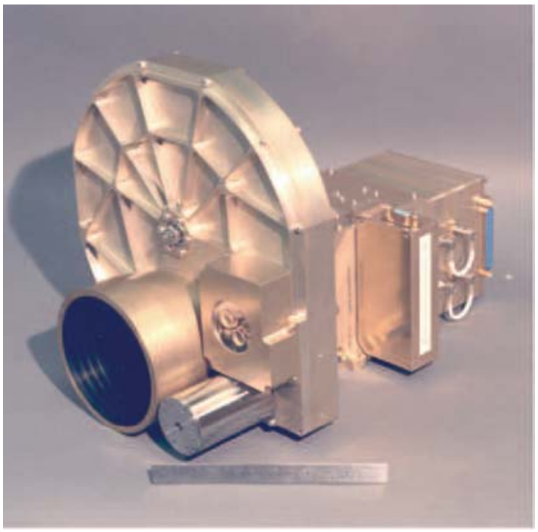


Figure 4. Photograph of the ISUAL imager camera flight unit.

6.2.3 The Spectrophotometer

The ISUAL imager produces an image that is a 2 dimensional luminosity distribution of the TLE in a specified wavelength band with moderate time resolution. For simultaneous measurements of the high time resolution (0.1 ms sampling) temporal profile of the TLE emission in several pass bands, the spectrophotometer (SP) was included into the ISUAL payload. The SP field of view is approximately the same as that of the imager.

Table 1. ISUAL imager filters. Note that the band limits are for paraxial rays only. The filter curves shift towards the blue for any object lying off axis. OI is atomic oxygen.

Imager Filters			
Channel number	Nominal filter	Lower limit 10% (nm)	Upper limit 10% (nm)
1	N_2 1PG	622.8	754
2	760 nm O_2 atmospheric band (airglow, aurora)	757.8	768.8
3	630 nm OI (aurora, airglow)	626.3	636.4
4	557.7 nm OI (aurora, airglow)	554.7	562.8
5	427.8 nm N_2^+ ionized N_2	425.3	431.8
6	Broad band no filter	425	890

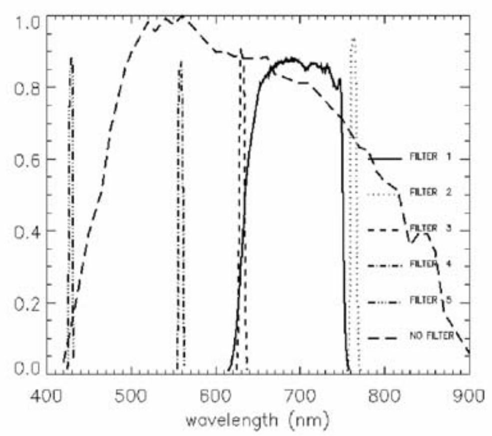


Figure 5. Imager filter profiles for the five filters and the measured responsivity of the unfiltered instrument labeled as filter 6. Its peak is normalized to one.

The spectrophotometer (SP) has six channels that are electrically and mechanically closely similar to each other. A typical channel module is illustrated in Figure 6. The light comes in through a collimator assembly (1) and encounters the filter in the filter assembly (3). The filter is mounted on a special mount that permits the temperature control of the filters by heaters (8). The filter temperature is monitored with a thermostat for telemetry and/or control. The lens, located behind the filter, focuses incoming parallel light on the aperture mask (5). A horizontal slit is cut out of the mask to define the field of view that is similar in size and shape to the imager field of view. The phototubes (6) were rugged photomultipliers procured from EMR in New Jersey. The tube windows and photocathodes were specially selected depending on the wavelength requirement of the channel module. Each visible channel contains a light emitting diode to produce a calibration stimulus for pre-flight and in flight checks on the instrument status. The SP channels operate in an analog mode and the PM tube current is sampled and digitized at a sampling rate of 10 kHz (0.1 ms integration time) in the standard fast mode intended for TLE studies. There is another data rate and the PM tube current is sampled simultaneously at a rate of 1.2 Hz. These data are used to synoptic studies of aurora and airglow. All

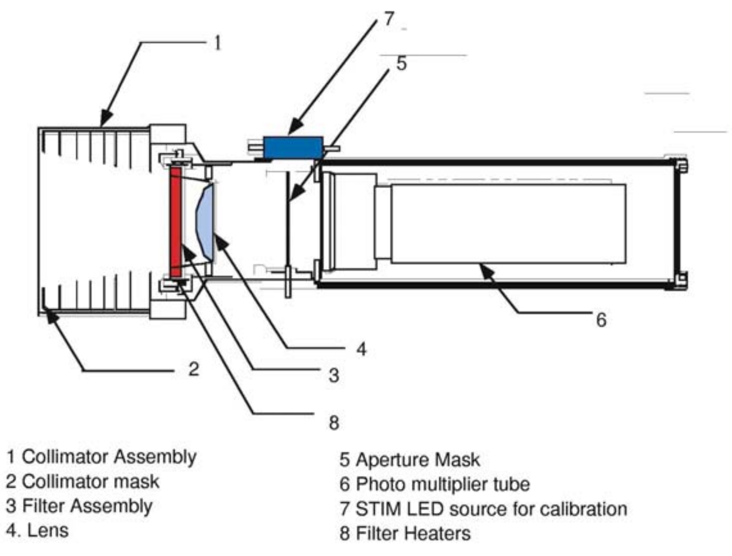


Figure 6. Photometer typical channel cross sectional view.

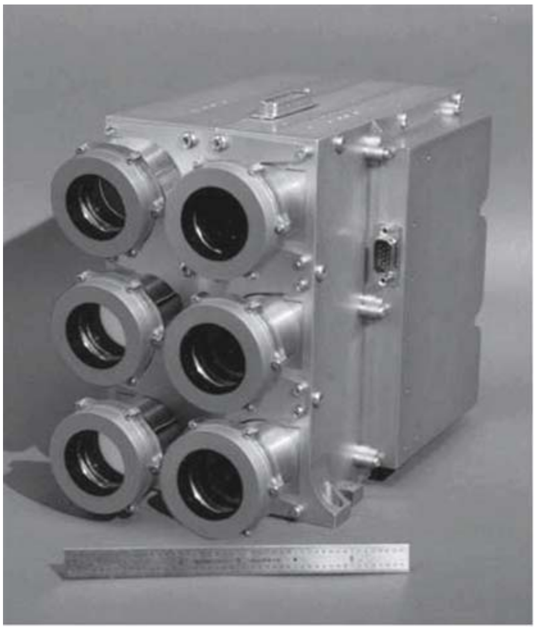


Figure 7. The ISUAL spectrophotometer.

the photometers are approximately boresighted with the ISUAL imager. The wavelength band selection for these photometers is shown in Table 2 and the band profiles are illustrated in Figure 8. The wavelength selection was guided by the following considerations: It was hoped that the far ultra-violet (FUV) channel 1 of the spectrophotometer would produce a clear UV signature from emissions that originate above the ozone layer and therefore it would not be affected by lightning and that this channel could be used as a TLE trigger for the ISUAL system. Channels 2, 3 and 4 were expected to observe the N_2 2^{nd} positive band at 337 nm, the N_2^+ 1^{st} negative band at 391.4 nm and the N_2 1^{st} positive band to provide information on electron energy distribution of the TLE events. Channel 5 is the permitted transition of O at 777.4 nm, a commonly observed feature in lightning. Channel 6 is a broad band middle UV detector. Channel 4 (mostly N_2 1^{st} positive band) is the most commonly observed spectral feature in TLEs, best understood from numerous ground-based measurements. The baseline design assumed that triggering of the imager would be using channel 4 however other channels could also be programmed to act as triggers. The imager and the photometer were calibrated in the laboratory during pre-flight test. The imager properties, field of view, resolution, absolute sensitivity in all filters, and the variation of sensitivity with MCP high voltage were recorded while the imager was exposed to light sources of known characteristics. The imager absolute sensitivity was obtained with a light source, which was spectrally a continuum and spatially an extended source. By expressing the extended source in equivalent Rayleighs[1] at the peak transmission of the filter an absolute calibration of the imager in digitized CCD signal versus Rayleighs source intensity was obtained. The SP channels were individually calibrated with respect to the size of the field of view, the absolute sensitivity and the variation of sensitivity with high voltage applied to the photomultiplier tube. Since the photometer is sensitive only to photon flux incident on its front lens, the photometer calibration flux is equivalent to the calibration source radiance times the size of the solid angle of the calibration source in units such as Rayleigh times steradians. So in order to find an unknown source intensity in Rayleighs we need to obtain the size of the source i.e. the solid angle that the

Table 2. ISUAL photometer filters. Note that the band limits are for paraxial rays only. The filter curves shift towards the blue for any object lying off axis. OII is singly ionized atomic oxygen.

Spectrophotometer (SP) channels			
Channel number	Nominal filter	Lower limit 10% (nm)	Upper limit 10% (nm)
1	UV Channel	150	280
2	N_2 2PG (0,0) 337	333.5	341.2
3	N_2^+ 391.4 nm (ionized N_2)	387.1	393.6
4	N_2 1PG	608.9	753.4
5	OII 777.4	773.6	784.7
6	Broad band UV	270	410.2

[1]Rayleigh, the unit of intensity of glowing atmospheric gases. It is equivalent to a source producing $10^6/4\pi$ photons per cm^2 per steradian per second at a detector (Chamberlain, 1961, pp. 569). For example a detector will observe a 1 Rayleigh source when viewing end on a column of gas of 1 cm^2 in cross-sectional area, containing 1 million particles where each particle produces 1 photon per second.

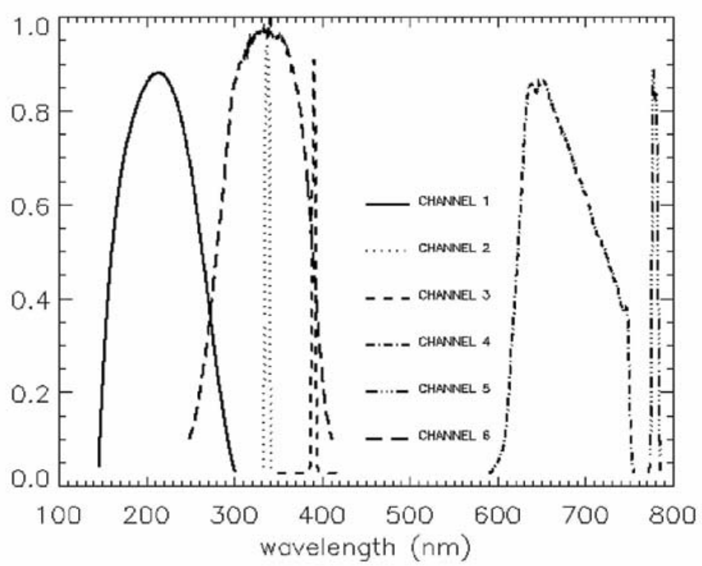


Figure 8. ISUAL photometer channel responsivities in arbitrary units.

unknown source subtended at the photometer. To obtain the unknown source intensity the measured signal has to be divided by the solid angle subtended by the unknown source. The size (solid angle) of the unknown source was derived from the simultaneous imager data.

6.2.4 Data Interpretation of the Spectrophotometer

In order to investigate the energetics of TLE production it would be desirable to relate the measurement to the production rate of a particular band. The SP detects only the fraction of the band emission that is within the photometer filter pass band. We integrated the product of the molecular band components and the wavelength profile of each photometer channel for all major N_2 bands to help us in relating the SP signals to the total molecular band production. In our calculation the channel responsivity maximum for each channel was normalized to unity because the preflight absolute responsivity calibrations (photometer counts per incident photon flux) were obtained at the response peak of each channel. We have adopted Vallance-Jones (1974) intensities for N_2 molecular band components in spite of the fact that the vibrational distribution and rotational temperatures may not be the same as in auroras. The results of these calculations, the fractional contribution of each molecular band of unit intensity for each SP channels is shown in Table 3.

In Table 3, for filter 1 we have included the O_2 absorption as well as the filter response. The absorption was calculated to 80 km altitude and the O_2 cross sections were calculated by a web tool using polynomial coefficients (Minschwaner et al., 1992) including the Herzberg continuum cross section in the range in the wavelength of interest (Yoshino et al., 1988). The O_2 absorption calculation has to be performed on a case-by-case basis because this depends on the geometry of the observation. Filter 1 transmits only in the far and middle UV and it is a very useful channel that can see only those emissions that are produced at altitudes higher than the ozone layer (30 km). The table shows that filter 1 appears to have a strong contribution by components of the Lyman-Birge Hopfield (LBH) band above 190 nm and that there are no other N_2 molecular band contributions. The degree that LBH is emitted depends of course on the lifetime of the $a^1\Pi_g$ state. The $a^1\Pi_g$ state life time was found to be 80 microsec by Shemansky (1969) or >76 but <116 μs by Pilling et al. (1971). Vallance-Jones (1974) states that the quenching coefficient for $N_2(a^1\Pi_g$, v' = 0) is $<3\ 10^{-10}$ with a quenching altitude of less than 95 km. However two-photon laser excitation measurements of the quenching rate of the N_2 $a^1\Pi_g$ state for N_2 (Marinelli et al., 1989) shows it to be $2.2\pm0.2\times10^{-11}$cm^3/s. Combining this with the above lifetimes the quenching height should be lowered to 70 km. In summary quenching of LBH is likely to be less important in elves than in sprites or jets.

A good recent reference for other emissions in the FUV (far ultra-violet) and MUV (middle ultra-violet) that are relevant to filters 1 and 2 is the auroral spectra taken by the Midcourse Space Experiment (MSX) satellite (Strickland et al., 2001). For example ISUAL channels 1 and 2 would pass the prominent auroral emission feature seen in the MSX spectra near 214.5 nm (Dick, 1978). The 247 nm OII and 297.2 nm OI emissions have relatively long lifetimes and

Table 3. Table of molecular band contributions into each ISUAL photometer channel.

	N_2 bands 1P	N_2 bands 2P	N_2 LBH > 150 nm	N_2^+ Meinel	N_2^+ 1NG
filter 1	–	–	17%		–
filter 2	–	27.80%	–	–	0.80%
filter 3	–	–	–	–	66%
filter 4	11%	–	–	4.60%	–
filter 5	2.6%	–	–	–	–
filter 6	–	84%	–	–	37%

the atomic O density required for the production of these is minimal at TLE altitudes. Similarly the lifetime of the upper state of the Vegard-Kaplan is also too long to be of significance below 100 km and therefore in TLEs.

The second filter passes the N_2 2P (0,0) band and Table 3 shows that 27.8 % of the emission is within this filter band. Since the filter curves were normalized to unity this number is the same as the (0,0) component value in the band computation of (Vallance-Jones, 1974). The 3^{rd} filter was intended for the measurement of the N_2^+ first negative (0,0) band, which band contains the 66% of all the first negative components. The excitation cross-section for producing the upper state of this by electron impact has been measured by Borst and Zipf (1970). They showed that the ratio of the total ionization cross section to the excitation was nearly constant over the energy range from 30 eV to 10 keV, and had a value of 14.1. This would indicate that where the high energy electrons are dominant i.e. in an aurora the measurement of the 391.4 nm emission of the N_2^+ first negative (0,0) is a direct measurement of the total ion production. However TLEs are likely to produce significant electron fluxes in the less than 30 eV energy range where the ratio between the two cross sections is variable.

Filter 4 is responsive to the N_2 1^{st} positive and N_2^+ Meinel bands with 11 and 4.6 % contribution to each, respectively. These bands were chosen because these bands had been found to be the most intense contributors in sprites and elves in ground based measurements (Mende et al., 1995; Hampton et al., 1996). Channel 5 centered on the 777.4 nm has a strong signal for lightning which is consistent with this feature being used to monitor terrestrial lightning e.g. Christian et al. (2003). It has a minimal response for TLEs in spite of the fact that it is a permitted transition and in this wavelength region the atmosphere is fully transparent. This is because of the lack of atomic oxygen at the altitudes in the mesosphere. On the other hand, lightning processes are sufficiently energetic to dissociate O_2 and excite the atomic O. In the thermosphere, at high altitudes, there is a high density of O and the excitation of this feature is commonly seen in aurora and airglow. Photometer channel 6 covers the broad band in the middle UV with substantial input from the N_2 2^{nd} positive and N_2^+ first negative bands.

6.2.5 The Array Photometers

As we have seen ISUAL has an imager which is capable of producing high spatial resolution images but only with modest time resolution which is insufficient to resolve the temporal variation of the TLE luminosities. There is also the SP, a photometer which has high time resolution but provides no information about the spatial distribution or development of the TLE. A third instrument was incorporated in the ISUAL payload that has the high time resolution characteristic of a photometer but which also provides some spatial resolution in the form of one dimensional vertical imaging. This instrument is called the Array Photometer.

The array photometer (AP) is a two-wavelength channel instrument, each takes data from sixteen separate regions located vertically above each other. This instrument has high temporal and spatial (altitude) resolution for determining the altitude propagation properties of the phenomena.

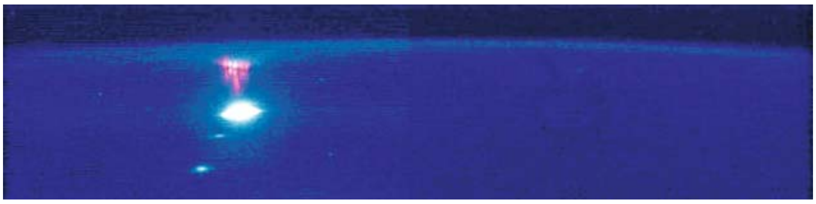
The ISUAL instrument includes two AP channels. Each channel consists of a bandpass filter, an objective lens and a multi-anode U5900-01-L16 Hamamatsu photomultiplier. One channel has a bandpass filter with a passband between 370-450 nm and the other channel is equipped with a filter of a passband between 530-710 nm. It was highly desirable that the AP have similar wide field of views as the other ISUAL instrument components. The photomultiplier has 16 strip anodes. The total anode area of the photo multiplier tube (PMT) is approximately a square with sides of 16 mm in length. Hence, an objective lens was needed to map the spatially wide image into the square 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 were used. The resulting FOV of the array photometer is 22° (horizontal) and 3.6° (vertical). Therefore, the FOV for each anode is 22° by 0.23°, corresponding to $\sim$14 km in height at a range of 3500 km. The two array photometers are bore sighted and 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; Sera et al., 2001).

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 lightning. After that the data is sampled at a lower rate at 2 kHz until $\sim$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 peak intensities 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.

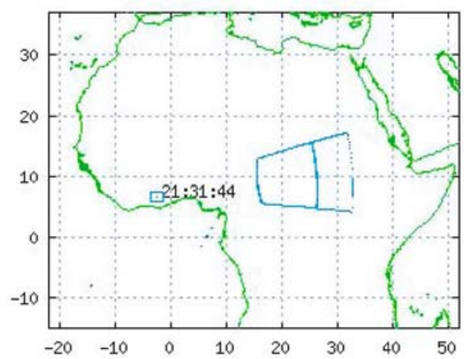
The AP also operates in a burst mode and is triggered by a signal issued by the SP signals and the trigger algorithm. The AP is able to run in pre-triggering or in immediate triggering modes according to the channel of the spectrophotometer used for initializing the triggering signal. Blue jets, aurora and airglow could also be studied by AP at a slow sampling rate of 200 Hz with a 100 Hz low pass filter. This relatively low sampling rate is used for long duration observations where the phenomena do not require the full time resolution of the instrument. One of the unique auroral objectives that could be studies by the AP is the flickering aurora, which is blinking at a rate of up to 100 Hz. In this case the data will be recorded continuously without a triggering signal. The sensitivities of photometers are adjustable by varying the high voltage of the PMTs, so that measurements of luminous emissions can be made with a large intensity range, covering faint airglow to intense filaments of sprite heads.

6.3 Initial Observations with ISUAL

Soon after commissioning the ISUAL instrument it was able to record various types of TLEs. A particularly nice sprite was observed on July 4^{th} 2004 and a colorized version of the sprite is shown in Figure 9a. Underneath, Figure 9b shows the geographic position of the field of view of the imager observing the sprite. Another nice event was observed on the 18^{th} of July 2004. The event is illustrated in Figure 10 where we present the image sequence of all 6 images (29 msec exposures each) taken by the ISUAL imager. The instrument operating mode saved one image prior to the trigger and therefore triggering occurred in the second frame. From the first frame we can see that there was a substantial lightning activity in progress before the trigger. The second frame shows the sprite in full bloom. There is a faint residue in the third frame. In the fourth frame we see another sprite which is located to the right of the one previously observed. The fifth frame is relatively dim but a new sprite is seen on the sixth frame. Whether this is a new sprite or a re-ignition of the one seen in the fourth frame is open to question. The corresponding photometer data is presented in Figure 11. Channel 1 (150-280 nm) is the far ultraviolet channel responding mostly to the LBH emission. Channel 2 (337 nm) is the (0,0) group of the N_2 2^{nd} positive band containing theoretically 27% of the entire band. The 3^{rd} channel is N_2^+ 1^{st} negative showing the presence of ionized N_2. Channel 4 has a filter that passes part of the N_2 1^{st} positive band and some of the N_2^+ Meinel band. It is a broad band filter (see Figure 8) for simplicity it was labeled "N_2 1P". Channel 5 is the 777.4 nm line of atomic O and is a relatively good representation of the total power output of the lightning. Channel 6 (250-390 nm) is a broad band UV filter passing a mixture of N_2 and N_2^+ bands. Note that lightning has a strong continuum emission that would be a contaminant in all TLE channels except in channel 1. The trigger occurred at 21:30:15.316. According to the image (N_2 1P) there was substantial emission in the frame prior to the one containing the trigger. Channel 4, the 1^{st} positive SP filter shows that the baseline was elevated even during the first exposure. Most of the other channels show two distinct peaks between $\sim$308 and 320 msec. The first peak seems to have been caused by the light-



(a) July 4, 2004/21:31:15.451



(b)

Figure 9. (a) Sprite event over Africa. (b) The map shows the satellite position in local time and the field of view of ISUAL observing the sprite.

ning. We believe that the second, the larger peak in the first two channels, is caused by the sprite. Channel 1 is the far ultraviolet channel, which is seeing emissions (LBH) that are emitted by the atmosphere above 30 km. There is a very nice strong signal in the second channel which is the N_2 2^{nd} positive. The quenching height of this emission is about 30 km and we would expect minimal contribution from lightning other than the continuum. There is a strong response in channel 4 (at 357 ms) which appears to be a data glitch or penetrating particle event because it is not repeated in any other channel. There are a couple of small flashes at about 372 and 382 ms, the peak that occurs at 372 msec is most likely to be caused by the lightning flash seen in frame 4. The second set of peaks that obey the same pattern is at 433 and 438 ms.

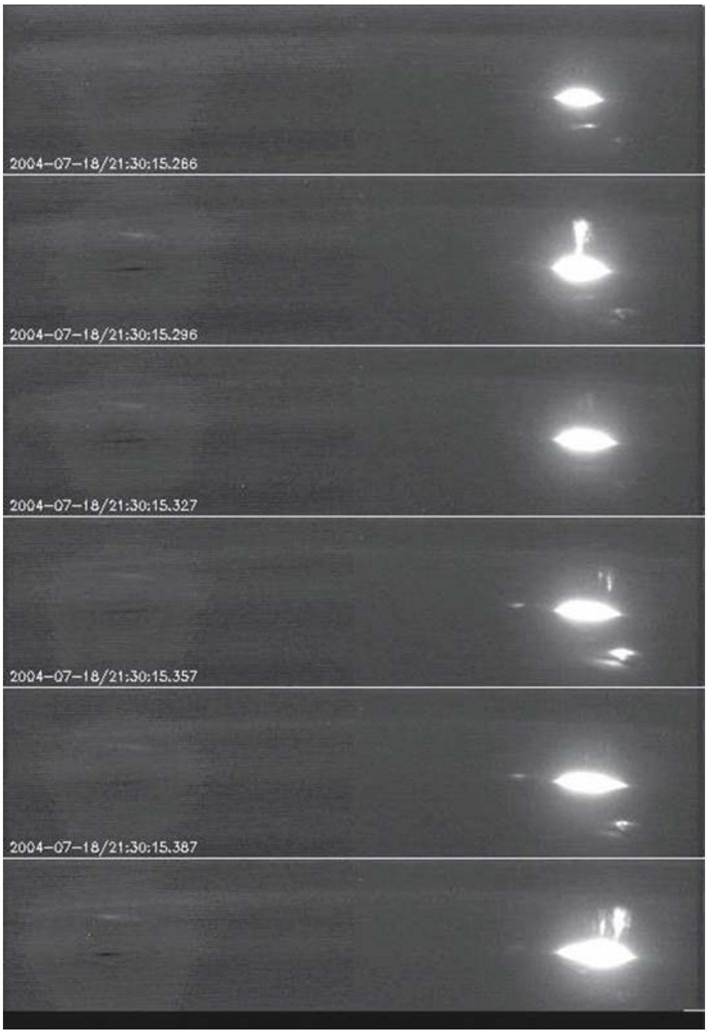


Figure 10. Sprite sequence that occurred on July 18, 2004 at 21:30:15.266 to 21:30:15.446

We see a strong contribution in channel 1 and 2 by the second feature which we believe is the sprite. Channel 3 is mostly sensitive to the N_2^+ 1^{st} negative band and shows the presence of ion production in the sprite or the lightning. It appears that the first sprite had the strongest contribution to locally produced ions. Channel 4 is mainly responsive to the 1^{st} positive and to some degree to the N_2^+ Meinel bands. The strong signal in channels 3 and 5 are showing the presence of energetic electrons that are capable of ionizing the atmosphere and they are characteristic of lightning. The set of peaks at 433 and 488 are consistent with image 6 showing that another lightning strike occurred at 433 msec, which was closely followed by a new sprite that can be seen in channels 1 and 2 at 438 msec. In Figures 12 and 13 we show an elve with minimal lightning

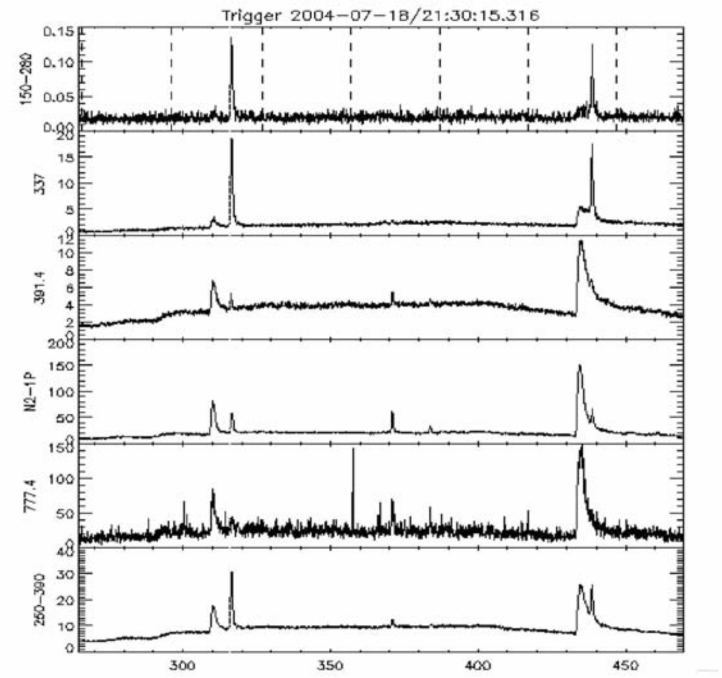


Figure 11. SP data for the sprite event of Figure 10. Vertical lines in channel 1 indicate the six (29 ms duration) exposures of the imager. The signal is shown calibrated in MR-s referenced to the wavelength of the peak filter transmission profile and to the solid angle subtended by the sprite on the second image (Figure 10). The x axis is time in ms. Channel 4 $N_2$1P filter wavelength profile is shown in Figure 8.

contamination. In Figure 13 the 777.4 nm channel shows that the lightning was a very sharp and sudden pulse at ∼456 msec. We assume that the elve caused the apparent longer lifetime of the luminosity in the other channels. There is a distinct amount of 391.4 nm emission showing that there is ionization during this event. Channel 6 the combined middle UV channel is actually saturated by this elve. The y axis was calibrated using the preflight calibrations and the angular size of the elve is derived from the camera image of Figure 12. The peak intensities reach very high values for example the $N_2 1^{st}$ positive (channel 4) reaches over 20 MR. In spite of this high intensity the elve appears to be relatively dim in the image because the phenomena is short- lived approximately 1 msec. Thus an auroral pulse of 1 sec duration would only need to be 20 kR for equivalent energy output.

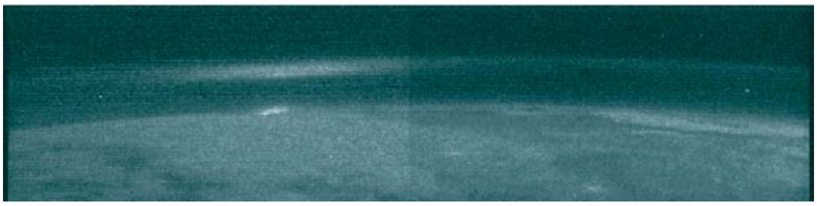


Figure 12. Elve observed on 04/07/05 with trigger time at 14:41:57.456

6.4 Summary

The new instrument the Imager of Sprites/Upper Atmospheric Lightning (ISUAL) has been in orbit since May 20, 2004 making new observations of TLEs from space. The ISUAL payload includes a visible wavelength intensified CCD imager, a boresighted six wavelength channel spectrophotometer, and a two channel Array Photometer (AP) with 16 vertically spaced horizon ally wide sensitive regions. The imager is equipped with 5 selectable filters on a filter wheel, for most observations a filter passing the N_2 1^{st} positive band was used. The two channel AP is fitted with broad band blue and red filters. In this chapter we have presented examples of ISUAL imager and photometer data. One of these is a sequence of sprites with strong accompanying lightning activity. The other is an elve with only minimal lightning intensity. The photometer and the imager were calibrated pre-flight and using these numbers it was possible to compare the various responses by the photometer to the various phenomena. We have tabulated the results in Table 4 where we present intensity ratios to SP channel 4 which is a measurement of the N_2 first positive band. This band has been found to be the most intense in ground based observations of high altitude TLEs. The 1^{st} SP channel with the UV pass band from 150-300 nm is mostly blind to lightning contamination because the atmosphere is opaque in the region well above the thunderclouds. In this channel the signals mainly represent N_2 LBH band emissions. Only the higher wavelength components of LBH can get through because of the strong O_2 absorptions for wavelength below 200 nm. This emission would also be quenched at low latitudes. Although there are strong signals in these bands due to sprites or elves, the intensity is less than a percent of the N_2 1^{st} positive in terms of absolute

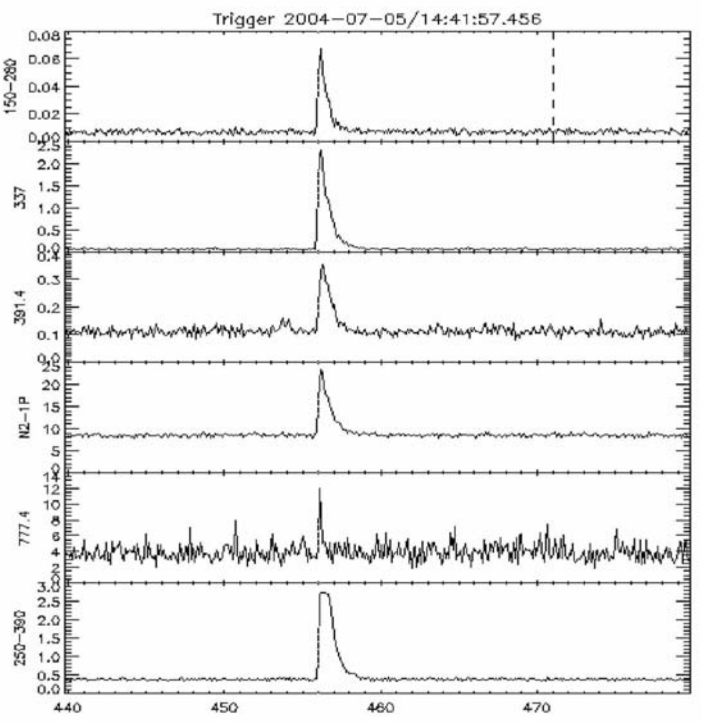


Figure 13. Photometer traces of the elve (shown in Figure 12).

quantities. Channel 2 is optimized for the detection of the N_2 2^{nd} positive (0,0) band at 337 nm. This is very bright in TLEs. This was relatively bright in our sprite observation, 50% of the N_2 1^{st} positive in the sprite and it was only about 12% in the elve. Channel 3, the 391.4 nm channel measures the $N_2^+ 1^{st}$ negative emission which is a direct indication of the presence of electrons with sufficient energy to ionize N_2. The lightning has the strongest relative signature in this emission (6%), the sprite is second with 4.3 and the elve produces the least, 1.6%. All these results are qualitatively consistent with the fact that lightning produces high energy electrons that can consistently ionize the gas whereas sprites produce a softer electron energy distribution while elves have an electron energy distribution with even softer characteristics.

The main focus of the ISUAL data analysis is to identify the temporal and spatial distribution of the emissions and compare them to the prediction of theoretically predicted processes leading to the various excitations seen. Using the satellite platform we expect to widen our case studies to larger samples and we hope to eventually produce statistical surveys of the global properties of TLEs.

Channel	Lightning	Sprite	Elve
1	0.00%	0.37%	0.35%
2	6.00%	53.33%	11.76%
3	6.00%	4.33%	1.65%
4	100.00%	100.00%	100.00%
5	120.00%	0.00%	0.00%
6	20.00%	66.67%	12.94%

Table 4. Approximate intensity ratios to channel 4 for the three types of events as derived from the measurements.

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