TLE DETECTION BY INSTRUMENT AND BY PROPOSED HUMAN VISION SYSTEM FOR SPACE-BASED MISSIONS

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ABSTRACT: This study, on both instrument and human detection of TLEs (transient luminous events), was made to help prepare for the MEIDEX Sprite mission. First, we estimated the apparent brightness and other features of TLEs, as viewed by a space-based instrument. Lightning interference with the detection, and storm-finding tactics, were also considered. It was found that sprites, elves, and jets should all be detectable, but care is needed to minimize lightning interference. Red to near-IR bands are suited to sprite and elve detection, and blue to near-UV bands for jets and starters.

Second, it is useful, and we think feasible, to have the crew of a manned spacecraft search for TLEs by eye. This would increase the value of instrument studies, and might even be used when an optical instrument is not available. However, the astronauts should be equipped with a suitable viewing system. The most important part of this system is a viewer with a filter designed specifically to admit TLE light visible to the eye while blocking lightning light at other wavelengths.

INTRODUCTION

This study emerged from a planning exercise for the MEIDEX Sprite experiment which was carried out aboard the STS-107 Space Shuttle mission. The goal was to estimate in advance the experiment's ability to detect TLEs, based on the specifications for the detecting instrument and also on established knowledge of different types of TLE. Theory of molecular emissions used in aurora studies was applied here. The results estimated how well the instrument might be able to detect each type of TLE, and helped the mission with tactical decisions such as filter selection and storm finding. Other issues, in particular interference by lightning light, were also considered. The conclusions from this study, done before the mission, can be compared to the actual mission results (see *Yair et al.,* 2003), to improve the technique of space-based detection for future missions.

As the work proceeded, it became apparent that detection of TLEs by eye on manned space missions might be useful to increase the volume of TLE data. There are, however, some problems in doing this. For example, it can be difficult to see the TLE against the lightning illuminated cloud. We did a concept study for a system designed to overcome these problems and permit efficient human viewing of TLEs from space. It was not possible to carry out such an experiment on STS-107, but we advocate that it should be attempted some time in the future from the Space Shuttle or the International Space Station.

INSTRUMENT USE

METHOD

The MEIDEX detection instrument was a Xybion IMC-201 camera recording images on a CCD detector (486 vertical x 704 horizontal pixels) through an optical filter. The exposure duration was 33.3 ms and the pixel size 1.365×10^{-7} sr. The instrument could be pointed at selected storms. The following six optical filters were available, expressed as central wavelength and passband width, in nm: (340, 4), (380, 4), (470, 30), (555, 30), (665, 50), (860, 40). For further details about the mission, see the paper by *Yair et al.* (2003) at this conference. A schematic representation of the instrument view of the storm with its TLEs is shown in Figure 1.

We worked on the premise that TLEs emit their light in systems of molecular emission bands, in the same manner as auroras do. We considered existing knowledge of TLEs to estimate the brightness, band system, size, shape, and duration for each type of TLE. Values of brightness, etc., presented here are order of magnitude values only since this paper is not intended to be a detailed discussion of TLE features; the method can be applied similarly if the values are changed. Using molecular emission tables, we estimated the brightness seen by the instrument through each filter band. From this, we could calculate the number of photons received per unit aperture per steradian per second. Knowing the features of the instrument, one could then calculate the number of photons received per pixel for each exposure period, and so judge how well the instrument might see the TLE through a given filter. Lightning brightness can be estimated by a similar approach. We can then suggest which filter to employ, how to avoid interference from lightning light, and how to find the most useful storms.

SPRITES

A sprite is associated with a specific large amplitude CG positive lightning flash, often over the stratiform region of a large mesoscale convective system. Typically its base height is about 50 km, its size of order 20 x 20 x 20 km, and its duration of order 5 ms. We assume that a moderate sprite emits about 10 kJ of optical energy in visible wavelengths. It is mainly a neutral nitrogen molecular emission.

We will show the calculation for the 665 nm filter passband, which was the one most used in the mission. By theory, 1 J represents 3.3 x 10^{18} photons at 665 nm emitted in all directions (4 pi steradians), which is 0.8 x 10^{6} photons per cm^2 for a 20 x 20 km sprite in limb view (Figure 1), or 0.8 R-s (Rayleigh-seconds) by definition.

Assuming all emission is neutral nitrogen, and using molecular emission tables, we estimate that 80% (8 kJ) of the 10 kJ is within this passband, and this gives 6.5 kR-s time-integrated brightness. 6.5 kR-s is about 5 x 10^{8} photons per sr per cm^2. This gives about 70 photons per pixel for our instrument for each cm^2 aperture. Similarly we find that the brightness ratio through the filters 860 nm, 665 nm, 380 nm, 340 nm is about 1.8 : 1 : 0.05 : 0.05 .

If the instrument aperture is known, and light loss within the instrument is allowed for, the number of photons received by the CCD detector can be estimated and the detectability of the TLE evaluated. Assuming an instrument with an aperture of a few cm^2 and allowing for moderate instrument light losses, this moderate sprite should be clearly detectable.

In fact, several sprites were clearly detected by the MEIDEX mission; see *Yair et al.* (2003).

ELVES AND AIRGLOW

An elve is associated with a specific large amplitude lightning flash, and is probably mostly a neutral nitrogen emission. It is an emission at the airglow layer, about 90 km altitude and a few kilometers deep, lasting at peak brightness about 0.5 ms. It can be several hundred kilometers broad.

We assume that a moderate elve has a brightness of about 2.5 MR viewed from space at an oblique angle (i.e., not edge-on), in the visible to near-IR. About 0.4 MR of this would be received through our 665 nm filter, assuming neutral nitrogen emission. However, note that the elve spectrum is not known as accurately as the sprite spectrum; it may, for example, have some atomic emissions like airglow. This gives, for 0.5 ms duration, 2.5 kR-s time-integrated brightness.

However, in a space-based experiment, we may be able to see the elve in an edge-on (limb) view, which can give a 10 to 1 brightness advantage. Assuming a 3 to 1 advantage for a near edge-on view, the instrument receives 7.5 kR-s, or about 80 photons pixel $^{-1}$ cm^{-2}. This is similar to the photon reception for sprites and should again be sufficient for effective detection.

Airglow can be mistaken for a dim elve. However, we find that its brightness would be an order of magnitude dimmer than the moderate elve. Also note that airglow is constant in time, unlike elves.

Elves were detected very well during the MEIDEX mission (*Yair et al.,* 2003).

JETS AND STARTERS

A jet or starter occurs above a storm with a high top and a high flash rate, but is not linked to a specific flash. It is likely to occur immediately after a rapid burst of flashes. A jet extends in a column or cone from cloud top up to about 40 km and lasts about 300 ms; a starter is similar but shorter. The light is mostly blue to near UV, but the actual spectrum (neutral nitrogen, ionized nitrogen, or broadband) is not yet well known. The brightness is also not well known; it might be 10^2 to 10^3 kR in the visible range viewed from the ground.

Therefore a quantitative evaluation of jet and starter detectability is not yet possible. Also our instrument short wave filters (340, 380, 470 nm), which were chosen for a dust detection study, are not optimum for this purpose. Our initial estimate is that a moderate jet or starter might be detected by the MEIDEX camera, and would probably be easily detected by a future filter designed for the purpose.

Jets and starters have not yet been identified in the MEIDEX data (*Yair et al.,* 2003). This may be due to a lack of measurements with the shorter wave filters over suitable storms.

LIGHTNING

Lightning is important to a TLE study for three major reasons: First, the lightning is important to the TLE creation process and must be evaluated to study the TLE. Second, forecasting and tracking lightning helps identify likely locations for TLEs. Third, the brightness of the lightning illuminated cloud can interfere with the detection of the TLE. Here we will discuss the interference issue briefly.

Lightning gives both broadband and specific line emissions, mostly in the visible and near IR, less in the UV. Ultraviolet lightning light viewed from space would be much reduced by atmospheric attenuation

If an exposure period containing a TLE does not include lightning light, then lightning interference is not a problem. The chance of this happening for a given case is not accurately known, but is probably rather small because of the known relations of TLEs to thunderstorms.

Assuming that lightning light is recorded during the exposure period, we estimate the brightness received from the lightning illuminated cloud, based on the lightning light statistics of *Goodman et al.* (1988). Typically a few tens of kR-s integrated brightness would be received for the exposure period through the 665 nm filter when there is a jet or starter (but less through a UV filter). The flashes commonly associated with sprites and elves are stronger, and might give a hundred to a few hundred kR-s.

We estimate that lightning would be 10-100 times as bright as a moderate sprite. Therefore one should view sprites with a limb or oblique view so they will be separate in the field of view from the lightning illumination. Elves would also be dimmer than the lightning, but would be easy to find because of their high altitude and large diameter.

Jets and starters occur at lower altitude and close to the cloud than the other TLEs. However, the interference from lightning is less because the flashes are weaker in this case and because we can use a short wavelength filter. We believe that the jets and starters, seen through the correct filter, will sometimes be at least as bright as the cloud and therefore visible.

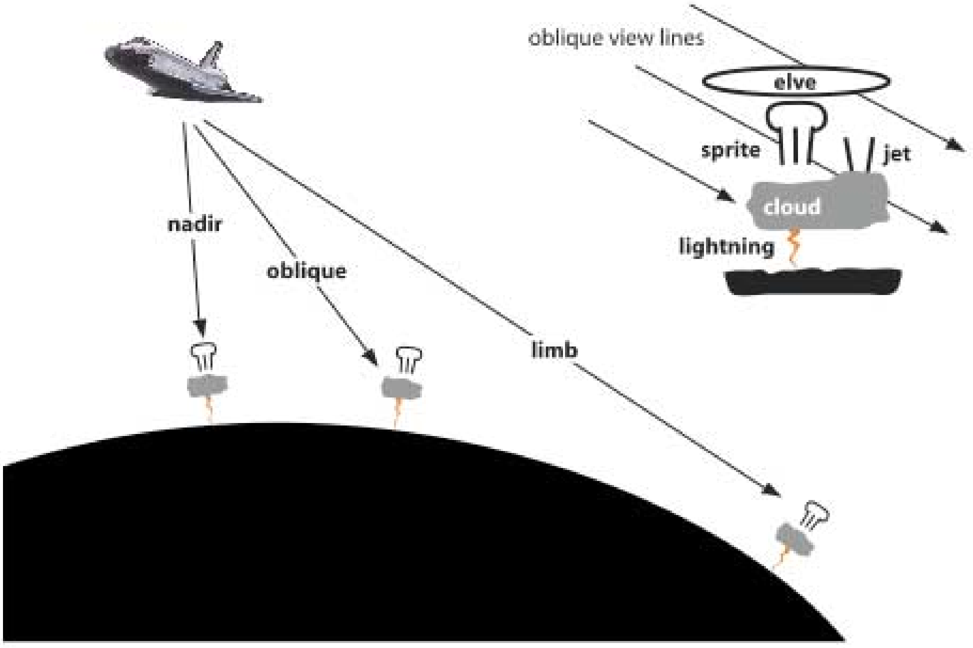

Figure 1. View from different directions of the storm and the TLEs – schematic diagram.

HUMAN VISION SYSTEM

CONCEPT

Sprites, jets, and elves have all been seen from the ground or from aircraft by eye; therefore it should be possible to see them from space. A human astronaut has certain advantages that ought to be exploited. The observing periods might not need to be rigidly scheduled long ahead of time. The astronauts can see dim objects; the Milky Way was easily seen from STS-107 without special equipment or preparation. A trained observer can recognize suitable storms. Human observation can be used by itself, or it can be used to enhance space-based or ground-based instrument data.

A design proposal was presented to the MEIDEX team. It was not possible to carry out this idea on STS-107, but the design is outlined here in the hope that it might be applied in the future.

VISION THEORY

The retina of the eye has detectors, called rods and cones, roughly analogous to the pixel receptors in a CCD instrument. Cones can see color but only work in bright light. Rods see only shades of gray, but can work in very dim light. In ideal circumstances, the eye can see a point source of light if it receives 100 photons. However, to see dim objects, the eye must be well dark adapted; this is especially important for rod vision. Dark adaptation begins immediately but takes about 20 minutes to complete. Unfortunately, any exposure to bright light reduces dark adaptation.

The eye's wavelength range is about 400 to 700 nm. However, the performance of the eye within this range is very wavelength dependent. The sensitivity of rod vision peaks at 510 nm and is better in the blue than the red. Cone (color) vision peaks at 555 nm and is better in the red than the blue. Therefore a dimmer object can be seen in the blue than the red, but the dim blue object will be seen only as gray. Dark adaptation is much more important in the blue than the red.

SYSTEM DESIGN

A system for human vision of TLEs has to pass as much of the TLE light as possible while reducing lightning light interference. The lightning light may obscure the TLE and also reduces the eye's dark adaptation. Sprites and elves will be seen in the red and jets and starters in the blue. Lightning light will appear much brighter than the TLEs partly because the eye is more sensitive to the green to orange light of the lightning. For this reason, optical filters, designed expressly for human vision, are needed to pass only those wavelengths that have bright TLE emissions while blocking all other wavelengths. Blocking lightning light is especially important for jet and starter observation.

Some study is needed to find the optimum filter passbands. A red filter to view sprites and elves might have a fairly broad passband of 590-700 nm to admit almost all of the neutral N_2(1P) visible light while still reducing the lightning brightness.

On the other hand, a blue filter to view jets and starters should probably have a narrow passband to reduce lightning light as much as possible. One option is a 425-430 nm passband; this contains significant emissions of both neutral N_2(2P) and ionized N_2^+(1N) light. Jets and starters have a relatively long duration; this should help with viewing.

Other features of the system would aid the viewing. It should be easily possible for the observer to look in different directions. A magnification aid would enable the TLE to be seen more clearly. Some means should be provided to help the observer record the results. The observer should be briefed in advance on the climatology and forecasts of storms.

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