LMS Mission And Science Requirements

Hugh J. Christian, Jr.

1. Overview

The Lightning Mapper Sensor (LMS) mission consists of fabricating a small, dual telescope, optical lightning sensor; flying it on a GOES spacecraft in CY2003; and measuring total lightning activity on a continuous basis over the continental United States, Central and South America and portions of the adjoining oceans.

The deliverables will consist of: 1) space qualified optical lightning sensors; 2) sufficient lightning data to thoroughly evaluate proxy relationships and contributions to the Earth Science enterprise; and 3) detailed evaluations of real time total lightning measurements for storm warning and nowcasting activities.

2. Mission Objectives

2.1. Objective 1

Measure total lightning activity over large areas of the Americas and nearby oceans on a continuous basis.

2.2. Objective 2

Develop an extensive lightning climatology to be used for global change research.

2.3. Objective 3

Demonstrate ability to deliver, on a real-time basis, lightning measurements that are of sufficient quality and quantity to for operational storm monitoring and severe weather warnings.

3. Mission Success Criteria

3.1. General

Demonstrate measurement of lightning from space using a staring optical imager that meet future research and operational mission requirements.

3.2. Specific

3.2.1. Produce and validate lightning measurements during daytime and nighttime, demonstrating high detection efficiencies with low false event rates.

3.2.2. Produce a set of raw instrument data with which advanced ground-based signal processing techniques can be developed for real-time, quality controlled data dissemination.

3.2.3. Demonstrate all technology issues that are critical to follow-on operational missions**:**

3.2.3.1. maintenance of instrument performance over the mission lifetime.

3.2.3.2. accounting for all sources of error associated with pointing control authority, pointing control accuracy, and pointing knowledge.

3.2.3.3. successful real-time data dissemination using both ground based and space based processing.

4. Mission Requirements

Tables 4.1 and A.3 provide the baseline set of science based requirements for the LMS mission. These requirements define the minimum performance needed to satisfy both the scientific and the operational elements of the mission.

4.1 Mission Science Requirements Matrix

Note: This table represents the P.I.'s best and current estimates of the requirements that would result in a successful mission. It is anticipated that there will be a need to undergo multiple iterations with special attention to the following issues: thermal management, pointing control and knowledge, data processing techniques, and data volumes/downlink rates.

	SCIENCE REQUIREMENT	
Large Area Coverage	Monitor lightning in the tropics, extra tropics to 50^0 latitude over both land and water	Provide data sets from as many areas of the globe that will assure unbiased performance statistics; assure operations over calibration/ validation sites;
High Detection Efficiency	Estimate the total lighting activity of each storm	Used for inferring convective activity, mixed phase precipitation, etc.
Low False Event Rates	accurately detect only lightning events	Less than 5% of total events Minimize ground based processing
Measurement Sensitivity	3.8×10^{-6} j m^{-2} um^{-1} sr^{-1} (preferred) 4.7×10^{-6} j m^{-2} $um^{-1}sr^{-1}$ (acceptable)	The sensitivity numbers include 6 dB of SNR margin.
Dynamic Range	> 2 orders of magnitude	After background subtraction, the system must maintain greater than 2 orders of magnitude dynamic range for lightning detection.
Spatial Resolution	Identify individual convective cell	8 km at nadir
Contiguous Observations	continuous observation of the monitored area;	
Single Wavelength Operation	Daytime lightning detection	7774 A
Radiometric Measurement	Determine lightning intensity	measure to 10% accuracy
Continuing current	Detect and quantize continuing current	Do not update background during active pixel periods
Data compression	High event rate throughput	multiple dimension, adjacent pixel compression
Platform Attitude	Earth viewing	
Command and Control	Must be able to • select subarray(s) • adjust threshold • select image area	map 20 subregions to 16 RTEPs preferred RTEP readout
Pointing Accuracy	Locate lightning to specific cell	110 microradians
Pointing Knowledge	Locate lightning to specific cell	40 microradians

4.2. Observational Requirements

The Lightning Mapper Sensor must operate on a continuous basis under both day and nighttime conditions. The data must be transmitted to MSFC in near real time, where it will be processed for quality assurance and redistributed with a maximum latency of 20 seconds.

As the real-time processing algorithms mature and become operational, it mat prove desirable to up load some of the software so that some of the processing, such as sun glint event filtering could be performed on orbit. This capability could be very valuable when the sensor is transition to operational status.

5. Calibration Requirements

Of highest priority for the LMS is the calibration (or validation of calibration) of the instrument and confirmation of the performance claims. Determinations of detection efficiency, location accuracy and false event rates must be made via laboratory calibrations prior to launch and ground base validation studies after launch. A detailed calibration plan for the LMS instrument will be developed. It will be similar in concept to the OTD and LIS plans.

5.1. Pre-launch

Prelaunch component, subsystem, and system end-to-end test and calibration shall include:

5.1.1. DC radiometric calibration

5.1.2. AC response calibration

5.1.3. Field of view measurement

5.1.4. Spectral response

5.1.5. Lightning simulator test

5.1.6. Pointing knowledge measurement

5.2. During Flight

The actual on-orbit performance will depend on the instrument performance and its calibration, the background scene stability, radiation effects, and source characteristics.

5.2.1. Ground Truth

Permanent ground validation sites will be established prior to launch. These sites will be used to validate instrument performance. Sites will likely include existing TRMM sites that are within the instrument field of view.

5.2.2. Field Campaigns

Intensive field campaigns will take place on a periodic basis to perform LMS validation and to investigate relationships between lightning and other convective parameters.

5.2.3 Navigation

Navigation will be verified using land marks identified from LMS images. Algorithms will be developed to compensate for identified pointing errors that occur as a function of the diurnal and seasonal cycles.

6. Data Requirements

6.1. Data Processing

Data will be processed and archived at the GHCC operations facility.

6.2. Data Downlink

A continuous data downlink operating at 80 Kbps is required throughout the life of the program.

7. Operations Requirements

This data will be processed and quality controlled on the ground in order to insure data reliability and integrity. Only quality controlled data will be disseminated to either scientific users or to real time operational users.

A. Appendices

A.1. Lightning Instrument

a.1.1 **LMS Measurement Approach**

The LMS images a scene much like a television camera. However, because of the transient nature of lightning, its spectral characteristics, and the difficulty of daytime detection of lightning against brightly lit cloud backgrounds, actual data handling and processing is much different from that required by a simple imager. In order to achieve the performance goals required to meet the scientific objectives, the LMS combines many off-the-shelf and custom components in a unique configuration. A wide field of view telescope, combined with a large, narrow-band interference filter is focused on a high speed mosaic array focal plane. The signal is read out from the focal plane into real-time event processors (RTEP) for event detection and data compression. The resulting "lightning data only" signal is formatted, queued, and transmitted via the satellite to ground.

The specific characteristics of the sensor design result from the requirement to detect weak lightning signals during the day. During the day, the background illumination produced by sunlight reflecting from the tops of clouds is much brighter than the illumination produced by lightning. Consequently, the daytime lightning signals tend to be buried in the background noise, and the only way to detect lightning during daytime is to implement techniques that increase or maximize the lightning signal relative to this bright background. These techniques take advantage of the significant differences in the temporal, spatial, and spectral characteristics between the lightning signal and the background noise. A combination of four methods will be employed by the LMS for this purpose. First, spatial filtering is used which matches the instantaneous field of view (IFOV) of each detector element in the LMS focal plane array to the typical cloud-top area illuminated by a lightning stroke (i.e., ~10 km). This results in an optimal sampling of the lightning scene relative to the background illumination. Second, spectral filtering is obtained by using a narrow-band interference filter centered on a strong optical emission line (e.g., OI(1) at 777.4 nm) in the lightning spectrum. This method further maximizes the lightning signal relative to the reflected daylight background. Third, the LMS employs temporal filtering which takes advantage of the difference in lightning pulse duration which is on the order of 400 microseconds versus the background illumination which tends to be constant on the time scale of seconds. In an integrating sensor, such as the LMS, the integration time specifies how long a particular pixel accumulates charge between readouts. The lightning signal-to-noise ratio improves as the integration period approaches the pulse duration. If, however, the integration period becomes too short, the lightning signal tends to be split between successive frames which actually decreases the signal-to-noise ratio. Since the median optical lightning pulse width when viewed from above is 400 microseconds, an integration time of 1 ms is most appropriate to minimize pulse splitting and maximize lightning delectability. Present technological limitations require that a 2 millisecond integration time be used in the LMS instrument design. As demonstrated by the OTD and the LIS, this compromise does not seriously degrade the sensor's performance.

Even with the three "filtering" approaches discussed above, the ratio of the background illumination to the lightning signal will often still exceed 100 to 1 at the focal plane. Therefore, a fourth technique, a modified frame-to-frame background subtraction, is implemented to remove the slowly varying background signal from the raw data coming off the LMS focal plane. A detailed discussion on the measurement approach proposed for the LMS is given in a later section of this document. Each real-time event processor generates an estimate of the background scene imaged at each pixel of its section of the focal plane array. This background scene is updated during each frame readout sequence and, at the same time, the background signal is compared with the off-the-focal-plane signal on a pixel-by-pixel basis. When the difference between these signals exceeds a selected threshold, the signal is identified as a lightning event and an event processing sequence is initiated. The implementation of this RTEP results in a 10^6 reduction in data rate requirements, while maintaining high detection efficiency for lightning events.

a.1.2 **INSTRUMENT DESCRIPTION**

The LMS will consist of a staring imager optimized to detect and locate lightning. An imaging system, a focal plane assembly, real-time event processors, a formatter, power supply, and interface electronics are the six major subsystems of the sensor. The imaging system is a fast f/1.2 telescope with a 12 cm aperture, and an 10 nm interference filter. The 5^o x 5^o LMS field of view must be restricted in order to minimize wavelength shifts through the interference filter. The focal plane assembly, (including a 700 x 560 pixel array, preamplifiers, multiplexers, and clock and drive electronics) provides an analog data stream of an appropriate amplitude to subsequent circuits. As noted earlier if, after background removal, the difference signal for a given pixel exceeds a threshold, that pixel is considered to contain an event. Subsequently, the event is time tagged, location tagged, background bin tagged, and passed to the satellite for transmission to the ground.

a.1.3 **Imaging System**

The imaging system includes an f/1.2, 11 cm diameter telescope and a 1 nm bandwidth interference filter. A broad-band blocking filter is placed on the front surface of the filter substrate in order to maximize the effectiveness of the narrow-band filter.

Because the bandeaus of interference filters shifts to shorter wavelengths for non-normal incidence, it is necessary to restrict the field of view of the optics and use two telescopes to cover the required FOV. That is, if the wavelength of interest is incident upon the filter at an angle that shifts it beyond the filter bandpass, the signal will not be passed. This problem is minimized by choosing a filter which passes the high wavelength end of its bandpass at normal incidence. As the angle of incidence increases to a maximum, the wavelength shifts down through the entire band pass to the low wavelength end, allowing the full filter bandwidth to compensate for the wavelength shift.

<u>Table A.1 - Performance Criteria</u>

pixel IFOV	8 km (at nadir)
FOV	8^{o} x 5^{o} FOV
wavelength	777.4 nm
threshold	<4.0 J m^{-2} sr^{-1}
SNR	6
array size	700 x 560 pixels
dynamic range	>100
detection efficiency	> 90% of all events
false alarm rate	<5% of total events
measurement accuracy	
location	1 pixel
intensity	10%
time	tag at frame rate
command interface	adjust threshold (threshold 63 = events disabled)
	record/image
	-power on/off
	-self test
	subregion selection
	active RTEP selection
	continuing current enable

	on board event processing enable
	safe mode
weight	35 kg
power	100 watts
telemetry	
data rate	80 kb/s
format	PCM
sample size	12 bits
operating temperature	-10 to 40^{o}C

The filter temperature is controlled with an active thermal heating system in order in insure minimal filter wavelength shift as a function temperature. Furthermore, the temperature control point can be adjusted on orbit.

a.1.4 **Real-Time Event Processor**

The data rate coming off the LMS focal plane will be on the order of 4 x 10^{8} pixels per second. It must be processed with at least 12 bits of resolution, yielding a data rate of 5 x 10^{9} bits per second. This far exceeds transmittable rates, thus the need for off-the-focal plane signal processing (i.e. the RTEP). Both the OTD and LIS use an RTEP. The concept has been successfully tested and demonstrated both in the laboratory and on-orbit. In addition, numerical analyses, evaluations, and trade-off options have been performed.

As noted previously, the RTEP detects weak lightning flashes from an intense, but slowly evolving background. The daytime background varies with sun angle, clouds, ground albedo, etc., and can reach in excess of 900,000 photo-electrons as compared to lightning produced signal electrons which may be as small as 6000 electrons. Typically lightning stroke will occur during a single integration frame producing a signal that is superimposed on top of the essentially constant background. The RTEP continuously averages the output from the focal plane over a number frames on a pixel-by-pixel basis in order to generate a background estimate. It then subtracts the average background estimate of each pixel from the current signal of the corresponding pixel.

The subtracted signal consists of shot noise fluctuating about zero with occasional peaks due to lightning events. When a peak exceeds the level of a variable threshold, it triggers comparator circuits and is processed by the rest of the electronics as a lightning event. The threshold must be set sufficiently high that false triggers are kept to a small percent of the total lightning rate. Clearly, the threshold must be higher during daytime when shot noise is dominated by the solar background

The components of the real-time event processor include a background signal estimator, a background remover, a lightning event thresholder, an event selector, and a signal identifier. Analog/digital hybrid processing is used in an unique way that takes advantage of the strengths of each technology in order to provide high processing rates while consuming minimal power. Much of the signal processing is performed in a pipeline fashion that maximizes throughput.

The background estimator (averager) and remover (subtraction) circuits combine to perform the functions of a time domain low pass filter. The signal coming off the focal plane is fed through a buffer and clipping stage in order to ensure that a strong lightning signal does not contaminate the background estimate. The signal is then multiplied by a fractional gain (B) and added to (1-B) times the previous background estimate for the same pixel. The inverse of the fractional gain is equivalent to the number of frames used in generating the background estimate and is analogous to setting the cutoff frequency in conventional frequency domain filters. Too high a fractional gain might permit lightning events to contaminate low background estimates and would increase the processing noise. Too low a fractional gain would not allow the background estimator to respond rapidly enough to changes in background intensity.

The proper operation of the background estimator requires that the background data are clocked through the estimator synchronously with the data being clock off the focal plane and that the number of discrete storage elements in the background memory is exactly the same as the number of pixels in the focal plane array. When data are properly synchronized, the signal appearing on the output of the delay line during a given clock cycle corresponds spatially to the signal being clocked off the focal plane. That is, it contains a history of what that specific pixel has measured over the last 1/B frames. These two signals are then subtracted using a difference amplifier in order to generate a difference signal. Since the original signal contains either background plus lightning or just background, the subtracted signal will be either a lightning signal, near zero or a false event.

The difference signal is then compared with the threshold level (which will be adaptive). If the signal exceeds the threshold level, a comparator triggers, which enables a switch and passes the lightning signal for further processing. In addition, the comparator output is encoded using a digital multiplexer in order to generate a row address which identifies the specific pixel that detected the lighting event. The digital outputs from the data processor represent the intensity of the lighting event and the location where the lightning occurred. These signals are then forwarded to encoding electronics in which the data are formatted into a digital bit stream and sent to the spacecraft. Experience from OTD and LIS have demonstrated that it is not necessary to remove all the false events with the RTEP. We have found that it is relatively straight forward to filter out the bad events via ground-based processing since the true lightning events have much different characteristics. The main function of the on-board processing is to capture all the lightning events and to reduce the number of false events to a manageable number that can be handled by the telemetry system.

The mapping of 20 subregions to 16 RTEPs should allow for the uninterrupted observations of the continental United States under the conditions of spacecraft yaw flips and one RTEP failure. This map be best accomplished by allowing each RTEP to be mapped to one of two subregions.

a.1.5 **Instrument Configuration**

After gaining on-orbit experience with the LMS, it may prove desirable to implement additional on-board signal processing. A forty percent reserve of processor resources must be preserved to support this requirement. The driver for this requirement would be improved real time data dissemination in support of operations. This level of signal processing would be implemented in software utilizing the LMS microprocessors. In addition, data record configuration options should allow for inclusion of event count and event amplitude summaries. A capability for selecting certain subregions for preferred event detection is also required. This allows full event rates in the preferred subregions at the expense of possibly missing event in other subregions.

a.1.6 **Interface Requirements**

The LMS requires power and data resources from the satellite bus. The packaging of the instrument will be driven by its location on the spacecraft, its field of view requirements, its need for passive thermal control and by the specific services provided by the bus. These issues require a detailed accommodation study to resolve. However since LMS is a small, lightweight sensor, it should be relatively easy to accommodate on the spacecraft with the main issue being heat dissipation and maintenance of pointing stability and knowledge.

A.2. Project Science Team

The LMS program will fund a project science team under the guidance of the P.I. that will be responsible for processing raw instrument data into lightning data, for validating the lightning data, for coordinating ground-based validation activities, for making mission data available to other researchers, and for providing an interface to the general science community. Additionally, other scientific work will be sought from other programs (e.g. Earth Science Enterprise).