Lightning Imaging Sensor (LIS) for the International Space Station (ISS): Mission Description and Science Goals

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ABSTRACT: In recent years, the NASA Marshall Space Flight Center, the University of Alabama in Huntsville, and their partners have developed and demonstrated space-based lightning observations as an effective remote sensing tool for Earth science research and applications. The Lightning Imaging Sensor (LIS) on the Tropical Rainfall Measuring Mission (TRMM) continues to acquire global observations of total (i.e., both intracloud and cloud-to-ground) lightning after 17 years on-orbit. In April 2013, a space-qualified LIS built as the flight spare for TRMM, was selected for flight as a science mission on the International Space Station (ISS). The ISS LIS (or I-LIS as Hugh Christian prefers) will be flown as a hosted payload on the Department of Defense Space Test Program (STP) H5 mission, with a February 2016 launch date aboard a Space X launch vehicle for a 2-year or longer mission. The LIS measures the amount, rate, and radiant energy of global lightning during both day and night, with storm scale resolution (~4 km), millisecond timing, and high, uniform detection efficiency, without any land-ocean bias. Lightning, a direct and most impressive response to intense atmospheric convection, can be quantitatively related to both thunderstorm and other geophysical processes. Therefore, the ISS LIS lightning observations will provide important contributions to pressing Earth system science issues across a broad range of disciplines, including weather, climate, atmospheric chemistry, and lightning physics. One unique contribution will be the availability of real-time lightning, especially valuable for operational applications over data sparse regions such as the oceans. The ISS platform will also enable LIS to provide simultaneous and complementary observations with other ISS payloads such as the European Space Agency's Atmosphere-Space Interaction Monitor (ASIM), exploring the connection between thunderstorms and lightning with terrestrial gamma-ray flashes (TGFs). Another important function of the ISS LIS will be to provide cross-sensor calibration/validation with other satellites, including the TRMM LIS and the next generation geostationary lightning mappers (e.g., GOES-R Geostationary Lightning Mapper and Meteosat Third Generation Lightning Imager), as well as with ground-based lightning detection systems. These inter-calibrations will improve the long term climate monitoring record provided by all these systems. Finally, the ISS LIS will extend the time-series climate record of LIS observations and expand the latitudinal coverage of LIS lightning to the climate significant upper middle-latitudes.

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INTRODUCTION

Lightning is a direct and most impressive response to intense atmospheric convection. Interest in lightning as a remote sensing measurement and variable of global change has grown with the recognition that lightning can convey useful information about many atmospheric processes (Davis et al., 1983), and therefore, provide important contributions to pressing Earth system science issues across a broad range of disciplines, including weather, climate, atmospheric chemistry, and lightning physics.

NASA Marshall Space Flight Center, the University of Alabama in Huntsville and their partners pioneered the observing technology that has made global scale lightning detection from space both feasible and a reality. The launch of the Optical Transient Detector (OTD) in 1995 ushered in this new era of space based lightning detection with sensors specifically designed to address the deficiencies of earlier measurements and provide accurate statistics on the frequency and distribution of lightning worldwide. The prior space based observations had been severely limited by one or more problems including low or unknown detection efficiency, poor spatial and temporal resolution, a limited number or brief periods of observations, and incomplete sampling of the diurnal cycle [Christian, 1989]. The OTD was launched into a near circular orbit of 740 km, 70º inclination, providing observations of lightning activity over most parts of the world. During OTD's five year mission, it optically detected total lightning (i.e., both intracloud and cloud-to-ground discharges) that occurred within its 1300º × 1300º km field-of-view with high, uniform detection efficiency (~50%) and storm scale spatial resolution (~10 km) during both day and night.

In November 1997, the original Lightning Imaging Sensor (LIS) joined the OTD in orbit when it was flown as a component of Tropical Rainfall Measuring Mission (TRMM). The LIS is basically the same instrument as its OTD predecessor except that its sensitivity is improved by a factor of three and it is in a 350 km altitude (boosted to 400 km in August 2001), 35º inclination orbit. The increased sensitivity results in a detection efficiency approaching 90%, while its lower orbit altitude improves the LIS spatial resolution to 4 km (but at the cost of a decreased field-of-view of 600º × 600º km). An important attribute of flying on TRMM is the acquisition of simultaneous visible, infrared, microwave, radar, and lightning measurements which provides an ability to directly test a number of hypotheses on the interrelationships between updrafts, ice formation, and lightning. TRMM LIS continues to operate flawlessly after 17 years in orbit.

The TRMM/LIS and its OTD precursor, shown in Figure 1, have provided the first truly unbiased climatology on the rates, distribution, and variability of lightning activity on the global scale [Christian et al., 2003]. These measurements represent a significant advance over earlier observations. Nonetheless, these lightning observations are being made from low Earth orbits, which greatly limit the total time available for acquiring lightning data. Since this climatology can be improved by increasing the total time the Earth is viewed, placing an additional sensor in orbit is an easy way to gain additional improvement. This paper describes an opportunity to fly an identical LIS on the International Space Station (ISS), taking advantage of unique features of the ISS platform (e.g., high inclination, real time data, co-located payloads), to extend and expand the science investigations begun with the TRMM/LIS and OTD missions.

A MISSION OF OPPORTUNITY – ISS LIS

In April 2013, a space-qualified LIS built as the flight spare for TRMM, was selected for flight as a science mission of opportunity on the ISS. The ISS LIS (or I-LIS as Hugh Christian prefers) will be flown as a hosted payload on the Department of Defense Space Test Program-Houston 5 (STP-H5) mission, with a target February 2016 launch date aboard a Space X launch vehicle for a nominal 2-year mission. The project will seek to extend the ISS mission operations beyond 2 years through the NASA senior review process that evaluates the value of continuing space-borne science missions beyond their funded life cycle. Figure 2 shows an advanced concept drawing of the planned STP-H5 payload.

The legacy LIS instrument selected for this mission has been carefully maintained in environmentally controlled storage since 1998, effectively providing an available off-the-shelf instrument for this ISS opportunity. Although this instrument is nearly 20 years old, its controlled storage and solid TRMM operating heritage – e.g., LIS still performing well after 17 years in space – give a high degree of confidence that this flight spare will perform without problems when it is launched in early 2016. Immediately after selection, an “aliveness” test verified that the hardware still functioned. Much more extensive functional tests and a full radiometric calibration will be completed prior to delivering the LIS in December 2014 for integration into STP-H5. The integrated package will then undergo additional testing in 2015 prior to its launch. Fortunately, many of the original scientists, engineers, and infrastructure involved with LIS development, calibration, operations and data handling, and science analysis are either still in place or still available to support pre-mission preparations and the post-launch mission and science operations. The primary mission risks faced by the project are obsolescent electronic components in the legacy LIS should a failure occur during its preparation, and the fast-track schedule that must be met.

SCIENCE AND APPLICATIONS

LIS Science Goals and Objectives

As noted in the introduction, it has been found that the lightning can be quantitatively related to both thunderstorm and other geophysical processes across a broad range of disciplines, making it an effective and valuable remote sensing tool to address a variety of science and application problems facing the nation and the world. The core science goals and objectives for LIS were first defined in NASA Technical Memorandum-4350 [Christian et al., 1992]. These research objectives have continued with various refinements and augmentations since the launch of OTD in April 1995 and TRMM LIS in November 1997, and they remain fully applicable for the ISS LIS mission. At the broadest level, LIS science goals and objectives are to acquire and investigate the global distribution and variability of total lightning and to advance the understanding of underlying and interrelated processes.

Specific research topics of scientific importance identified in NASA TM-4350 include: (1) Provide information on the total rain volume and degree of convective activity in the core regions of tropical and extra-tropical storms and storm systems, particularly as relevant to severe weather occurrence; (2) Study the global distribution of lightning and its relationship to storm microphysics and dynamics, its dependence on regional climatic environments and their changes, its relationship to precipitation and cloud type, and the incorporation of these relationships into diagnostic and predictive models of global precipitation, the general circulation and the hydrological cycle; (3) Develop global lightning climatology in order to study the distribution and variability in lightning frequency as an indicator of the intensity of the Walker and Hadley circulations and assess the impact of sea surface and land surface temperature changes on the distribution and intensity of thunderstorms, including extreme weather events; (4) Study the production, distribution, and transport of trace gases attributed to lightning and determine the contribution (and the sources of variability) to the global amount of trace gases; and (5) conduct observational and modeling studies of the global electric circuit and the factors that cause it to change. This last topic also includes investigating the relationship of lightning with ionospheric/magnetospheric processes, as well as basic lightning physics.

For example, since lightning activity is closely linked to storm dynamics and microphysics [Deierling and Petersen, 2008; Deierling et al. 2008], it can be related to the global rates, amounts, and distribution of convective precipitation [Goodman and MacGorman, 1986; Goodman and Buechler, 1990; and Petersen and Rutledge, 1998, 2001; Petersen et al., 2005] and the release and transport of latent heat. The location and distribution of latent heating associated with convection, in turn, influences larger scale atmospheric circulations and weather patterns [Hartman et al. 1984; Lau and Peng, 1987; Sui and Lau, 1989; Chang et al., 1999]. Williams [1992] hypothesized that global lightning activity may provide a very sensitive measure of temperature change associated with climate variability, hinted by signals observed in ENSO activity [Goodman et al., 2000; Chronis et al, 2008]. Lightning from LIS will help assess the impact of indirect aerosol effects associated with anthropogenic sources of pollution have been hypothesized to generate a robust response in the ice phase of deep convection, possibly increasing the frequency of heavy precipitation events and lightning. As such, long term monitoring of lightning with coincident measures of the ice process should provide a robust proxy for either supporting or refuting the hypothesized indirect effect by virtue of its coupling to the ice process [e.g., Rosenfeld et al. 1999, Bell et al., 2008, Petersen and Carey, 2009].

Lightning measurements serve to increase knowledge of the amount, distribution, and variability of deep convection and natural sources and sinks of key trace gases on a global scale. The high temperatures attained within lightning channels provide the mechanism for the production of nitrous oxides and other trace gases [Chameides, 1986]. Additional details of the global lightning occurrence are needed in order to properly assess the impact of this natural production of trace gases [Levy, 1996]. Lightning relationships are also being sought with atmospheric electrical processes such as the global electric circuit [Blakeslee et al., 1989, 2014; Driscoll, 1993; Hutchins et al., 2014; Mach et al., 2009, 2010, 2011; Rycroft et al., 2007; Rycroft and Harrison, 2011; Williams, 2009]. The more recent discoveries of TLEs (e.g., sprites, jets, elves) and terrestrial gamma-ray flashes (TGFs) further motivates the desire for space-borne lightning measurements [Fishman, et al. 1994].

Unique Science Contributions from the ISS Platform

Even though TRMM LIS has acquired a lightning climatology that now spans 17 years**,** there are several unique and highly valuable science benefits to be gained by also taking LIS to the International Space Station, and these represent key reasons why the LIS was selected to fly on ISS. These benefits trace to the ISS orbital characteristics – especially its higher 54º orbit inclination for greater global latitudinal coverage, the ISS communication advantages, and the opportunity to engage in important complementary science observations.

The first benefit is the higher latitude coverage that will be gained from the ISS as depicted in Figure 3. TRMM LIS misses up to 30% of the lightning in the northern hemisphere in the warm season months. The ISS LIS will detect nearly all of that lightning to enhance regional and global weather, climate, and chemistry models, studies and assessments. Also, the ISS LIS will provide CONtinental US (CONUS) needed for the NASA sponsored National Climate Assessment program.

Another unique important benefit gained from the ISS platform will be the availability of real time lightning brought down via the station's low rate telemetry channel which LIS will use. This will provide real time lightning for operational applications in data sparse regions, especial over the oceans. It would be used to support storm forecasts and warnings, nowcasts, and oceanic aviation warnings and SIGMETs. The ISS LIS mission has been strongly endorsed by several operational partners, including the NOAA Ocean Prediction Center, Aviation Weather Center, Joint Typhoon Warning Center, and the National Weather Service (NWS) Pacific Region. The best latency that TRMM provided was on the order of 90 minutes from its quick look orbit files – we hope to reduce this to a few minutes or better with ISS.

Next, the ISS platform will uniquely enable LIS to provide simultaneous and complementary observations with other ISS payloads such as the European Space Agency (ESA) sponsored Atmosphere-Space Interaction Monitor (ASIM) or the Japan Aerospace Exploration Agency (JAXA) sponsored Global Lightning and sprIte MeasurementS (GLIMS) missions. The combination of LIS, ASIM, and GLIMS will enable simultaneous acquisition of optical (NASA), x-ray, gamma-ray (ESA), and very high frequency or VHF (JAXA) lightning measurements that represent a unique measurement capability providing great science value, heretofore not achieved before on a single satellite platform. Gaining a better understanding of terrestrial gamma-ray flashes (TGFs) represents a prime focus of ASIM. Although a connection between TGFs and lightning/thunderstorms is apparent, a detailed understanding of the relationships remains elusive, primarily because of the lack of simultaneous TGF and lightning measurements. The LIS on ISS would be capable for the first time of observing the individual lightning strokes associated with TGF events and record this information on a millisecond time scale. The type of thunderstorm, the altitude of origin and the beaming angle of the hypothesized electron beam could then be determined, leading to a greatly improved understanding of the TGF process. The present ASIM instrument suite is incapable of detecting optical lightning events on the millisecond time scale that is required for one–to-one comparisons with TGFs. Furthermore, the conventional ASIM video cameras can only detect lightning at night, while as LIS detects lightning during both day and night. This capability alone results in an 80% increase in the probability of simultaneous observations. TGFs may pose at times significant radiation hazard to aircraft pilots and passengers. This joint LIS-ASIM observations will advance our understanding of this threat, and, if necessary, guide mitigation strategies.

Finally, a very important function of the ISS LIS will be to provide cross-sensor calibration/validation observations with other satellites, including the low Earth orbit TRMM LIS (if it is still in orbit in early 2016, and the prospects for this remain promising) and TARANIS (Tool for the Analysis of Radiations for lightNings and Sprites), the next generation geostationary lightning mappers (e.g., GOES-R Geostationary Lightning Mapper and Meteosat Third Generation Lightning Imager), and even with ground-based lightning detection systems. These inter-calibrations will improve the long term climate monitoring record provided by all these systems. The ISS LIS will extend the time-series climate record of LIS observations and expand the latitudinal coverage of LIS lightning to the climate significant upper middle-latitudes.

Science User Community and Infrastructure

There will be no delay in getting ISS LIS data into the hands of users and into science and applications activities. First, the ISS LIS mission will leverage the large and established LIS science user's community. Since many are already active users of TRMM LIS and OTD data, they will be eager to get their hands on the expanded ISS LIS data sets. In addition, new users, such as the operational users, will also be eager to get the real time LIS observations made available from the enhanced communications capabilities of the ISS platform. Second, ISS LIS leverages the well-established processing, archival, and distribution TRMM LIS infrastructure. This means that this mission will not have to "reinvent the wheel," nor will users have to learn or write new software to access or used the data. We will be immediately ready to deliver data into users' hands through the existing distribution system. Third, the LIS data is highly respected by the international science community. In fact, the LIS data is viewed and used as a "benchmark" for global climatology because of its high detection efficiency and uniformity, and all global lightning data sets are compared to LIS. Again, LIS facilitates valuable cross-sensor, cross-network intercomparisons. Taken together, these reasons virtually assure that the ISS LIS data will be immediately used as soon as it is available – and we plan to make it available immediately.

INSTRUMENT DESCRIPTION

The legacy LIS is a small, solid state optical imager that detects lightning from low Earth orbit with high detection efficiency and location accuracy, marks the time of occurrence, and measures the radiant energy. An imaging system, a focal plane assembly, a real-time signal processor and background remover, an event processor and formatter, power supply and interface electronics comprise the major elements of the sensor. The optical and electrical elements are combined into a cylindrical sensor assembly (20 × 37 cm) and an electronics assembly (31 × 22 × 27 cm), with a total mass of approximately 20 kg, less than 30 W of power, and a telemetry data rate of only 8 kb/s. Table 1 summarizes the overall instrument parameters and performance criteria, while Figure 4a shows the legacy LIS hardware.

Table 1. LIS Parameters and Performance Criteria

Field-of-View (FOV)	80º × 80º	Measurement Accuracy	
Pixel IFOV (nadir)	4 km	location	1 pixel
Interference Filter		intensity	10 %
wavelength	777.4 nm	time	tag at frame rate
bandwidth	1 nm	Dimensions	
Detection Threshold	4.7 μJ m^{-2} sr^{-1}	sensor head assembly	20 × 37 cm
Signal to Noise Ratio	6	electronics box	31 × 22 × 27 cm
CCD Array Size	128 × 128 pixels	Weight	20 kg
Dynamic Range	> 100	Power	30 Watts
Detection Efficiency	~ 90 %	Telemetry	
False Event Rate	< 5 %	data rate	8 kb/s
		format	PCM

The LIS primarily operates as a transient event detector, although it also provides periodic background images that help with long term navigation and calibration monitoring. The sensor design was driven by the requirement to detect weak lightning signals during the day when the sunlight reflecting from the tops of clouds is much brighter than the illumination produced by lightning. This requirement was met by implementing special filtering techniques in the instrument hardware to take advantage of the significant differences in the temporal, spatial, and spectral characteristics between the lightning signal and the background noise. The design employs an expanded optics wide field-of-view lens, combined with a narrow-band interference filter, centered on the strong oxygen emission line (i.e., the oxygen multiplet at OI(1) at 777.4 nm) in the lightning spectrum, that focuses the image on a small, high-speed 128×128 CCD focal plane. The final step in this process is to apply a frame-to-frame background subtraction to remove the slowly varying background signal from the raw data coming off the LIS focal plane. The signal is read out from the focal plane at 500 images per second into a real-time event processor for event detection and data compression. The resulting "lightning data only" signal is formatted, queued, and sent to the spacecraft for transmission to ground stations. Boccippio et al. [2002] and Mach et al. [2007] provided more details about the LIS instrument and its operation. The LIS science product generation includes events, groups, flashes, areas, higher order gridded lightning statistics, and background images [Christian et al., 2000; Cecil et al., 2014].

ISS ACCOMMODATION

There are no significant differences in how the legacy LIS hardware is used and operates on ISS versus how it is used and operates on the TRMM platform with the minor exception of the availability of real time data delivery. However, it is necessary to provide an additional interface unit for the ISS implementation to translate the ISS power and communications into a form that makes ISS platform appear like the TRMM satellite to the heritage LIS electronics assembly. Functional testing early in the ISS LIS mission development will establish that this interface unit performs properly to pass LIS commands and science data between the LIS instrument and the ground-based operations center. Figure 4b shows the new interface unit and the mounting configuration expected on the STP-H5 payload.

The ISS LIS will be located in a nadir viewing position. The ISS platform is presently operated at an altitude of about 425km, which is close to that of the current TRMM mission. As such, the pixel resolution and field-of-view footprint on the Earth will be almost identical to that of TRMM – on the order of 4 km at nadir. On ISS, a small portion of the LIS field-of-view will experience obstruction as a solar panel and radiator translate through the instrument's field-of-view on a predictable time schedule. An analysis has shown that the maximum mean (peak) percent obscuration that would be experienced by LIS on an orbit would be 3.6% (12.3%). This will have no impact on meeting the LIS science objectives. OTD had a permanent obstruction of similar magnitude to this peak amplitude in its field-of-view from its gravity gradient boom with no detrimental impact on science.

A LIS pixel, obtained from laboratory measurement, is approximately 38.94 arcmin in one dimension. It was required by the LIS science team that accuracy in pointing be within one pixel and the uncertainty in pointing, sometimes called knowledge (about the nominal pointing direction), be within one half of a pixel, or about 19.47 arcmin. Similar requirements will be imposed for the ISS LIS instrument on the STP-H5 payload. Fortunately, the STP-H5 payload will include a star tracker that will provide much better pointing knowledge than the minimum LIS requirement (the star tracker itself will be 0.66 arcmin at 3-sigma). If the star tracker should have problems, another instrument on the ISS has demonstrated that pointing close to the science team requirement is possible using ISS navigation data.

Another area of concern for the ISS LIS is solar glare/glint. This concern traces to the fact that glint, the direct specular reflectance of sunlight into the instrument, could possibly produce an excessive amount of false detections that temporarily fill the LIS's first-in first-out (FIFO) data buffer. Only if the real event rate plus the false event rate (from glint in this case) exceeds the maximum LIS sustained event rate of about 300 events per second would real science data be lost. Ground-based algorithms in the LIS processing software easily identify and remove glint signals in the case where data has not been lost due to a FIFO overflow. A detailed analysis was conducted that evaluated glare from the solar panels and radiator by simulating lighting for a complete range of ISS solar beta angles from -75° to +75° in 5° increments with images generated at one minute intervals. This analysis, for nadir or 5° off-nadir viewing, found no glare areas or fast changing illumination for either the solar panels or the radiator. This model result is consistent with an examination of a series of photos from a current ISS instrument with a similar nadir position as planned for LIS. This result, along with other photographic and video examples from ISS, provide strong evidence that glint reflecting off the solar panels or the radiator will not impact ISS LIS.

CONCLUSIONS

In April 2013, a space-qualified LIS built as the flight spare for TRMM, was selected for flight as a science mission of opportunity on the International Space Station (ISS). This ISS LIS mission, with an initial two years period of operations, will extend the time-series climate record and expand the latitudinal coverage obtained from the long running TRMM LIS mission to the climate sensitive upper middle-latitudes. The mission will support on-going and future science investigations across across a broad range of disciplines that includes weather, climate, atmospheric chemistry, and lightning physics, making it an effective and valuable remote sensing tool to address a variety of science and application problems facing the nation and the world.

An especially unique contribution will be to provide real-time lightning in support of operational applications over data sparse regions such as the oceans. Also, the ISS platform will enable LIS to provide simultaneous and complementary observations with other ISS payloads such as the ESA ASIM, which is exploring the connection between thunderstorms and lightning with terrestrial gamma-ray flashes (TGFs) or the JAXA GLIMS, which is investigating sprites and other transient luminous events using VHF observations. Finally, another important function of the ISS LIS will be to provide cross-sensor calibration/validation with other satellites, as well as with ground-based lightning detection systems. These inter-calibrations will improve the long term climate monitoring record provided by all these systems.

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REFERENCES

Blakeslee, R. J., Christian, H. J., and Vonnegut, B., 1989: Electrical measurements over thunderstorms, *J. Geophys. Res*., **94** (D11), 13135-13140.

Blakeslee, R. J., D.M. Mach, M.G. Bateman, and J.C. Bailey, 2014: Seasonal variations in the lightning diurnal cycle and implications for the global electric circuit, *Atmos. Res.*, http://dx.doi.org/10.1016/j.atmosres.2012.09.023, 228-243.

Boccippio, D. J., W. J. Koshak, and R. J. Blakeslee, 2002: Performance assessment of the Optical Transient Detector and Lightning Imaging Sensor: 1. Predicted diurnal variability, *J. Atmos Ocean Tech*, **19**, 1318-1332.

Cecil, D.J., D. E. Buechler, and R. J. Blakeslee, 2014: Gridded lightning climatology from TRMM-LIS and OTD:Dataset description, *Atmos.Res*., http://dx.doi.org/10.1016/j.atmosres.2012.06.028, 404-414.

Chameides, W. L., 1986: "The Role of Lightning in the Chemistry of the Atmosphere," in *The Earth's Electrical Environment*, National Academy Press, pp. 70-77.

Chang, D. –E., Morales, C. A., Weinman, J. A., and Olson, W. S., 1999: Combined microwave and sferics measurements as a continuous proxy for latent heating in mesoscale model predictions, *Preprints, 11th Int. Conf. on Atmos. Electr*., ed. H. J. Christian, *NASA/CP–1999–209261*, Guntersville, AL, pp. 742-745, June 7-11.

Christian, H. J., Blakeslee, R. J., and Goodman, S. J., 1989: The detection of lightning from geostationary orbit, *J. Geophys. Res*., **94** (D11), 13329-13337.

Christian, H. J., Blakeslee, R. J., and Goodman, S. J., 1992: Lightning Imaging Sensor (LIS) for the Earth Observing System, *NASA TM-4350*, Available from Center for Aerospace Information, P.O. Box 8757, Baltimore Washington International Airport, Baltimore, MD 21240, 44 pp.

Christian, H. J., Blakeslee, R. J., and Goodman, S. J., and D. M. Mach, Revised February 1, 2000: Algorithm Theoretical Basis Document (ATBD) for the Lightning Imaging Sensor (LIS), available on the Web at: http://eospso.gsfc.nasa.gov/sites/default/files/atbd/atbd-lis-01.pdf.

Christian, H. J., R. J. Blakeslee, D. J. Boccippio, W. L. Boeck, D. E. Buechler, K. T. Driscoll, S. J. Goodman, J. M. Hall, W. J. Koshak, D. M. Mach, and M. F. Stewart, 2003: Global frequency and distribution of lightning as observed from space by the Optical Transient Detector, *J. Geophys. Res*., **108** (D1), 4005, 10.1029/2002JD002347, 03 January.

Chronis, T., S. J. Goodman, D. Cecil, D. E. Buechler, F. R. Robertson, J. V. Pittman, and R. Blakeslee, 2008: Global lightning activity from the ENSO Perspective, *Geophys. Res. Lett*ers, **35**, L19804, doi:10.1029/2008GL034321.

Davis, M. H., M. Brook, H. Christian, B. G. Heikes, R. E. Orville, C. G. Park, R. G. Roble, and B. Vonnegut, 1983: Some scientific objectives of a satellite-borne lightning mapper, *Bull. Am. Met. Soc.*, 64 (2), 114-119.

Deierling, W., and W. A**.** Petersen, 2008: Total lightning activity as an indicator of updraft characteristics. *J. Geophys. Res***., 113**, D16210, doi:10.1029/2007JD009598.

Deierling, W., W. A. Petersen, J. Latham, S. E. Ellis, and H. J. Christian, Jr., 2008: The relationship between lightning activity and ice fluxes in thunderstorms. *J. Geophys. Res.*, **113**, D15210, doi:10.1029/2007JD009700.

Driscoll, K. T., 1993: A time-averaged analysis of the electric currents in the vicinity of isolated thunderstorms, Ph.D. dissertation, Auburn University.

Fishman, G.J., et al., 1994: Discovery of intense gamma-ray flashes of atmospheric origin, *Science*, **264**, 1313.

Goodman, S. J., and D. R. MacGorman, 1986: Cloud-to-ground lightning activity in mesoscale convective complexes, *Mon. Wea. Rev*., **114**, 2320.

Goodman, S. J., and Buechler, D. E., 1990: Lightning-rainfall relationships, *Preprints*, Conf. on Operational Precipitation Estimation and Prediction, Anaheim, CA, Feb. 7-9, Amer. Met. Soc., Boston.

Goodman, S. J., Buechler, D. E., Knupp, K., Driscoll, K., and McCaul, E. W., 2000: The 1997-98 El Nino event and related wintertime lightning variations in the southeastern United States, *Geophys. Res. Lett*., **27**(4), 541-544.

Hartman, D. L., H. H. Hendon, and R. A. Houze, Jr., 1984: Some implications of the mesoscale circulations in tropical cloud clusters for large scale dynamics and climate. *J. Atmos. Sci.,* **41**, 113-121.

Hutchins, M. L., R. H. Holzworth, and J. B. Brundell, 2014: Diurnal variation of the global electric circuit from clustered thunderstorms, *J. Geophys. Res. Space Physics*, **119**, doi:10.1002/2013JA019593, 10pp.

Koshak, W. J., Stewart, M. F., Christian, H. J., Bergstrom, J. W., Hall, J. M., and Solakiewiez, R. J., 2000: Laboratory calibration of the Optical Transient Detector (OTD) and the Lightning Imaging Sensor (LIS), *J. Atmos. Oc Tech.*, **17**, 905-915.

Lau, K.-M, and L. Peng, 1987: Origin of low-frequency (intraseasonal) oscillations in the tropical atmosphere. Part I: Basic Theory. *J. Atmos. Sci*., **44**, 950-972.

Levy, H., II, Moxim, W. J., and Kasibhatla, P.S., 1996: A global three-dimensional time-dependent lightning source of tropospheric NOx, *J. Geophys. Res.*, **101**, 22,911-22,922.

Mach, D.M., H.J. Christian, R.J. Blakeslee, D.J. Boccippio, S.J. Goodman, and W.L. Boeck, 2007: Performance Assessment of the Optical Transient Detector and Lightning Imaging Sensor. Part II, *J. Geophys. Res*., **112**, D09210, doi:10.1029/2006JD007787.

Mach, D.M., R.J. Blakeslee, M.G. Bateman, and J.C. Bailey, 2009: Electric fields, conductivity, and estimated currents from aircraft overflights of electrified clouds, *J. Geophys. Res*., **114**, doi:10.1029/2008JD011495.

Mach, D.M., R.J. Blakeslee, M.G. Bateman, and J.C. Bailey, 2010: Comparisons of total currents based on storm location, polarity, and flash rates derived from high altitude aircraft overflights, **J. Geophys. Res**., **115**, D03201,doi:10.1029/2009JD012240.

Mach, D.M., R. J. Blakeslee, and M. G. Bateman, 2011: Global electric circuit implications of combined aircraft storm electric current measurements and satellite-based diurnal lightning statistics, *J. Geophys. Res*., **116**, D05201, 13pp, doi:10.1029/2010JD014462.

Petersen, W. A., and Rutledge, S. A.,1998: On the relationship between cloud-to-ground lightning and convective rainfall, *J. Geophys. Res*., **103**, 14025-14040.

Petersen, W.A., and S.A. Rutledge, 2001: Regional Variability in Tropical Convection: Observations from TRMM. *J. Climate*, **14**, 3566-3586.

Petersen, W. A., Christian, H. C., and S. A. Rutledge, 2005: TRMM Observations of the global relationship between ice water content and lightning. *Geophys. Res. Lett*., **32**, L14819, doi:10.1029/2005GL023236.

Rycroft. M. J., A. Odzimek, N. F. Arnold, M. Fullekrug, A. Kulak, and T. Neubert, 2007: New model simulations of the global atmospheric electric circuit driven by thunderstorms and electrified shower clouds: the roles of lightning and sprites, *J. of Atmos. Solar-Terr. Physics*, **69**, doi: 10.1016/j.jastp.2007.09.004, 2485-2509.

Rycroft, M. J. and R.J. Harrison, 2011: Electromagnetic atmosphere-plasma coupling: The global atmospheric electric circuit, *Space Sci. Rev.*, **168** (1-4), 363-384, doi:10.1007/s 11214-011-9830-8.

Sui, C.-H., and K.-M. Lau, 1989: Origin of low-frequency (intraseasonal) oscillations in the tropical atmosphere. Part II: Structure and propagation of mobile wave-CISK modes and their modification by lower boundary forcings. J. Atmos. Sci., **46**, 37-56.

Williams, E. R., 1992: The Schumann resonance: A global tropical thermometer, *Science*, 256, 1184—1187.

Williams, E. R., 2009: The Global Electrical Circuit: A Review, *Atmospheric Research*, **91** (2), doi: 10.1016/j.atmosres.2008.05.018, 140-152.

FIGURES

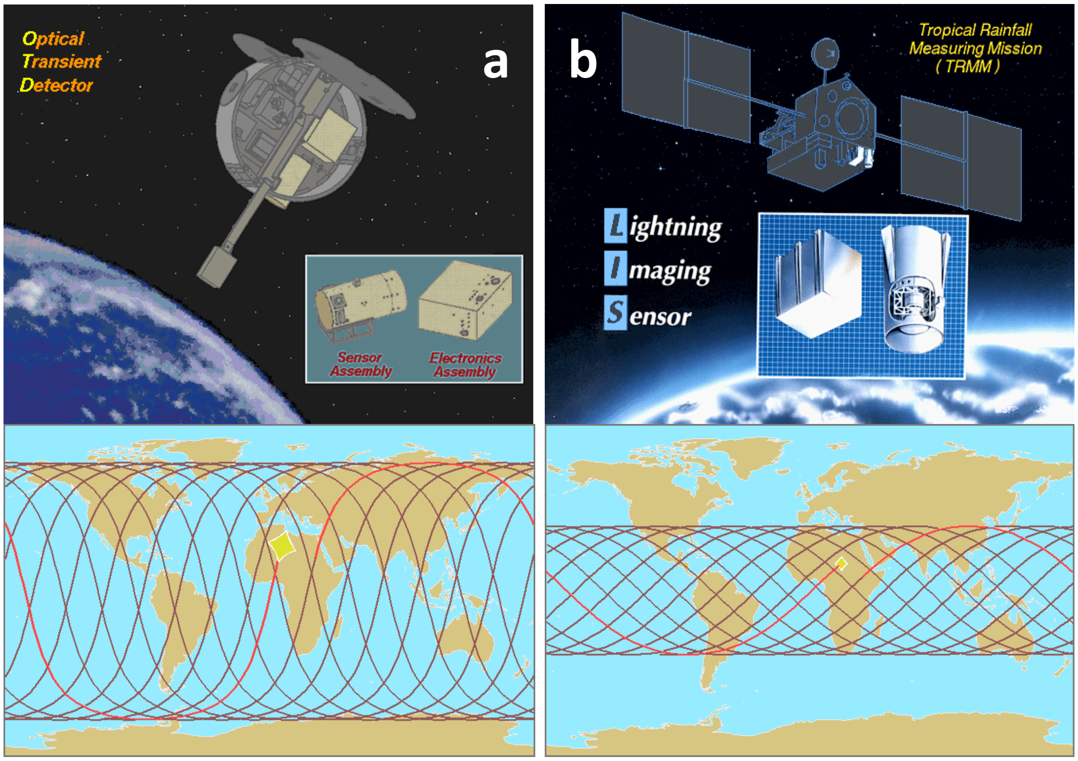

Figure 1. a) The Optical Transient Detector (OTD) and its orbit. OTD detected lightning to 75º N/S latitude and 55 days required to complete the sample of the diurnal cycle. b) Lightning Imaging Sensor (LIS) on the Tropical Rainfall Measuring Mission and its associated orbit. LIS detects lightning to 38º N/S latitude and 49 days are required to completely sample the diurnal cycle.

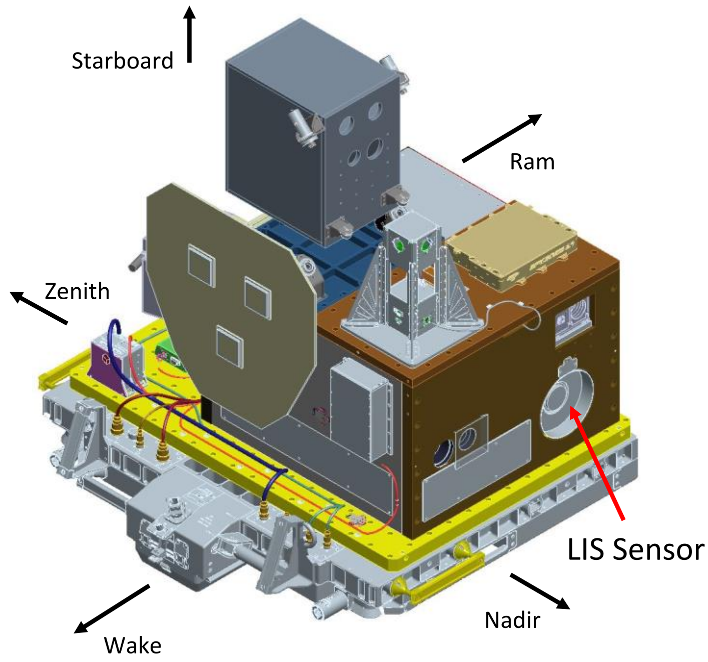

Figure 2. An advanced design concept for the Department of Defense Space Test Program-Houston 5 (STP-H5) mission payload. The LIS, one of thirteen instruments on STP-H5, is shown in its nadir viewing position.

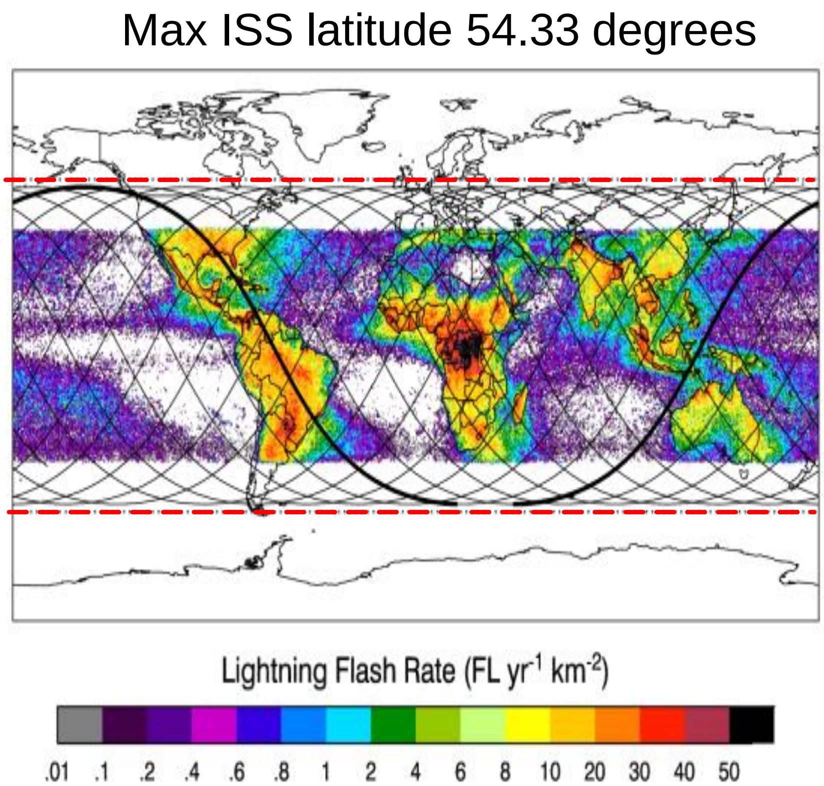

Figure 3. This shows the global coverage provided by ISS LIS. It will detect lightning to ± 54.3º latitude. This region represents 81% of the Earth's surface, but includes 98% of the global lightning on an annual basis.

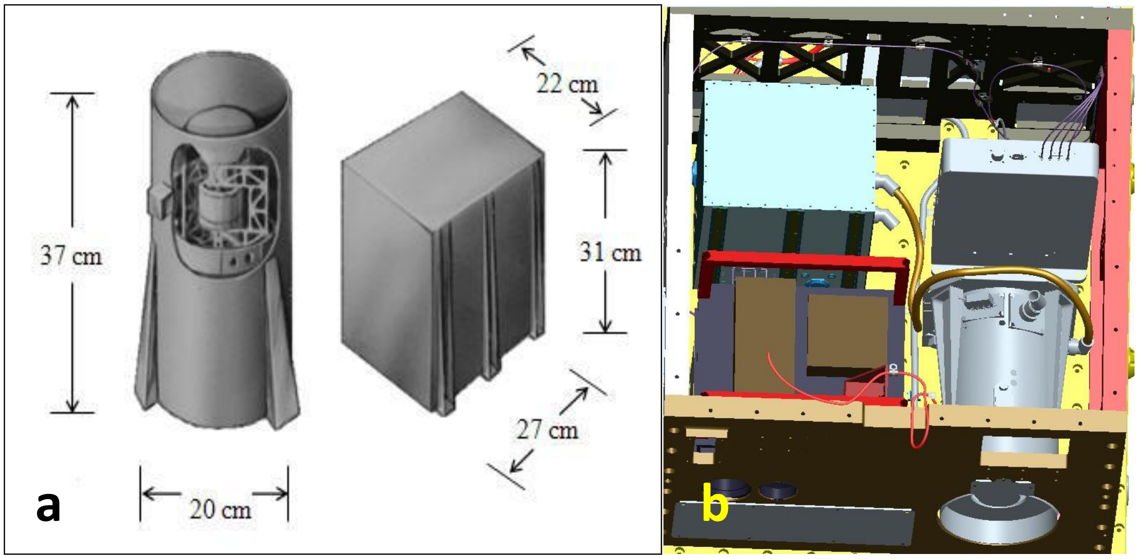

Figure 4. a) Legacy flight spare LIS the sensor assembly (left) and the electronics box (right). b) This is an advanced concept drawing showing how the Legacy LIS hardware will be mounted on the STP-H5 payload. The grey box behind the sensor assembly is the new interface unit (IFU) that will enable the legacy hardware to receive power and communications from the International Space Station.