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Lightning Imaging Sensor on the International Space Station: Assessments and Results from First Year Operations

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ABSTRACT: Over two decades, the NASA Marshall Space Flight Center, the University of Alabama in Huntsville, and their partners have demonstrated the effectiveness and value of space-based lightning observations as a remote sensing tool for Earth science research and applications, and, in the process, established a robust global lightning climatology. The Lightning Imaging Sensor (LIS) on the Tropical Rainfall Measuring Mission (TRMM) provided global observations of tropical lightning for an impressive 17 years before that mission came to a close in April 2015. Now a space-qualified LIS, built as the flight spare for TRMM, has been installed on the International Space Station (ISS) for a minimum two year mission following its SpaceX launch on February 19, 2017. The LIS, flown as a hosted payload on the Department of Defense Space Test Program-Houston 5 (STP-H5) mission, was delivered to the ISS in the Dragon trunk and robotically installed in an Earth-viewing position on the outside of the ISS. Following successful activation and checkout, LIS has continuously observed the amount, rate, and radiant energy lightning within its field-of-view as it orbits the Earth. Placing LIS on the Space Station provides a great opportunity to not only extend the 17-year TRMM LIS record of tropical lightning measurements but also to expand that coverage to higher latitudes missed by the previous mission. Furthermore, this mission continues the important science focus to better understand the processes which cause lightning, as well as the connections between lightning and subsequent severe weather events. This understanding is a key to improving weather predictions and saving lives and property here in the United States and around the world. The LIS measurements, along with observations from the new Geostationary Lightning Mapper (GLM) operating on NOAA's newest weather satellites, the Geosynchronous Operational Environmental Satellite-16/17 (GOES-16/17), are being used to cross-validate both systems. An especially unique contribution from the ISS platform is the production of real-time lightning data, especially valuable for operational forecasting and warning applications over data sparse regions such as the oceans. Finally, LIS provides simultaneous and complementary observations with other ISS payloads such as the European Space Agency's Atmosphere-Space Interaction Monitor (ASIM) that is exploring the connection between thunderstorms and lightning with terrestrial gamma-ray flashes (TGFs). Leveraging TRMM's well-established processing and data handling assures that LIS data can be quickly delivered to users.

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INTRODUCTION

Lightning is an impressive and direct response to intense atmospheric convection. Since lightning is intimately tied to thunderstorm microphysics and dynamics, it can be used to remotely probe the developmental state, severity, and evolution of thunderstorms and thunderstorm complexes, and can also serve as a valuable indicator for monitoring long-term climate change. In fact, it has been found that lightning conveys useful information about many atmospheric processes and provides scientific insight across a broad range of disciplines, including weather, climate, atmospheric chemistry, and lightning physics [Davis et al., 1983].

Over two decades, the NASA Marshall Space Flight Center, the University of Alabama in Huntsville, and their partners have demonstrated the effectiveness and value of space-based lightning observations as a remote sensing tool for Earth science research and applications, and, in the process, established a robust global lightning climatology (Figure 1). Prior to 1995, space-based lightning 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 an inability to measure lightning during the daytime, leading to incomplete sampling over the diurnal cycle [Christian, 1989]. The launch of the Optical Transient Detector (OTD) in 1995 ushered in a 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 [Christian et al, 2003]. The Lightning Imaging Sensor (LIS) on the Tropical Rainfall Measuring Mission (TRMM) joined OTD in November 1997, and then proceeded to provide global observations of tropical lightning for an impressive 17 years before that mission came to a close in April 2015.

MISSION OF OPPORTUNITY

A mission of opportunity to not only extend the 17-year TRMM LIS record of tropical lightning measurements but also to expand that coverage to climatically sensitive higher latitudes missed by TRMM was made possible with the selection in April 2013 of a space-qualified LIS – built as the flight spare for TRMM – to be flown on the International Space Station (ISS). This mission continues the important science focus of the prior missions to better understand the processes which cause lightning, as well as the connections between lightning and subsequent severe weather events. This understanding is a key to improving weather predictions and saving lives and property here in the United States and around the world. LIS on ISS will also support on-going climate and atmospheric chemistry studies. Lightning is an excellent variable for climate monitoring because it is sensitive to small changes in temperature and atmospheric forcing. LIS on ISS will continue to support atmospheric chemistry estimates of lightning produced NO_x for climate and air quality studies. Lightning produced NO_x impacts ozone, an important greenhouse gas. Climate is especially sensitive to ozone in the upper troposphere, exactly where lightning is the most important source of NO_x,

The well characterized measurements of LIS on the ISS, along with the observations from the new Geostationary Lightning Mapper (GLM) operating on NOAA’s newest weather satellites, the Geosynchronous Operational Environmental Satellite-16/17 (GOES-16/17), can be used to cross-validate both systems. Furthermore, there are plans to seek an extension of LIS on ISS beyond the planned two-year timeframe in order to extend cross-sensor observations and calibrations to the European

Meteosat Third Generation Lightning Imager (MTG-LI), currently scheduled for launch in 2022 (LIS can also be used to develop proxy data for MTG-LI just as it was for GLM). The intercomparisons between LIS and GLM and between LIS and MTG-LI would effectively allow for transitive cross-hemispheric comparisons between the two geostationary missions. Coincidence datasets collected between LIS on ISS and members of the recently launched Global Precipitation Measurement (GPM) mission satellite constellation will enable fusion and study of active and passive microwave measurements of clouds and precipitation and associated responses in lightning activity, similar to TRMM but now expanded over a much larger region of the globe and much larger sample of cloud and precipitation regimes. Also, the ISS platform will uniquely enable LIS to provide simultaneous and complementary observations with other ISS payloads, such as the European Space Agency's Atmosphere-Space Interaction Monitor (ASIM), which is exploring the connection between lightning and terrestrial gamma-ray flashes (TGFs), and NASA's Stratospheric Aerosol and Gas Experiment III (SAGE III) mission's ozone observations.

Another especially unique contribution from LIS being on the ISS platform is providing real-time lightning data over data-sparse regions (e.g., over the ocean) to operational users to improve situational awareness for forecasts, warning decisions, and aviation advisories.

INSTRUMENT DESCRIPTION

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 give a high degree of confidence that the flight spare will also perform without problems once launched. A recalibration of the flight-spare LIS performed in preparation for this ISS mission showed its performance and calibration has remained unchanged. It is also worth noting that by monitoring the reflected sunlight from deep convective clouds, LIS on TRMM showed no degradation in its sensitivity during its many years in orbit.

The LIS instrument is a small, solid-state, optical imager optimized to detect and pin-point lightning from thunderstorms within its field of view, mark the time of occurrence, and measure the radiant energy. The instrument 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 optimally sampling the lightning signal relative to the bright solar background in the spatial, temporal, and spectral domains.

LIS is divided into a Sensor Unit and an Electronics Unit. The Sensor Unit contains a wide-field-of-view lens, combined with a narrow-band interference filter centered on a strong emission line in the lightning spectrum (i.e., the oxygen multiplet at 777.4 nm), which focuses the image on a high-speed, 128 x 128-pixel charge-coupled device (CCD) focal plane. The signal is read out from the focal plane at 500 images per second into the real-time event processor located within the Electronics Unit for event detection and data compression. A new Interface Unit was designed and built to make the ISS platform appear like the TRMM spacecraft to LIS so that no modifications would be necessary with the legacy hardware. Table 1 summaries the overall instrument parameters and performance criteria.

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 unit (SU)*	20 × 37 cm
Signal to Noise Ratio	6	*electronics unit (EU)*	31 × 22 × 27 cm
CCD Array Size	128 × 128 pixels	*interface unit (IFU)*	25 × 6 × 35 cm
Dynamic Range	> 100	Weight	25 kg
Detection Efficiency	~ 90 %	Power	35 W
False Event Rate	< 5 %	Telemetry Data Rate	8 kilobytes/second

LAUNCH, INSTALLATION, AND MISSION ACTIVATION

The STP-H5 payload containing LIS launched to the ISS from NASA's Kennedy Space Center on February 19, 2017 aboard the SpaceX Cargo Resupply Services-10 (CRS-10) mission. STP-H5 was carried to the ISS in the unpressurized "trunk" of the Dragon spacecraft. After the Dragon was berth to the ISS, the STP-H5 payload with LIS was robotically installed in a nadir viewing exterior location at the site of ExPRESS Logistics Carrier-1 (ELC-1). The LIS instrument components, its location within STP-H5, and its position on the ISS are shown in Figure 2. Following its successful activation and checkout on February 27, 2018, LIS has continuously observed the amount, rate, and radiant energy lightning within its field-of-view as it orbits the Earth**.**

SCIENCE OPERATIONS AND DATA MANAGEMENT

Orbital science operations are managed from the newly established LIS Payload Operations Control Center (LIS POCC), located at the National Space Science and Technology Center (NSSTC) in Huntsville, AL. Activities from the LIS POCC will be conducted during the work week at regular business hours, and will include monitoring the operation of the LIS and its science and housekeeping data, and commanding the instrument as necessary. More extensive 24/7 monitoring of the LIS will be provided by the Payload Operations Integration Center (POIC) at MSFC. The LIS data handling involves a close partnership between the LIS Science Team and the Global Hydrology Resource Center (GHRC), one of NASA's Distributed Active Archive Centers (DAACs) that extends to the earlier OTD and LIS on TRMM. The well-established and robust processing, archival, and distribution infrastructure used for TRMM was easily adapted to the ISS mission. This assures that lightning data observations from LIS on ISS can be quickly delivered to science and application users soon after routine operations are established and underway. A full suite of space-based lightning observations is available from the GHRC DAAC (***ghrc.nsstc.nasa.gov***). The LIS data products consist of geolocated and time-tagged lightning events, background images ("snapshots" of the LIS CCD acquired about every 30 seconds, depending on the flash rate), orbit statistics, and metadata. Visit the GHRC's lightning data portal (***lightning.nsstc.nasa.gov/data/index.html***) to access these and other lightning datasets, related tools, and documentation. Figure 3 shows the data flow from the LIS to the LIS POCC and GHRC DAAC.

ASSESSMENTS AND VALIDATION

At the time of this writing (April 2018), the LIS has been acquiring observations from ISS for just over one year. Throughout the first year, the LIS science team carefully examined and assessed the time tagged and geolocated lightning and background images (i.e., level 2 data products) resulting from the processing of the on-orbit LIS observations (i.e., also known as level 0 data). Assistance was also provided through feedback from some experienced LIS data users from the broader science community. The most significant issues that were identified and subsequently resolved were inaccuracies with the LIS timing and geolocation. During the first year, there have been three public releases of the data. The initial public release of Beta level data occurred in September 2017. Beta level data (see Appendix 1 for a description of data maturity levels) still had known significant errors in the timing and location accuracy of the science data, but this data was made available to outside science users to help provide feedback to the LIS science team as it carefully addressed these issues. A Post Launch Assessment Review for LIS was successfully completed in October 2017 with the key result being that the LIS mission was declared fully operational, recognizing that it was meeting or had an identified path to meet all of its science requirements, including acceptable timing and geolocation accuracy. Provisional and near real time (i.e., 2 minute latency) data were publically released in January 2018 with the timing corrected to within 1 millisecond. A second release of the Provisional data occurred in April 2018 with the pointing accuracy now improved to better than 4 km when cross-compared to the Geostationary Lightning Mapper. The data will be classified as fully Validated once the quality control process is verified, fully implemented, and applied to first year of data collection. It is anticipated that the release of the Validated dataset will occur in May or June 2018. At that time, gridded and other climatological data products will be produced similar to what is available for TRMM LIS and OTD [Cecil et al., 2014].

Timing Accuracy

A timing chain is used in the acquisition and processing of the LIS data to provide time accuracy that is good to within 1 millisecond. The chain begins with the time tag that LIS events and background images receive in the on-board Electronics Unit (EU). The free running EU clock is synchronized once per second to the free running clock of the LIS Interface Unit (IFU) so that there is at most only a 200 microsecond difference between EU and IFU time. In turn, the IFU time is synchronized once per second to the on-board ISS broadcast time, which is finally corrected during ground processing for a known departure it has from Global Positioning System (GPS) time to produce highly accurate GPS time tags for lightning events and background images.

Three independent reference data sets, including data from the GLM on GOES-16 and two long-range ground-based lightning detection systems – Earth Networks Global Lightning Network (ENGLN) and Vaisala's GLD360 – were used to validate the LIS timing accuracy. Figure 4 shows the temporal offsets, referenced to LIS group time, between LIS and the three reference data. The temporal offsets are all within 1 millisecond of LIS group time. Some systematic tendencies are apparent with each source.

Geolocation Accuracy

Obtaining good geolocation accuracy required first determining and applying accurate time to the ephemeris (position and velocity) and attitude (quaternion and rate) navigation variables. The second step involved fine turning the yaw, pitch and roll variables in an iterative manner to minimize the distance offset between the geolocation of LIS groups and those of the reference data sets. Of special interest here, were the comparisons between LIS and GLM since these two space-based systems detect cloud top optical signal produced by lightning using the same approach.

Figure 5 shows the distance offsets between LIS and GLM in the three month period December 20, 2017 to March 19, 2018 after GLM data had been declared Provisional. The distance offset peaks at 3 km (3.5 km) for the descending (ascending) phase of the orbit, with the width at half max of 5 km for both descending and ascending. It is anticipated some small additional decrease in the peak and the width may still occur as the final steps in the fine tuning are completed. A similar result is obtained when LIS is compared to ENGLN and GLD360 but with a slightly larger peak distance offset of 4 to 7 km, a width at half max of 10 km. The larger peak offset and broader width found with ENGLN and GLD360 are not particularly surprising since these systems detect lightning in the radio frequencies while LIS and GLM both detect lightning in the same manner using optical signals.

Near Real Time Data Products

Near real time data processing and display has been successfully conducted since on-orbit activation. This acquisition and display of real time data represents a first for the LIS program. Except for short Loss of Signal (LOS) periods, LIS data flows continuously from the ISS to both the processing computers and the LIS Payload Operations Control Center (LIS POCC). Presently, this data is processed and made available in 2 minute intervals. The latest 2 minute and a 12 hour browse images are displayed on the Web at ***https://lightning.nsstc.nasa.gov/isslisib/isslisnrt.html***. Figure 6 shows a screen capture of the 12 hour browse image created in real time and updated every 2 minutes.

EARLY RESULTS

The LIS science team has focused most of its attention over its first year on validated the LIS data and bringing up the data quality to the place where it can be used for science studies. Science analyses have now begun but at the time of this writing (again, April 2018) we only have a few results to report. It is anticipated that by the time of the ICAE conference in June many more statistics will be available to compare to the prior OTD and TRMM LIS monthly, seasonal, annual, and climatological statistics. Already, plots of the monthly, seasonal, and annul raw LIS detections have been found to be qualitatively similar to those of OTD and TRMM LIS during their first year of operation. These data have now been adjusted for view time to produce the first estimates of the seasonal and annual global flash rate (flashes km^{-2} yr^{-1}) as shown in the plots in Figures 7 and 8. The distributions and magnitudes of the global flash rates are in general agreement with the long term climatology derived from OTD and TRMM LIS but the precession period (the period it takes LIS to sample the full diurnal cycle) of 60.5 days still has not included in the plots presented here by including a moving average of twice the precession period centered on each day (a slightly different approach being necessary for the first and final two months of a mission).

CONCLUSIONS

Placing LIS on the ISS not only extends the 17-year TRMM LIS record of tropical lightning measurements, it expands the global coverage once again to the climate sensitive higher latitudes missed by TRMM. Furthermore, this mission continues to support and contribute to many important science studies on weather, climate and atmospheric chemistry. Among these studies are efforts to better understand the processes which cause lightning, as well as the connections between lightning and subsequent severe weather events, long term climate trends, and atmospheric trace gas production. The well characterized LIS measurements, along with observations from the new GLM on GOES-16/17, provide an excellent opportunity to obtain cross-platform validation of detection efficiency, location accuracy and radiances for both systems. Later, if the LIS on ISS remains operational until the launch of the MTG-LI satellite, its measurements could serve as a transfer standard between GLM and LI, improving the long term climate modeling provided by all these systems. Now that LIS is fully operational it is hoped that the production of real-time lightning data will soon find applications for operational forecasting and warning over data sparse regions such as the oceans. The ISS platform will uniquely enable LIS to provide simultaneous and complementary observations with other ISS payloads such as ASIM's exploration of the connection between thunderstorms and lightning with TGFs, and SAGE-III's ozone observations. Blakeslee and Koshak [2016] provide additional in-depth details for the LIS on ISS mission.

ACKNOWLEDGMENTS

The LIS mission on ISS is supported by the NASA Headquarters Science Missions Directorate and by the International Space Station Program Office at Johnson Space Center, and is currently overseen by Charles Webb, Program Executive for Operating Missions in the Earth Science Division (ESD), and the Earth Systematic Program Office at Goddard Space Flight Center. We would also like to acknowledge the lightning team at NASA Marshall Space Flight Center and the University of Alabama in Huntsville who have support LIS over the years, as well as users from the science community who provided valuable feedback during its initial year of operation.

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APPENDIX (*Data Maturity Levels*)

Beta

These products are intended to enable users to gain familiarity with the parameters and the data format. Errors, some serious, may exist so the data should not be used for rigorous scientific analyses.

Provisional

These products are defined to facilitate data exploration and process studies that do not require rigorous validation. These data are partially validated and improvements are continuing. Quality may not yet be optimal since validation and quality assurance are still ongoing.

Validated

These products are high quality data that have been fully validated and quality assured, and are deemed suitable for systematic studies such as detailed case study analyses or longer term climate research activities. These are publication quality data with well-defined uncertainties, but they are also subject to continuing validation, quality assurance and further improvements in subsequent versions. Users are expected to be familiar with quality summaries of all data before publication of results, and when in doubt, to contact the LIS science team.

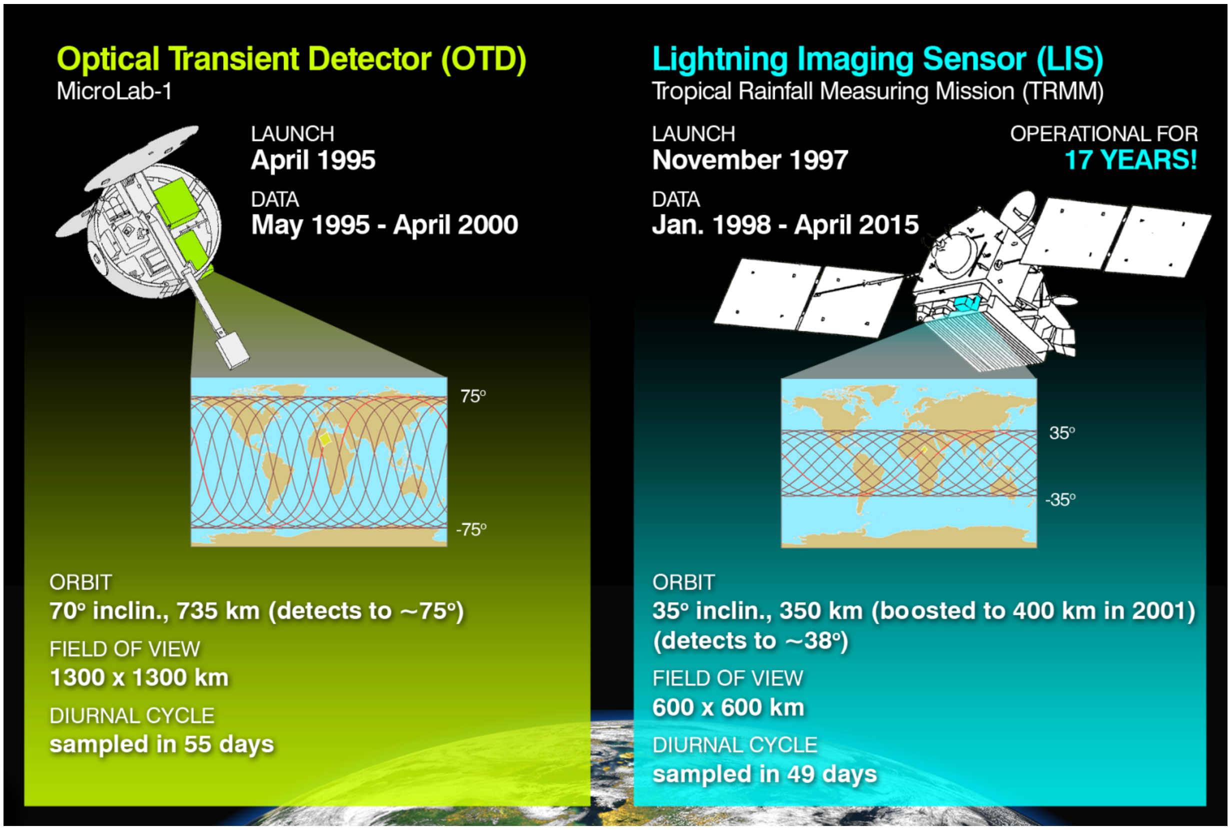


Figure 1. LIS on ISS builds on a solid foundation of 20 years of on-orbit observations from OTD and LIS

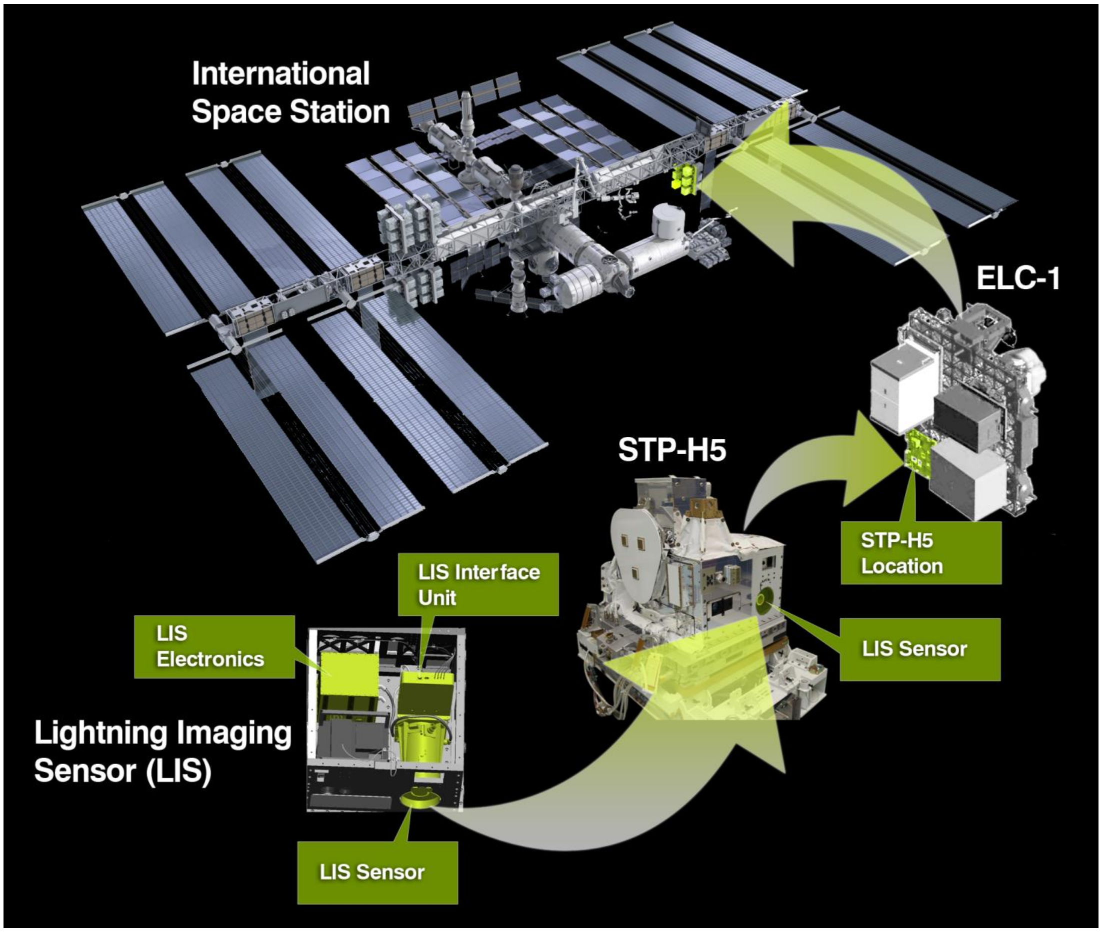


Figure 2. Graphic shows where the LIS hardware is installed within the STP-H5 payload, and where STP-H5 is installed on the ELC-1 in a nadir viewing location.

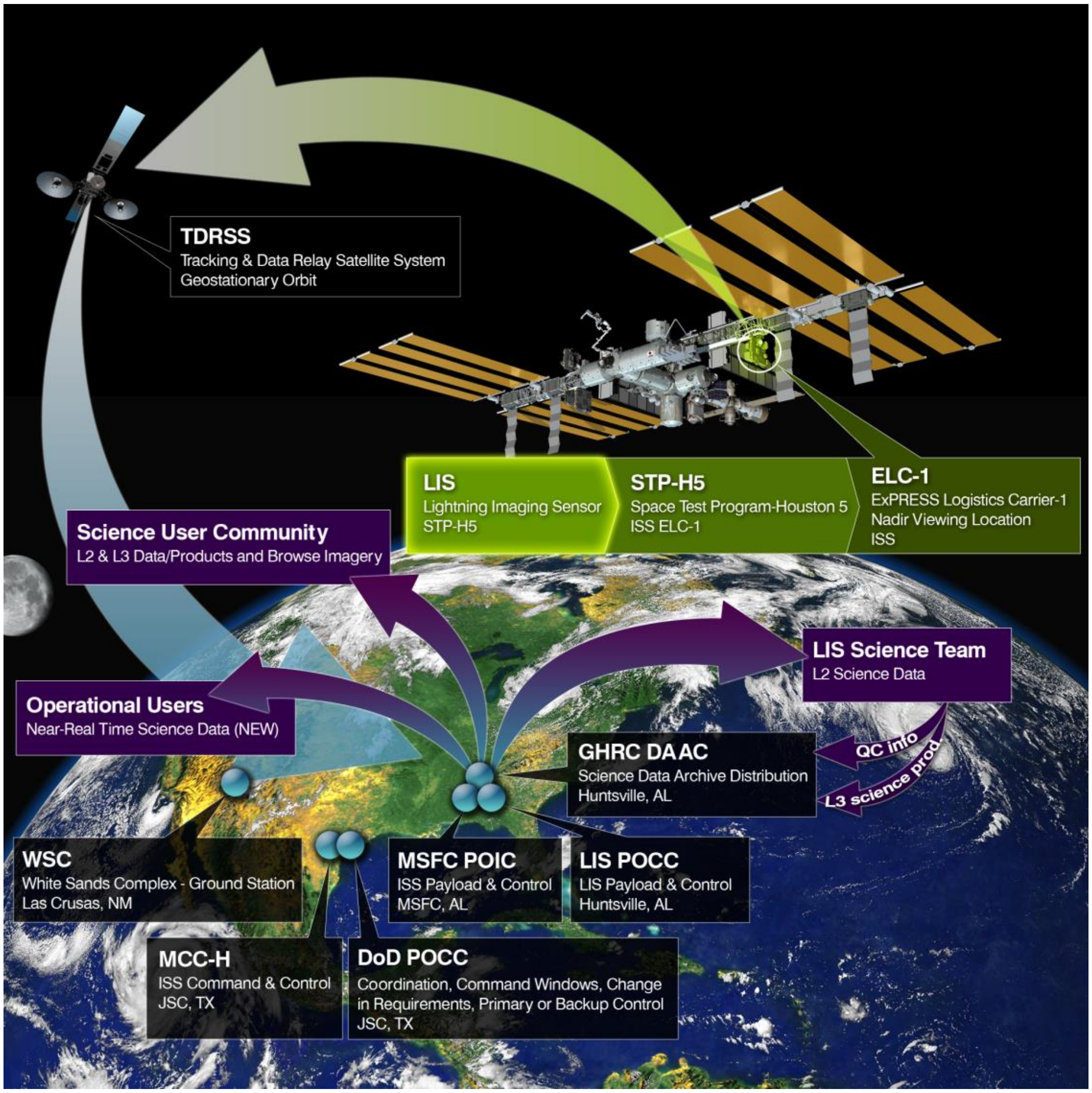


Figure 3. Graphic shows the data flow from the LIS instrument to the LIS POCC and GHRC DAAC where it is processed and distributed to the user community.

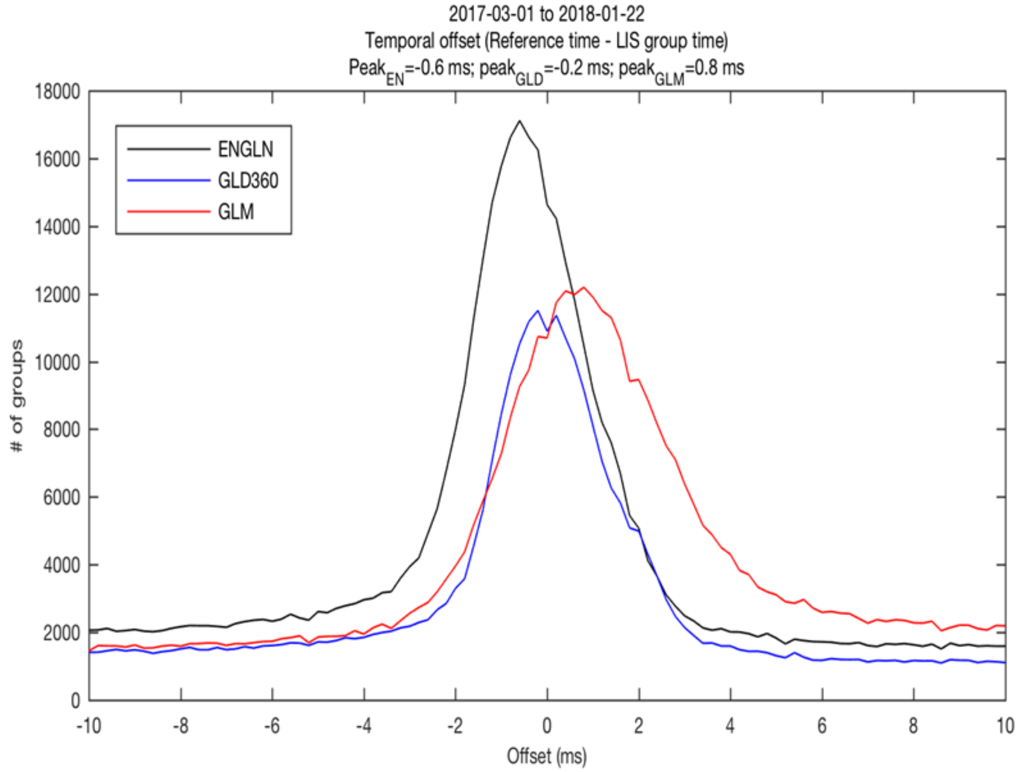


Figure 4. Temporal offsets between LIS group time and the corresponding group time in the ENGLN, GLD360 and GLM reference data sets.

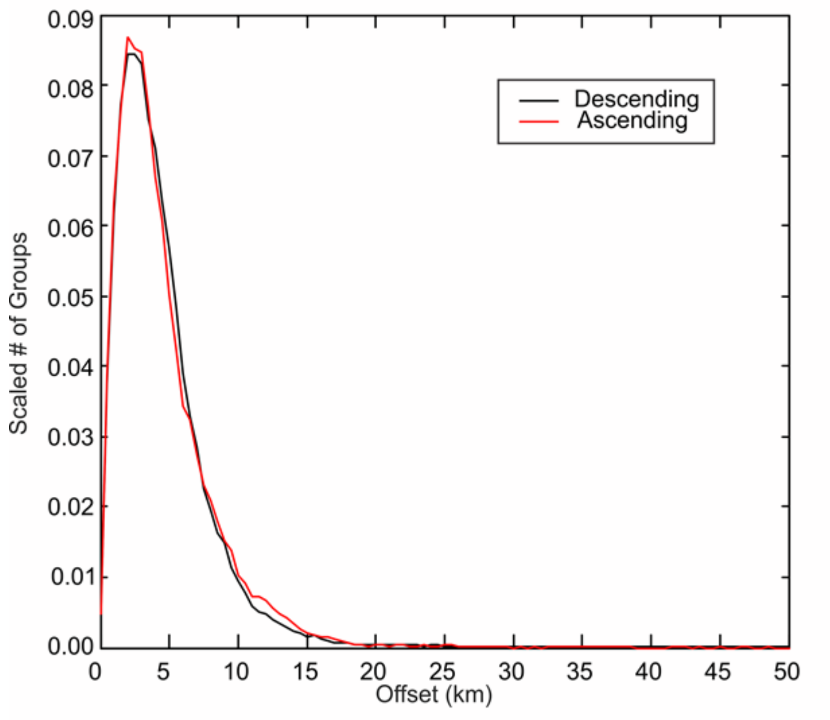


Figure 5. Peak distance offset between corresponding LIS and GLM geolocated groups over a three month period.

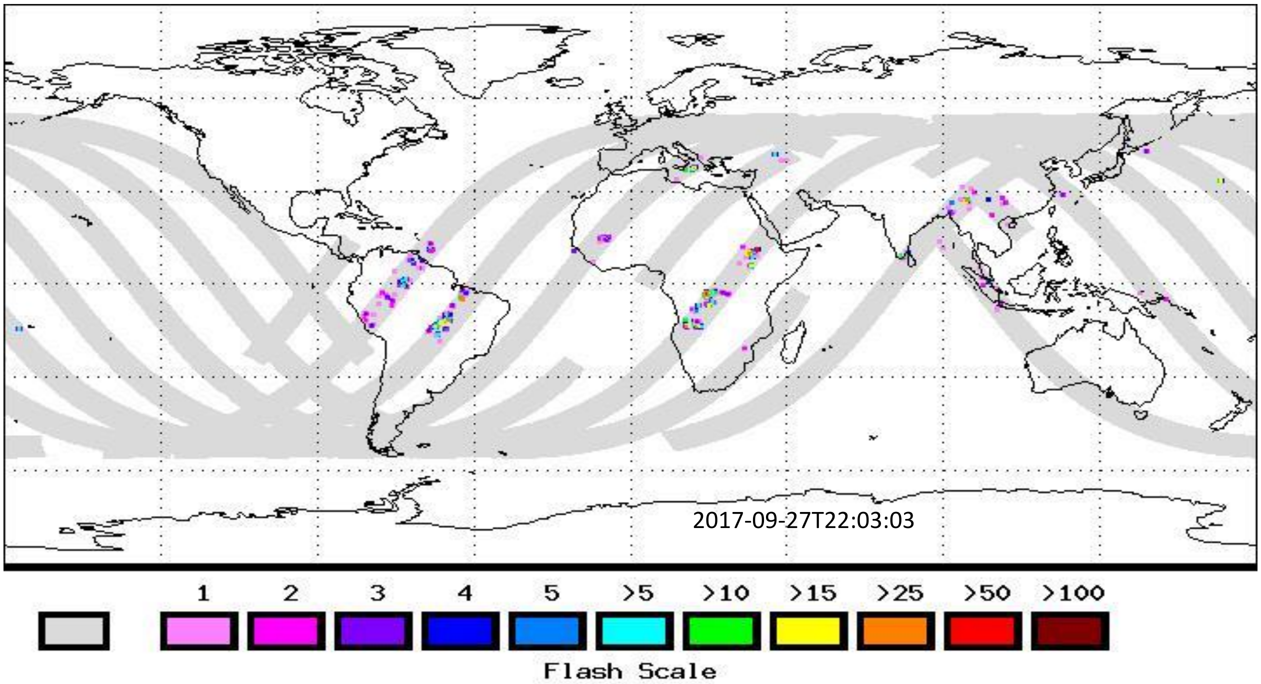
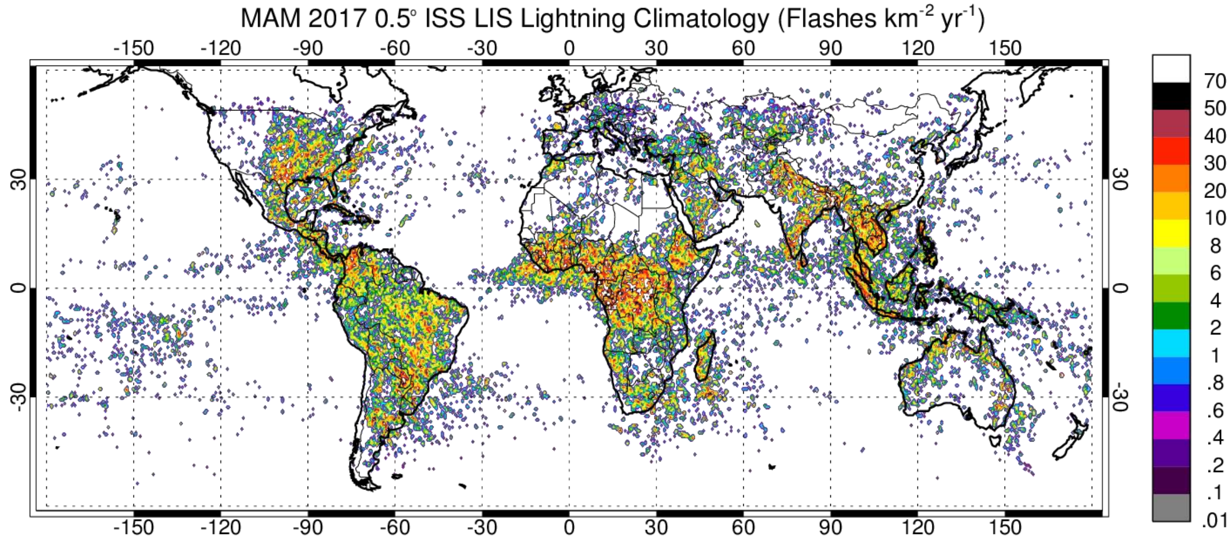
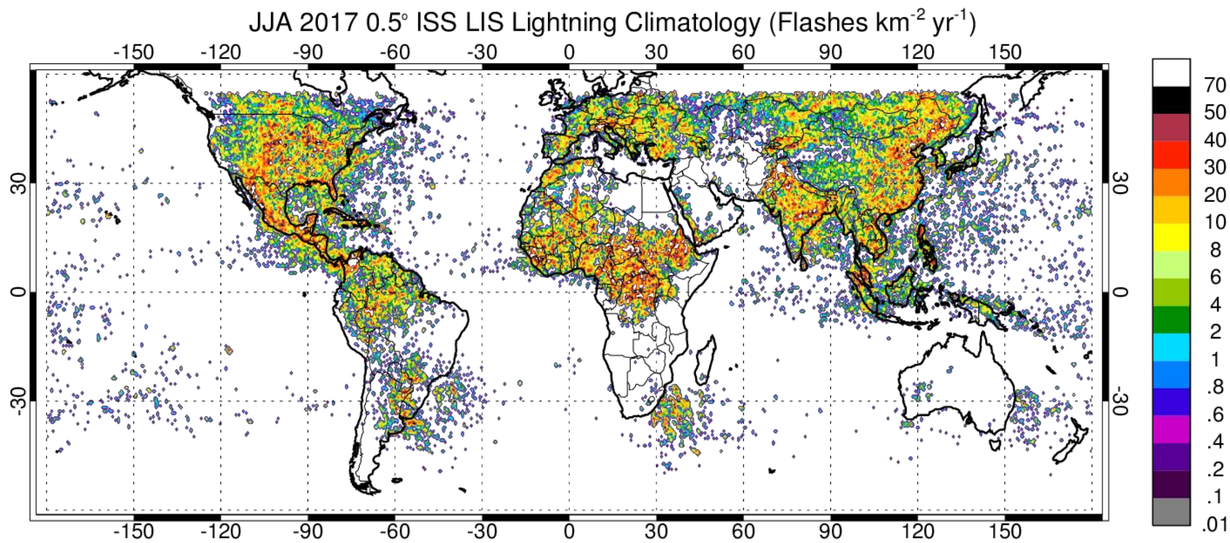


Figure 6. A screen capture of a12 hour browse image created in real time in 2 minute increments.

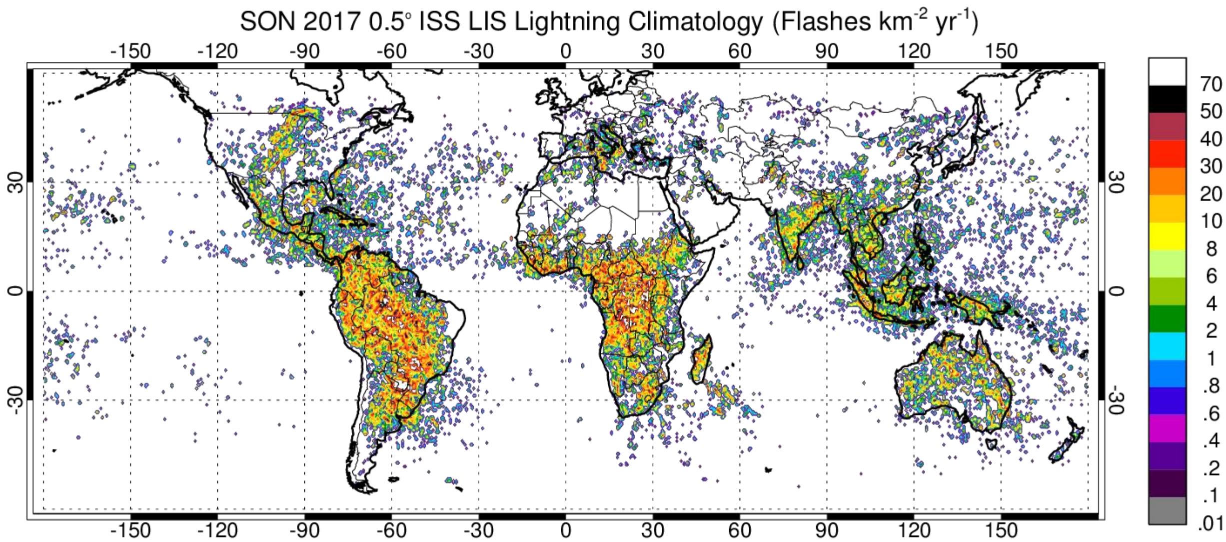


A

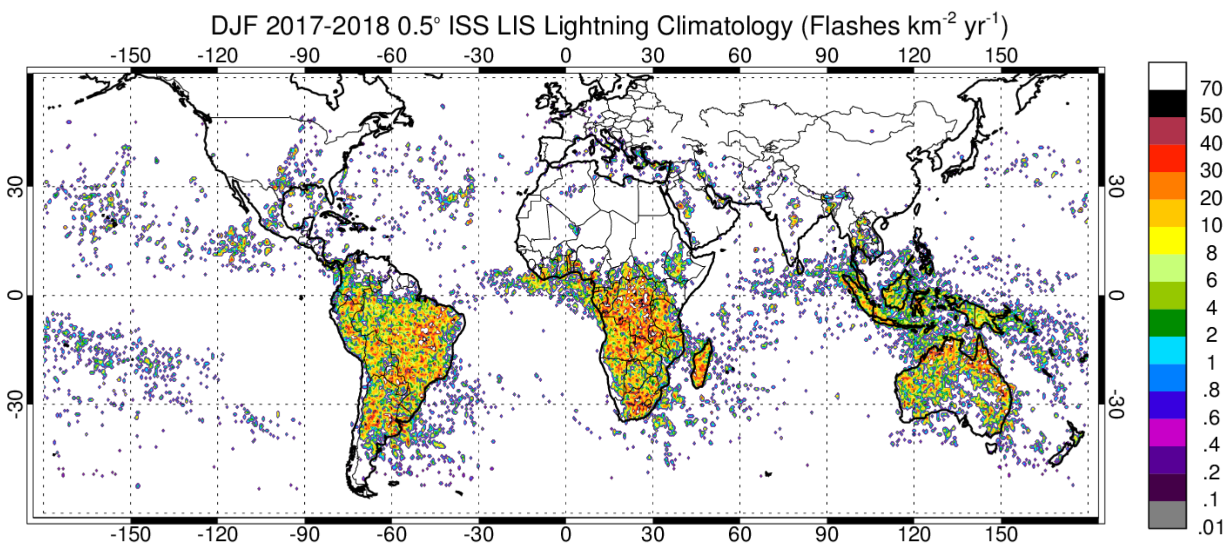


B

Figure 7. Global 0.5° mean seasonal flash rates (flashes km^{-2} yr^{-1}) over first year operation of LIS on ISS for A) Spring (March 2017-May 2017) and B) Summer (June 2017-August 2017)



C



D

Figure 7 (cont.). Global 0.5° mean seasonal flash rates (flashes km^{-2} yr^{-1}) over first year operation of LIS on ISS for C) Autumn (September 2017-November 2017) and D) Winter (December 2017-February 2018)

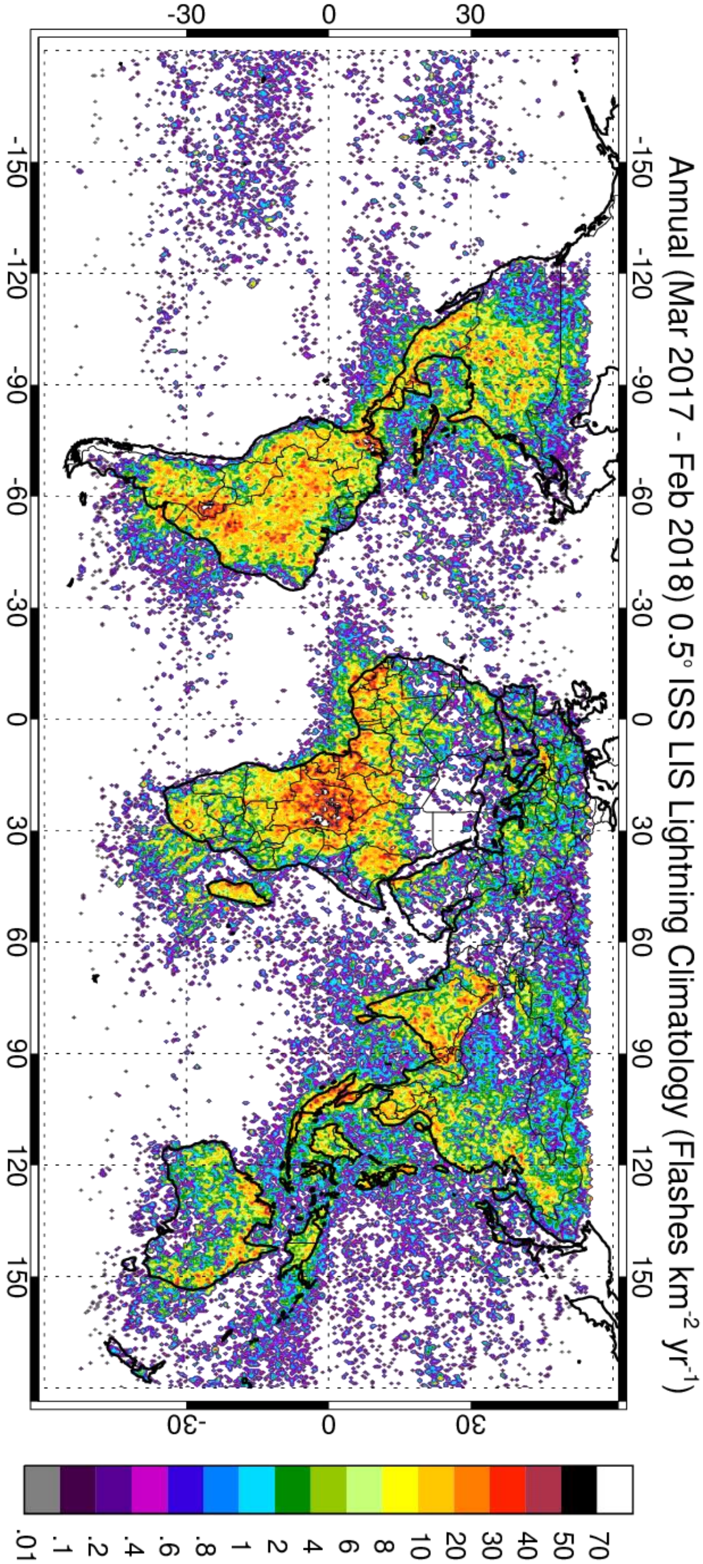


Figure 8. Map depicts 0.5° mean annual flash rate (Flashes km^{-2} yr^{-1}) for first year (Mar 2017 – Feb 2018). LIS observes 81% of the Earth's surface but this region includes 98% of the annual global lightning.