Three years of the Lightning Imaging Sensor onboard the International Space Station: Expanded Global Coverage and Enhanced Applications

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Abstract

The Lightning Imaging Sensor (LIS) was launched to the International Space Station (ISS) in February 2017, detecting optical signatures of lightning with storm-scale horizontal resolution during both day and night. ISS LIS data are available beginning 1 March 2017. Millisecond timing allows detailed intercalibration and validation with other spaceborne and ground-based lightning sensors. Initial comparisons with those other sensors suggest flash detection efficiency around 60%, false alarm rate under 5%, timing accuracy better than 2 ms, and horizontal location accuracy around 3 km. The spatially uniform flash detection capability of ISS LIS from low-Earth orbit allows assessment of spatially varying flash detection efficiency for other sensors and networks, particularly the Geostationary Lightning Mappers. ISS LIS provides research data suitable for investigations of lightning physics, climatology, thunderstorm processes, and atmospheric composition, as well as realtime lightning data for operational forecasting and aviation weather interests. ISS LIS enables enrichment and extension of the long-term global climatology of lightning from space, in particular to higher latitudes (± 55°) than was recently possible. The global spatial distribution of lightning from ISS LIS is broadly similar to previous datasets, and globally averaged seasonal/annual flash rates agree within 5-10% as well. The expected land/ocean contrast in the diurnal variability of global lightning is also observed.

Plain Language Summary

The Lightning Imaging Sensor on the International Space Station (ISS LIS) has been operating on-orbit since February 2017. The instrument has met all of its major science objectives, including detecting lightning day and night, identifying the specific locations within storms that are producing lightning, millisecond timing accuracy, and high probability of detecting lightning. The instrument also measures energy emitted by lightning, provides background images of storms and their surroundings, and delivers realtime lightning data. This has enabled enrichment and extension of the long-term global climatology of lightning from space, in particular to higher latitudes (+/- 55 degrees) than was recently possible. In addition, the instrument is serving as a standard for comparison to other spaceborne lightning sensors, such as the Geostationary Lightning Mapper (GLM). The realtime data from ISS LIS have enabled new applications for the benefit of the public, including weather forecasting and public safety. Finally, ISS LIS - in conjunction with other satellite instruments - is providing opportunities for new scientific study in areas such as lightning physics, thunderstorm processes, and atmospheric composition.

Key Points

1. The Lightning Imaging Sensor (LIS) has been operational on the International Space Station (ISS) since February 2017.
2. ISS LIS provides storm-scale resolution (4-km) and millisecond timing of global lightning with high uniform detection efficiency (~60%).
3. The 3-year global lightning climatology is consistent with previous studies (within 5-10%), while extending results to higher latitudes.

1. Introduction

Lightning is a spectacular and direct response to strong thundercloud electric fields, which in turn are generated by intense atmospheric moist convection and (normally) the onset of active precipitation processes involving ice particles [*Saunders*, 2008]. Since lightning is inherently coupled to storm microphysics and dynamics, it can be used as a valuable tool to remotely probe the developmental state, severity, and evolution of thunderstorms and thunderstorm complexes [e.g., *Yoshida et al.*, 2017; *Darden et al.*, 2009 and references therein]. Because a lightning discharge produces lightning nitrogen oxides (LNO_x), which in turn affect greenhouse gas concentrations (such as ozone), lightning also serves as a key indicator for monitoring long-term climate change, and plays an important role in affecting air quality forecasts [*Koshak et al.*, 2014a,b; *Koshak et al.*, 2015]. Overall, lightning provides useful information about a variety of atmospheric processes and offers vital scientific insight across a broad range of disciplines, such as weather, climate, atmospheric chemistry, and lightning physics.

The Lightning Imaging Sensor (LIS) on the International Space Station (ISS) plays a special role in improving our understanding of these complex interrelationships. The optically based lightning detection instrument was launched to the ISS in February of 2017, and has successfully operated with limited downtime since. The ISS, which is in a low-Earth orbit (LEO) inclined near 55°, has been increasingly used as a host for a number of Earth-observing instruments due to its accessibility; ample space, power, and data bandwidth; and ability to precess through the diurnal cycle.

This paper will describe the ISS LIS instrument and its data products, document key performance metrics and science results from its first three years on orbit, discuss applications enabled by near-realtime ISS LIS data, and point toward new opportunities for cross-platform science that are enabled by using ISS LIS in conjunction with other Earth-observing instruments.

2. ISS LIS instrument and data structure

The ISS LIS instrument heritage spans multiple decades. The National Aeronautics and Space Administration (NASA) Marshall Space Flight Center (MSFC) - along with support from other science, academic, and commercial partners - developed a unique space-based lightning detection instrument, the Optical Transient Detector (OTD). The instrument design concept began in earnest in the 1980s with high-altitude aircraft measurements of cloud-top lightning optical signatures [*Christian et al., 1983*]. These measurements helped determine optimal space-based instrument requirements (e.g., what sensitivity would be required to detect lightning under both day and night conditions). The OTD was then engineered from these requirements in the early 1990s, and was launched aboard the MicroLab-1 satellite in 1995 from Vandenberg Air Force Base. It provided the first global-scale lightning climatology for its operational lifetime (1995-2000) [*Christian et al.*, 2003].

The OTD was essentially a prototype design for the LIS concept developed as part of the NASA Earth Observing System (EOS). The LIS was selected as an EOS instrument to fly on both a polar platform and the ISS, then known as Space Station Freedom. However, all the EOS instruments for ISS were descoped within about a year because NASA wanted to focus primarily on getting the ISS built. Later, LIS was moved to the Tropical Rainfall Measuring Mission

(TRMM) instrument complement because it had strong synergies with the core TRMM science instruments [*Kummerow et al.*, 1998]. TRMM LIS was launched in November of 1997 and ended its mission with the deorbiting of the TRMM satellite in April of 2015 (i.e., a very successful 17+ years of operational lifetime).

Building on this long and dynamic heritage, the flight spare instrument for TRMM LIS was adapted to work on the ISS platform, resulting in ISS LIS. ISS LIS was part of the 5th Space Test Program - Houston mission (STP-H5), which is sponsored by the US Department of Defense (DoD). ISS LIS is currently located on the Express Logistics Carrier 1 (ELC-1) module of the ISS (Fig. 1).

Relative to TRMM LIS, ISS LIS extends the program of record for global coverage of low-latitude lightning (± 38°). Relative to OTD, ISS LIS extends the program of record for higher latitude lightning (up to ± 55°). And relative to geostationary lightning sensors, ISS LIS enables fully global coverage as well as cross-platform validation. Thus, ISS LIS is a unique Earth-observing instrument that provides near-realtime observations of lightning, including global coverage to high latitudes (observing an estimated 98% of all global lightning) throughout the diurnal and seasonal cycles.

In terms of NASA EOS Data and Information System (EOSDIS) Data Processing Levels, the ISS LIS science data are Level 2 (i.e., derived geophysical variable), while the background data are Level 1B (i.e., reconstructed instrument data processed to sensor units). The data are available in the TRMM LIS heritage Hierarchical Data Format Version 4 (HDF4) as well as the modern Network Common Data Format Version 4 (netCDF4), with corresponding browse images in Graphics Interchange Format (GIF).

ISS LIS products are produced and distributed by the NASA Global Hydrology Resource Center (GHRC) Distributed Active Archive Center (DAAC; Figs. 1 and 2) and can be discovered via the NASA Earthdata Search tool [*Earthdata*, 2020], the GHRC Hydrology Data Search Tool [*HyDRO*, 2020], and the GHRC website for ISS LIS [*ISS LIS*, 2020].

The LIS measurement concept, which is based on time-differenced geolocated images at 777.4-nm wavelength [*Christian et al.*, 1989], an oxygen-absorption line that enables detection of lightning signals at cloud top during both day and night, was recently adapted to work from geostationary orbit [*Goodman et al.*, 2013; *Rudlosky et al.*, 2018]. This enables continuous spaceborne lightning observations over a hemispheric field of view (FOV).

3. Results

ISS LIS has operated successfully for more than three years. Among many other accomplishments, all major science objectives for the instrument have been achieved. In addition, a climatology of global lightning has been produced and compared to similar datasets. Cross-platform validation against other datasets has been performed, and new cross-platform science applications are being developed. Finally, a diverse user community is developing due to applications enabled by near-realtime ISS LIS data. These results are summarized in the subsections below.

3.1 Achievement of major science objectives

A primary and fundamental accomplishment in the past 3 years has been the successful achievement of all major science objectives of the instrument. These objectives include the detection of lightning during day and night, with storm-scale spatial resolution, millisecond timing, and high flash detection efficiency without a land/ocean bias. ISS LIS was designed to measure radiant energy and provide background images/intensity, and its deployment on the ISS enables the delivery of realtime lightning data. These objectives were achieved by successfully meeting the following instrument/platform requirements.

3.1.1 Successfully characterize the instrument's field of view (FOV)

The ISS LIS instrument has a 78.5° x 78.5° rectangular FOV imaged on a 128 x 128 pixel charge coupled device (CCD). At 400-km altitude this provides "storm-scale" pixel resolution (nadir) of ∼4 km (and 50% larger at off-nadir boundaries), which is similar to TRMM LIS after its orbit boost in 2001. Obscuration of the FOV by ISS solar panels and radiator that periodically pass through the FOV was quantified. Worst-case mean and peak obscuration is 4% and 12.5%, respectively. Since ISS is a moving platform, small obstructions in the FOV will only lower view-time of a point on the ground (e.g., storm) momentarily, so there is no impact to science provided the view times are appropriately adjusted. Current version 1 ISS LIS data likely have a slight, artificially reduced (~1-2%) detection efficiency (DE) due to overestimates of viewing times. FOV analysis remains an ongoing process, and improved viewing time estimates are expected in version 2 ISS LIS data.

3.1.2 Mitigate solar glare/glint, and control the thermal and contamination environments

Reflection of direct sunlight into the sensor will not damage LIS, but sufficient glint signal could momentarily "blind" LIS by filling its first-in/first-out (FIFO) buffer. Pre-launch, Manipulator Analysis Graphics and Interactive Kinematics (MAGIK) analysis was performed by NASA Johnson Space Center (JSC) to assess potential glare/glint and its impact. No glare spots or rapidly changing illumination were detected from either the solar panels or radiator. Images obtained from nadir-viewing cameras in STP-H4 (another STP mission located close to ISS LIS) qualitatively corroborate this result. Analysis of numerous other ISS images and videos also supported this inference (not shown).

During mission development, STP-H5 and LIS engineers examined both survival (during transfer) and temperature exceedance during operation. It was found that on-orbit temperatures remained within acceptable limits. Realtime housekeeping data from ISS LIS, including relevant temperatures, are gathered and posted to an internal website. These data are regularly monitored to ensure nominal instrument performance.

Modeling analysis was conducted for the molecular contamination effects on the LIS window transmission at 777.4 nm. The modeling was based on previous flight data from materials exposed in the ISS environment and estimations of outgassing rates in that environment for the mission duration of 3 years. Values were taken from baseline external contamination assessments collected during pre-launch testing. Worst case scenario showed only a 5% decrease in absolute transmission over 3 years due to typical contaminates. Note that the nearly identical TRMM LIS instrument showed very limited performance degradation over its 17-year life span [*Buechler et al.*, 2014].

3.1.4 Laboratory calibration

The laboratory calibration of TRMM LIS is discussed in detail in *Koshak et al.* [2000], and this was the same calibration approach applied to the spare LIS unit (i.e., ISS LIS). The calibration consisted of four main efforts: (1) a static response test, a (2) transient response test, (3) a spectral test, and (4) an FOV test. Additional elements of the calibration pertinent to LIS performance characteristics are discussed in *Boccippio et al.* [2002].

The calibration tests, which are referred to here as the original calibration (OC), were carried out on both the original TRMM LIS and the spare unit (the future ISS LIS) in the summer of 1997. TRMM LIS was subsequently launched to orbit, while the spare unit was stored in a safe box in an environmentally controlled facility for many years, until it was integrated on STP-H5. In the summer of 2014 and prior to the integration on STP-H5, a retest calibration (RC) was performed on the spare unit to evaluate if there were any significant changes in the OC given the many years that the unit was in storage. The RC instrumentation and procedures employed were made as similar as possible to that employed in the OC, but unfortunately the OC and RC methodologies were not identical.

A brief overview of the OC tests applied to both the TRMM LIS and ISS LIS are provided below:

- **Static Response Test**: The OC static response test provided the linear response of each pixel, and hence also quantified uniformity across the charge coupled device (CCD) array. It employed an 8-inch integrating sphere calibration standard. The sphere lamp source emitted a static radiance that was nearly isotropic and uniform over the 2-inch diameter exit port (source stability at 3000 K color temperature was specified at ± 0.5% over a 1-hr duration, and ± 2.0% over 100 hr). The radiance was continuously adjustable over a range of five orders of magnitude without changing the color temperature. Since the sphere output could not fill the sensor FOV, a motorized positioning system (containing precision Newport/Klinger rotation stages) was used to yaw and pitch the sensor head to effect full FOV coverage.

- **Transient Response Test**: The purpose of the OC transient response test was to determine the transient response of the sensor to optical pulses of various integrated energies, against several different levels of steady-state background radiance, and for several different pixels across the CCD array. Pulse energy was varied by varying the pulse duration within a 2-ms LIS frame. The primary component of the test system was a 2-inch integrating sphere containing a near-infrared light emitting diode (LED) and a small quartz tungsten halogen (QTH) lamp. The LED was mounted behind a pinhole in the far surface of the sphere. Background radiance levels were adjusted by a variable aperture in the lamp input port, thus maintaining a constant color temperature.
- **Spectral Response Test**: The OC spectral test employed a high-resolution grating monochromator (500-mm focal length, f/5 aperture, and 0.1-nm resolution) as the primary component. The attached source module contained a QTH lamp and a krypton rare gas discharge lamp as a wavelength reference. The monochromator output was fed through a fiber-optic cable whose output was approximately collimated by a small off-axis paraboloid mirror. By scanning in wavelength, the spectral test determined the sensor end-to-end relative spectral response. This test covered only the wavelength region near and within the passband of the narrowband interference filter.

- **FOV Test**: The FOV test in the OC employed a 9-inch diameter, off-axis paraboloid mirror and an infrared LED. The LED was used to illuminate a total of 31 pixels that were evenly spaced across the CCD, and the associated source incidence angles for each pixel was computed. The LED incidence angles to the lens could be viewed equivalently as lightning source angles. The geometrical mappings were mathematically unique and were used to build a lens transfer function (i.e., boresight angle vs. pixel distance from center of the CCD). These results are fundamental to the process of geolocating lightning. The overall sensor FOV (approximately 78.5° x 78.5°) was determined by simply illuminating pixels on the CCD perimeter.

As mentioned previously, the RC methodology and equipment were not identical to the OC. In the fall of 2013, prior to beginning the RC, it was deemed necessary to upgrade much of the equipment employed in the OC, since these were out of date and were no longer compatible with current technology. For the static response test, two integrating sphere systems were procured. The first was a 12-inch sphere with a large aperture which was intended to allow uniform illumination of a larger portion of each quadrant of the ISS LIS instrument. The second was a 6-inch sphere that was comparable but not the same size as the 8-inch sphere used in the OC. This second sphere was acquired for the purposes of transient testing, as it had a removable port in the back for attaching an LED.

Ultimately the 12-inch sphere was deemed unusable for the static response test because the large opening allowed for “hotspots” where the luminosity was greater surrounding the tungsten bulbs. The 6-inch sphere worked for testing the static response of the instrument; however, it only covered a fraction of each of the quadrants. After comparing the results with the legacy calibration, it was noticed that there was a form factor difference, so the legacy 8-inch sphere was then used to determine if the values were still the same as the legacy calibration. Using the legacy sphere as a one-to-one comparison with the previous calibration was a success.

Use of the 6-inch sphere for transient testing was originally the plan; however, after inserting the newly painted LED insert there were noticeable differentials in the reflectivity of the new insert, especially around the edges. It was decided to use the LED as the source for the backgrounds for each pixel and then on top of that send the pre-programmed transient signal. This allowed for a very controllable and fluid process for the transient calibration.

For the spectral test, the grating monochromator used in the OC could no longer be used because the controller was no longer available, and the connections were obsolete. Instead, a new monochromator was employed for the RC. The FOV test for the RC was performed in much the same way as in the OC, and the results were essentially identical.

ISS LIS alignment measurements were conducted in the RC. The alignment measurements were obtained by illuminating different sides of a mirror-faced alignment cube (attached to the outside of the LIS sensor head assembly) with a theodolite; this allowed determination of the overall rigid alignment of the LIS lens/CCD systems with the STP-H5 module and ISS platform.

While the RC procedure was acceptable, it was not optimal. The intent of the RC was to ensure that nothing significantly changed with the instrument during the years in storage. For expediency, and because the RC results showed no significant changes from the OC results for

TRMM LIS (Fig. 3), the OC results for the TRMM LIS were applied in the ISS LIS processing code, which produces the version 1 dataset available at the GHRC.

However, a plan is being implemented to replace the TRMM LIS OC results in the ISS LIS processing code with the ISS LIS OC results, since identical procedures could not be followed due to the passage of time. In particular, the RC static response test was incomplete because it did not cover all pixels in the CCD array; it only illuminated a small circular portion in the center of each quadrant. This leaves some lingering calibration uncertainties in the version 1 ISS LIS dataset. The ISS LIS science team is working to retrieve the digital OC calibration data for the spare unit, and before updating the ISS LIS processing code the ISS OC and RC results will be compared in detail, as well as with the OC results for TRMM LIS. Based on initial analysis, an improvement of 2-5% in key instrument performance parameters (e.g., flash detection efficiency, flash false alarm rate, geolocation accuracy, and optical amplitudes) is expected after a future switch to the ISS LIS OC.

<u>3.1.5 Quantify timing, geolocation/pointing, detection efficiency, and false alarm rate</u>

Like TRMM LIS, ISS LIS has a frame rate of 500 s^{-1}. This implies a native 2-ms timing precision. The actual on-orbit timing *accuracy* of ISS LIS was determined by comparison against multiple ground-based and spaceborne reference datasets. The ground-based reference datasets were the EarthNetworks Global Lightning Network (ENGLN), which operates wideband sensors (1 Hz to 12 MHz), and the Vaisala Global Lightning Dataset 360 (GLD360), which detects waveforms in the very low frequency range (VLF; ~500 Hz to ~50 kHz). Both of these are global datasets. The spaceborne reference datasets were the Geostationary Operational

Environmental Satellite (GOES) 16 and 17 Geostationary Lightning Mappers (GLM-16 and GLM-17) [*Goodman et al.*, 2013, *Rudlosky et al.*, 2018]. GLM is built on the LIS/OTD optical detection heritage and is sensitive to both IC and CG lightning.

The timing data as initially received from ISS exhibited offsets up to ± 1 s with respect to the reference data, with an alternating drift pattern that cycled approximately every 9 days. This drift was accurately characterized based on careful analysis. On the basis of this, timing correction variables, and an additional constant offset, were applied to produce the current timing accuracy (Fig. 4 left).

After correction, ISS LIS has modal temporal offset of +1 ms, or approximately one-half the LIS frame duration, when compared with GLM-16/17 (Fig. 4 left). The standard deviation in the offset is less than 2 ms in either direction, compared to GLM-16/17. This comparison was based on group timings between ISS LIS and the GLM datasets. Relative to the ground-based reference datasets, there is zero modal offset, and the standard deviation is also below 2 ms. Thus, after correction for the ISS timing errors, the ISS LIS timing accuracy is less than the native timing precision of the instrument itself (2 ms).

ISS LIS geolocation accuracy was analyzed through a coordinate system transform technique that allowed LIS location errors with respect to the reference data to be displayed in the native LIS field-of-view. This analysis revealed that the ISS navigation variables used for LIS geolocation vary systematically during each orbit, creating location errors of up to 25 km. The ISS LIS team worked diligently to troubleshoot the initial issues with geolocation (and timing), as these posed complex interconnected problems that took focused analysis, data deep-dives, and skilled interpretations to resolve.

An iterative tuning process resolved these initial problems and produced corrected geolocation data and the current analysis of ISS LIS spatial accuracy (Fig. 4 right). Relative to GLM-16/17, corrected ISS LIS spatial offsets are almost entirely less than 10 km, with the vast majority below 5 km. Offsets relative to ENGLN and GLD360 are distributed more broadly, but for each of the spaceborne and ground-based reference datasets the modal offset is approximately 2-3 km. This means that ISS LIS has achieved sub-pixel (< 4 km) location accuracy.

Timing, location, flash DE, and false alarm rate (FAR) have been stable during most of the mission to date. Figure 5 shows the time series of these parameters through early 2020. ISS LIS temporal accuracy offset shifted by about 1 ms on 16 December 2018, such that LIS now slightly leads the reference data (Fig. 5 top). A few larger deviations occurred during two periods in early 2019, related to atypical ISS maneuvers. However, in most circumstances the absolute magnitude of the offsets remain less than 2 ms. LIS geolocation accuracy also has been stable throughout the mission (Fig. 5 middle), with the peak offset normally less than 5 km. The detection performance of ISS LIS is also stable over time (Fig. 5 bottom), aside from the known deviations in early 2019 mentioned above. The flash DE is stable with respect to each of the reference datasets (64% relative to GLM, and 56-57% relative to ENGLN/GLD360), and the FAR, calculated over the Americas domain where the greatest quantity and best quality reference data are available, is under 5% on average.

3.2 Lightning climatology

The ISS LIS lightning climatology has been completed for the first three years of data (March 2017 - Feb 2020; Fig. 6a). Within ± 38° latitude, these results are broadly similar to the more than 13-year (after orbit boost; September 2001 - December 2014) TRMM LIS climatology (Fig. 6b). During this period, TRMM had a nominal orbit altitude of 402.5 km - very similar to the ISS orbit altitude range of 400-405 km. (The TRMM pre-boost orbit altitude was substantially lower, at 350 km, and thus is not considered here to keep the comparison more direct.)

Because ISS LIS has a shorter period of record, the lightning density maps are not as smooth despite the 0.5° gridding (Fig. 6a). However, notable hotspots [*Albrecht et al.*, 2016] from the TRMM LIS climatology (Fig. 6b), such as central Africa, Paraguay/northern Argentina/Rio Grande do Sul (Brazil), Lake Maracaibo (Venezuela), the Himalayas/Indian Subcontinent, and the Maritime Continent stand out, and feature comparable flash rates between ISS and TRMM LIS. For example, peak flash rates over central Africa exceed 80 km^{-2} yr^{-1} in both datasets. The well-known stark contrast between land and ocean lightning flash rates also stands out in both plots, as do the coastal enhancements in lightning over the Gulf Stream, near west Africa, the Caribbean and near Central America, near southeastern Brazil, the Bay of Bengal, etc. ISS LIS also has been able to observe the small enhancements in lightning over the open Pacific, between ± 30° latitude, west of -120° (south Pacific) and -150° (north Pacific) longitude (including the Intertropical Convergence Zone, ITCZ). This is similar to TRMM LIS (Fig. 6b), but the patterns are more diffuse due to fewer samples.

In the global aggregate, lightning flash rates (between ± 38° latitude) are comparable between ISS LIS and TRMM LIS (Fig. 7). Both datasets show globally averaged flash rate ranging between 25 and 55 s^{-1}. This, along with Fig. 6, demonstrates that ISS LIS is making fundamentally similar observations to TRMM LIS, and thus is capable of extending the TRMM LIS dataset over the tropics and subtropics for a longer time period.

ISS LIS enables coverage of higher latitudes (± 55°) compared to TRMM LIS (± 38°). This allows more complete viewing of the Great Plains of the United States (US), which features flash rates ~30 km^{-2} yr^{-1} extending as far north as the border with Canada (Fig. 6a). The improved coverage of the continental US is a particularly important advantage of ISS LIS, because this coverage allows for a more robust examination of lightning/climate relationships within ongoing National Climate Assessment (NCA) studies [*Koshak*, 2017]. Another mid-latitude hot spot over Manchuria is also observed by ISS LIS, and the coastal enhancement of lightning near eastern South America is seen to extend further south. ISS LIS also provides coverage of most of Europe, including the lightning enhancement near the Alps. Lightning enhancement over Turkey is observed by ISS LIS.

The combined TRMM LIS and OTD dataset [*Cecil et al.*, 2014] provides a useful point of comparison for ISS LIS. OTD was in LEO orbit at 70° inclination and 740-km altitude [*Christian et al.*, 2003], so it provided coverage at higher latitudes than ISS LIS, but with reduced spatial resolution and geolocation accuracy. Table 1 shows a comparison of globally averaged flash rates from ISS LIS relative to the OTD and TRMM LIS climatology published by *Cecil et al.* [2014]. ISS LIS is measuring slightly lower flash rates, but the numbers are within 5-10% of the previous climatology, which is well within the magnitude of expected offset from the slight viewing time overestimates in version 1 ISS LIS data (Section 3.1.1), as well as interannual variability (e.g., Fig. 7). In addition, there is significant lightning northward of 55° during boreal summer due to northern hemisphere land masses; thus, even with improved viewing time estimates, ISS LIS is not expected to provide global flash rates as high as *Cecil et al.* [2014] during June-August.

Relative to *Cecil et al.* [2014], ISS LIS has observed potentially higher flash rates in notable mid-latitude areas - such as Turkey and the Middle East, southern Canada, Manchuria, Europe and Northern Africa (Fig. 6a). However, caution in interpreting the 3-year ISS LIS dataset is required, since the relative impacts of individual storms may be influencing these differences. Integration of ISS LIS observations into the full LIS/OTD gridded dataset, which will enable detailed quantitative comparisons for individual regions, is planned for a future study.

The seasonal distribution of lightning from ISS LIS also follows expectations established by previous global climatologies (Fig. 8). Globally, lightning is maximized during June-August (Fig. 8b); however, both March-May and September-November also have significant activity (Fig. 8a, c). Notably, in boreal autumn the northern Great Plains of the US can remain active, even as similar latitude locations in Europe, for example, see a substantial decrease from the summertime peak (Fig. 8c). The Manchuria lightning peak is primarily a boreal summertime phenomenon, with a significant decrease in both spring and fall. Lightning in the Middle East is most prevalent during boreal spring and fall, while Turkey reaches its maximum in summer. Boreal winter leads to a significant reduction in northern hemisphere lightning (Fig. 8d); however, there are noticeable hot spots remaining in the US Gulf Coast. The lightning peak near Paraguay is most distinctive during austral spring (Fig. 8c).

Globally averaged diurnal variability of lightning (Fig. 9) follows the typical patterns observed in previous climatologies [*Virts et al.*, 2013; *Blakeslee et al.*, 2014; *Cecil et al.*, 2014]. Namely, the diurnal cycle over land drives the overall global diurnal variability in lightning, with the ocean flash rate essentially flat throughout the day and night. On average, lightning peaks in the local afternoon (3-4 pm Local Solar Time, LST), and reaches a minimum near 10 am LST (Fig. 9a). However, viewed in UTC time coordinates (Fig. 9b), lightning follows the classic Carnegie curve structure [*Mach et al.,* 2011], peaking during 18-19 UTC.

3.3 Use as a tool for GLM calibration and validation

A high-priority effort at NASA MSFC has been to properly validate the GLM instruments on GOES-16 and GOES-17. This includes examining the GLM flash detection efficiency (DE), the flash false alarm rate, the lightning location/timing accuracy, maximum data rate capability, and long-term instrument degradation. Specific GLM instrument requirements have to be validated to confirm that GLM performance is acceptable for critical operations and decision making. GLM validation often makes use of several different ground-based lightning detection networks. These are high-quality data sources, but they are all land-based. A large part of the GLM FOV, especially GLM-17, is over the ocean where the quality of ground-truth data is highly variable. Fortunately, ISS LIS has provided vital data of uniform quality out over the oceans.

Another problem with comparing GLM to ground sources is that the comparison is not truly one-to-one. The GLM is an optical sensor, whereas all of the ground-based networks consist of RF sensors. The RF sensors look at fundamentally different physics and different parts of the lightning flash, making one-to-one comparisons difficult. Since ISS LIS is an optical sensor very similar to GLM, it is the only source of direct comparison for GLM. Indeed, because ISS LIS is a heritage sensor of GLM, with similar operation and data structure, it has provided particularly easy/efficient inter-comparisons (i.e., both optical, both spaceborne, and both detect lightning over land/ocean).

GLM-16 has been observed to have a substantially depleted flash DE over the northwestern CONUS (e.g., Washington and surrounding states). A detailed plot of GLM-16 flash DE for the period January 2018 to December 2019 is shown in Fig. 10. The GLM flashes were compared with observations from ISS LIS (Fig. 10 left), as well as data derived from two ground-based RF lightning detection networks - ENGLN (Fig. 10 middle) and GLD360 (Fig. 10 right). All three comparison datasets agree on the basic structure of GLM-16's northwestern CONUS DE depletion. The fact that both optical spaceborne (ISS LIS) and RF ground-based (ENGLN and GLD360) measurements agree provides increased confidence that the DE depletion is the result of GLM instrument effects near the edges of its FOV.

ISS LIS continues to provide important one-to-one comparisons with GLM data, and will remain a key dataset for current and future GLM validation [e.g., *Zhang and Cummins*, 2020], as well as potentially other future geostationary lightning observations, such as from the forthcoming Meteosat Third Generation (MTG) Lightning Imager (LI). ISS LIS further provides a single observation system that will enable direct intercomparisons between GLM, LI, and other space-based observations.

3.4 ISS LIS data products and user community

Unlike its predecessor, ISS LIS has the ability to transmit and disseminate lightning data in near realtime. This ability is significant as it enables usage of ISS LIS in operational applications. The near-realtime capabilities are particularly beneficial in data-sparse regions, such as over oceans, to contribute to storm warnings, nowcasts, oceanic aviation, and international Significant Meteorological advisories (SIGMETs). The near real-time ISS LIS data are provided to the US National Weather Service (NWS) and other interested users in partnership with both NASA's Land, Atmosphere Near real-time Capability for EOS (LANCE) project and the Short-term Prediction Research and Transition (SPoRT) center [*Jedlovec*, 2013]. As ISS LIS detects total lightning (near globally) with high detection efficiency, it can therefore fill gaps in the depiction of lightning activity of interest to NWS forecasters over land and ocean areas. These data, as well as non-real-time analyses are being used by several applied and operational institutions to improve decision-making and to benefit humankind. These institutions include, for example, the NWS, the Aviation Weather Center (AWC), the National Hurricane Center (NHC), the Ocean Prediction Center (OPC), the World Weather Research Program (WWRP), and other government, business, and military organizations.

The GHRC DAAC coordinates with the LIS science team to process and archive the ISS LIS datasets. The ISS LIS mission currently produces four products: (1) Near-realtime (NRT) science lightning data [*Blakeslee*, 2019a], (2) NRT background cloud scene data [*Blakeslee*, 2019b], (3) Non-quality-controlled (NQC) version 1 science lightning data [*Blakeslee*, 2019c], and (4) NQC background cloud scene data [*Blakeslee*, 2019d].

The NRT data are available within two minutes of observation and are appropriate for applications requiring low-latency data (e.g., AWC and NHC). NRT data and browse images age off the server after ten days and are not a static archived data collection. Due to the nature of NRT data transmission, some data may be missing. Hence, the NQC data are produced daily and are more complete than the NRT data. Although the version 1 NQC data have not been reviewed to assure data quality, they are more appropriate for science and applications with less stringent latency requirements. The version 1 NQC data have been validated, however, as described in Section 3.1, and are currently undergoing quality control that will be included in a future release.

The ISS LIS provides a variety of observations from the raw optical events that are combined into groups that are, in turn, combined into flashes as well as optical energy that can be used to observe lightning energetics. These base observations can be used to derive multiple products, as will be discussed below. Traditionally, the flash observation has been the most widely used, particularly in near real-time operations. This is a latitude/longitude point showing the centroid of the flash. This flash centroid is typically plotted as a density product (i.e., number of flash centroids per 8 km^2). Users can recreate this basic visualization capability via a python data recipe provided by GHRC DAAC [*GHRC*, 2020].

The ISS LIS dataset has had widespread use in the past 3 years, with over 6,100 users to date. Specifically, the GHRC DAAC has tallied downloads of the data based on the application science discipline. As with the OTD and TRMM LIS predecessors, there has always been an enthusiasm from the user community to apply lightning data in diverse ways, especially in weather and chemistry/climate studies. For the most recent full calendar year (2019), ISS LIS data made up two of the top five most downloaded datasets at GHRC DAAC. Two others, including the top dataset, were from the ISS LIS predecessor, TRMM LIS.

While not exhaustive, several uses of ISS LIS are described below, and demonstrate a variety of impacts by these observations. As mentioned previously, the near-realtime ISS LIS data are provided to the AWC. The AWC's area of responsibility covers vast oceanic regions.

The ISS LIS flash observations are vital to provide lightning observations in locations where ground networks are unavailable or have limited detection efficiency. Just a single flash observation provides confirmation of a convective system to the AWC, enabling aircraft to be rerouted safely around these systems. The near-realtime data have also been an integral component of the World Meteorological Organization's High Impact Weather Lake Systems (HIGHWAY) project [*Virts and Goodman*, 2019]. Centered on Lake Victoria in East Africa, the near-realtime ISS LIS data from NASA LANCE support local decision makers by helping better characterize storms as observed by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) Meteosat Second Generation (MSG) satellite, and provide early warning to at-risk communities. This also serves as an operational demonstration to help prepare the community for MTG-LI.

Another collaborative project was with NASA DEVELOP and GHRC DAAC. Here, data from both TRMM and ISS LIS were used to develop a lightning risk assessment for Bangladesh and Nepal [*Evans et al.*, 2018]. The LIS data provided the necessary lightning observations for the project. Instead of simply creating a lightning climatology, the DEVELOP team combined the lightning observations with socioeconomic information. The result (Fig. 11) gave the government authorities an easy-to-interpret view of where lightning was the greatest threat due to a combination of lightning activity, available shelter, and types of jobs. Such information can help government decision-makers direct funds to improve lightning safety in the most at-risk locations.

Lastly, the World Meteorological Organization has deemed lightning an Essential Climate Variable. Space-based observations play an integral role in providing global lightning coverage. The ISS LIS observations extend the record of the earlier OTD and TRMM LIS instruments, and are included with those instruments in the Global Climate Observing System (GCOS). As part of this, ISS LIS observations will be used as part of a proposed 10x10 km^2, global product that blends both space- and ground-based lightning observations into daily and monthly time scales [*Aich et al.*, 2018].

4. Current and future cross-platform science

Although ISS LIS observations have been used for assessments of current and future geostationary lightning mappers [*Erdman et al.*, 2020; *Hui et al.*, 2020], they also offer very complementary information for other types of atmospheric investigations.

4.1. Investigations into lightning discharge physics

Comparisons of optical and RF emissions from lightning have provided a wealth of insights on processes involved in the lightning discharge [*Suszcynsky et al.*, 2000; *Thomas et al.,* 2000; *Ushio et al.*, 2002; *Noble et al.*, 2004; *Zhang and Cummins*, 2020]. Hence, the capability of ISS LIS to detect the optical fingerprint of lightning on a global scale with a relatively high detection efficiency makes for a unique dataset to compare with RF-based and other measurements of lightning and related atmospheric electrical phenomena.

Current and planned space-based missions to investigate lightning and upper atmospheric electrical phenomena include measurements across several parts of the electromagnetic spectrum that complement those obtained with ISS LIS. One of these is the Atmosphere-Space Interactions Monitor (ASIM), which is an instrument suite developed by the

European Space Agency and installed on the ISS in April 2018 [*Neubert et al.*, 2019]. The imager onboard ASIM has a 42x slower frame rate than LIS, but it has a 10x greater pixel resolution at nadir than the LIS camera [*Chanrion et al*., 2019]. Furthermore, ASIM is capable of measuring light intensity across its FOV about 200x faster than LIS. This complementary nature of ASIM and LIS enables resolving the spatial and temporal components of lightning in more detail.

Both instruments detected a lightning flash on 7 February 2019, at 1941 UTC over Madagascar (Fig. 12). During its 150-ms duration, the flash illuminated three frames of the ASIM camera, while LIS detected nine groups. Figure 12 highlights one of these frames from the ASIM camera, along with the LIS events and temporal evolution of LIS groups and ASIM's 777.4-nm photometer. Each of the three LIS groups detected during this ASIM camera frame had a corresponding relative peak irradiance measured by the ASIM photometer. Although ASIM's photometer was able to detect these distinct flash subcomponents, LIS was used to locate where in ASIM's photometer FOV they occurred, which is especially important for separating multiple source regions within active thunderstorm complexes. One of the strokes illuminated 36 pixels of the LIS camera for 2 ms, and the higher-resolution ASIM camera observations revealed the thinnest parts of that lightning channel to be roughly half a LIS pixel wide (~2 km). Hence, this comparison of the ASIM and LIS cameras provides insight into how the lightning channel geometry of this flash caused the intensity pattern detected by LIS.

Localized source extension below the LIS resolution and above the ASIM resolution can be intense enough to trigger a LIS event without the ability to infer the true spatial extent. Also, curved channels within one or more pixels and dark regions between emitting parts of a cloud may not be resolved by LIS. Instead, the intensity measured by LIS would be proportional to the seemingly more active part of the cloud, obscuring whether the respective source was wider and less intense or small and bright. This is important because it has implications for characterizing the LIS sub-pixel variability of lightning and better understanding the physics of the lightning discharge.

Satellite missions such as ASIM and the upcoming Tool for Analysis of Radiation from lightning and Sprites (TARANIS) [*Lefeuvre et al.,* 2008], which focus on investigating transient luminous events (TLEs) and terrestrial gamma ray flashes (TGFs), will be compared with observations from ISS LIS for calibration and validation of their optical instruments and used to better determine the spectral fingerprint of these upper atmospheric electrical phenomena. Additionally, LIS observations are being compared with ground-based electric field measurements from the Huntsville Alabama Marx Meter Array (HAMMA) [*Bitzer et al.*, 2013] sensors deployed in Panama to investigate signatures of TGFs measured at the ground to their optical characteristics observed in space. The HAMMA sensors in Huntsville, Alabama, and Panama also are being compared with ISS LIS to observations to further investigate the extent of optical emissions by narrow bipolar events [*Jacobson et al.*, 2013; *Rison et al.*, 2016; *Liu et al.*, 2018].

4.2. Precipitation and lightning in mid-latitude cyclones

Since the ISS LIS operates during the era of the Global Precipitation Measurement (GPM) mission [*Hou et al.*, 2014; *Skofronick-Jackson et al.*, 2018], global observations of lightning and precipitation are being combined to expand upon related findings from TRMM in the tropics [*Petersen and Rutledge*, 2001; *Liu et al.*, 2012] and gain new insights of mid- and high-latitude storm systems. Coincident ISS LIS and GPM observations are being combined into a new lightning-enriched GPM-based Precipitation Feature (PF) dataset to facilitate these investigations. For example, this new dataset is being used to study the microphysical and dynamical response of the extratropical transition of tropical cyclones (TCs) [*Gatlin et al.*, 2019]. ISS LIS is extremely important to this study since it enables inclusion of cyclones in the Pacific and Indian Oceans. The ISS LIS-enriched PF database dates to 2017, and the number of ISS and orbital GPM coincidences continue to increase with time, which should soon enable meaningful statistics on the convective characteristics of mid-latitude-transitioning TCs.

4.3. LNO_x estimation for climate and air quality studies

Lightning produces nitrogen oxides ($NO_x = NO + NO_2$) that affects the concentration of greenhouse gases such as ozone [*Huntrieser et al.*, 1998]. Since climate is most sensitive to ozone in the upper troposphere, and since lightning is the most important source of NO_x in the upper troposphere at tropical and subtropical latitudes, lightning is a particularly useful parameter to monitor for climate assessments. Satellite-based optical lightning mappers have been used to make preliminary estimates of lightning NO_x (LNO_x) and used to examine its interannual variability and begin monitoring the annual trend [*Koshak*, 2017]. Continuing these data records using ISS LIS observations is planned, and is particularly important for supporting the NCA program.

LNO_x also impacts ozone estimates made by regional air quality models [e.g., *Koshak et al.,* 2014a]. Hence a better understanding of the contribution of LNO_x to greenhouse gas pollution in the lower troposphere is needed. Also onboard the ISS is the Stratospheric Aerosol and Gas Experiment (SAGE) III [*Flittner et al.*, 2018], which provides observations of nitrogen dioxide (NO_2) that will provide ideal comparisons with ISS LIS retrievals of LNO_x. New geostationary instruments - Tropospheric Emissions: Monitoring of Pollution (TEMPO), Sentinel-4, and Geostationary Environment Monitoring Spectrometer (GEMS) - will provide unique NO_2 measurements [*Zoogman et al.*, 2017; *Courrèges-Lacoste et al.*, 2017; *Kim et al.*, 2020] for comparison with ISS LIS. This combination of satellite-based chemistry measurements together with ISS LIS offer an unprecedented opportunity to fully probe LNO_x production that is so vital to climate and air quality studies.

5. Summary and conclusions

ISS LIS has completed more than three years on orbit. During that time, it has met all of its major science objectives, including detection of lightning during day and night, at storm-scale (~4-km) spatial resolution, with millisecond timing and high flash detection efficiency (64% relative to a comparable optical sensor) without a land/ocean bias. ISS LIS also measures radiant energy, provides background images/intensity, and delivers near-realtime lightning data. In addition, it has produced a lightning climatology that is fundamentally consistent with previous lightning climatologies, while also enabling the extension of the climatologies into the current era as well as to higher latitudes (± 55°). Global flash rates (3-year average: ~44 s^{-1}) are within 5-10% of previous datasets [e.g., *Cecil et al.*, 2014], and the spatial and diurnal distributions of global lightning are consistent with expectations. ISS LIS has demonstrated its value as a calibration/validation tool for current and future spaceborne lightning datasets. The near-realtime ISS LIS data have opened up applications within operational weather forecasting and related applications, including public safety. Finally, ISS LIS is demonstrating utility as part (or potential part) of cross-platform studies examining a diverse array of topics, including lightning physics, thunderstorm processes, and atmospheric composition.

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Tables

Table 1. ISS LIS global flash rate (s^{-1}) versus the space-based TRMM LIS/OTD climatology [*Cecil et al.*, 2014].

Region	Annual	MAM	JJA	SON	DJF
TRMM LIS/OTD World	45.7	44.1	55.7	47.2	35.9
ISS LIS < 55°	43.8	45.1	53.5	45.6	30.8
TRMM LIS/OTD < 38°	40.7	40.9	42.5	44.6	34.9
ISS LIS < 38°	39.5	42.8	41.0	43.8	30.3

Figure Captions

Figure 1. Visualization of the ISS LIS instrument, its location on the ISS, as well as its data collection, processing, and distribution.

Figure 2. Basic workflow showing the data processing of initial observations at the ISS through ground processing by GHRC and the LIS science team, to publication for end users.

Figure 3. The close comparison between the original TRMM LIS calibration (OC; labeled TRMM) and the retest calibration (RC) of ISS LIS (labeled ISS). Left: Static Response Test. Right: Transient Response Test.

Fig. 4. Left: ISS LIS temporal offset relative to ENGLN, GLD360, GLM-16, and GLM-17. Right: ISS LIS spatial geolocation offset relative to these comparison datasets.

Figure 5. Top: Time series of peak temporal offset between ISS LIS and three difference reference datasets (ENGLN, GLD360, and GLM-16). Middle: Time series of peak spatial offset between ISS LIS and these reference datasets. Bottom: Time series of ISS LIS DE and FAR relative to the reference datasets.

Figure 6. a) Three-year (March 2017 through February 2020) climatology of global lightning from ISS LIS. b) Post-boost climatology of lightning from TRMM LIS (September 2001 through December 2014).

Figure 7. Monthly time series of global lightning flash rate (between ± 38° latitude) from TRMM LIS and ISS LIS.

Figure 8. ISS LIS lightning climatology, broken out seasonally. a) March-May. b) June-August. c) September-November. d) December-February.

Figure 9. ISS LIS diurnal variability of global lightning flash rate, including land/ocean breakdown. a) Adjusted to local solar time. b) UTC time.

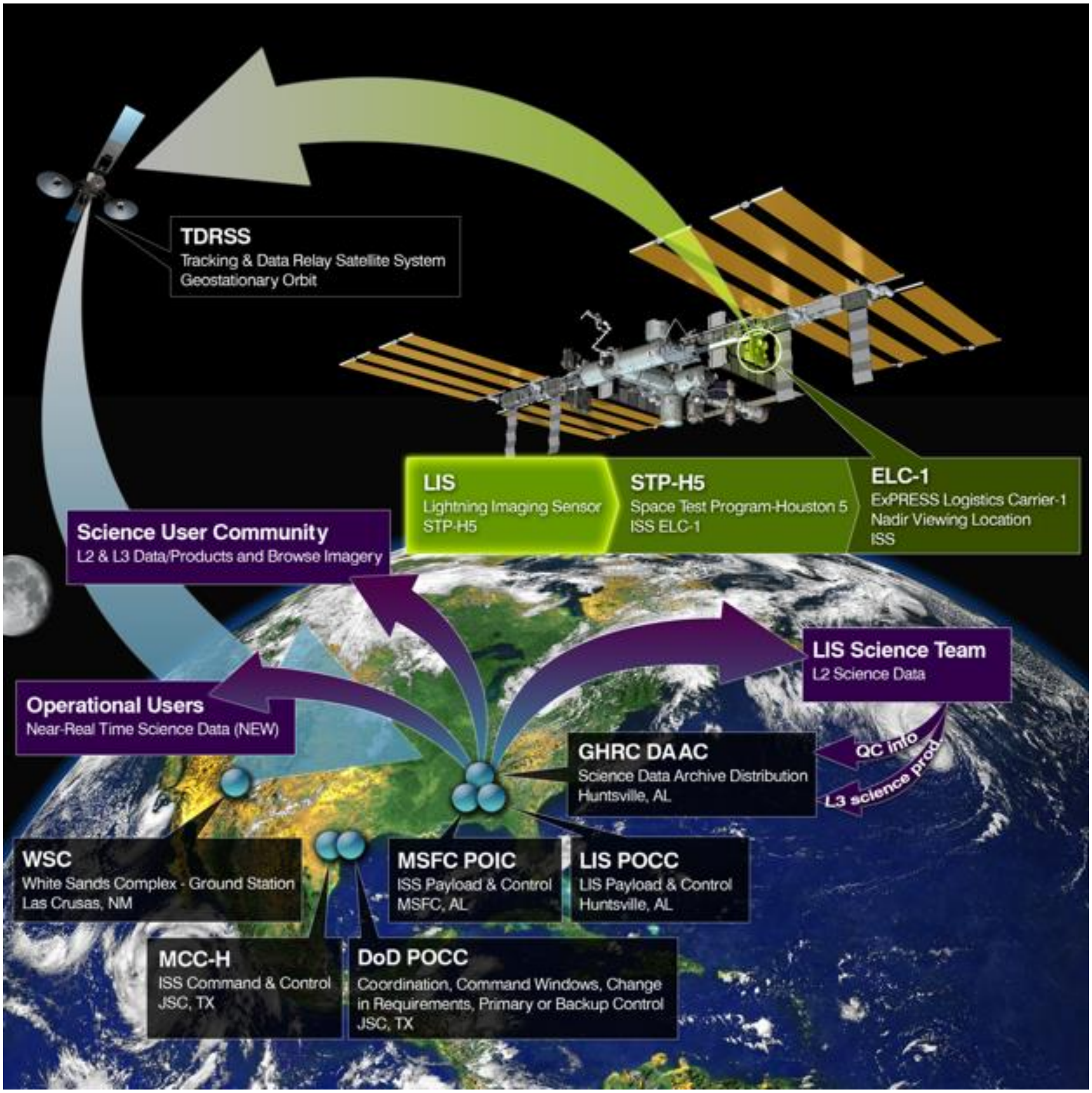
Figure 10. GLM-16 flash DE with respect to ISS LIS (left), ENGLN (middle), and GLM360 (right).

Figure 11. Lightning risk analysis for Nepal and Bangladesh, based on a combination of LIS flash rates and socioeconomic factors.

Figure 12. Comparison of ASIM and ISS LIS observations of a lightning flash over Madagascar. (top) an image of the lightning flash captured by the ASIM camera with ISS LIS events from the group closest in time to the frame (i.e., black line in bottom panel) plotted as green symbols whose size correspond to the radiance measured by the LIS camera and scaled (10^{-4}) to match

the same units of ASIM radiance, which are given in logarithmic scale to enhance the illuminated pixels. (bottom) time-series of ASIM 777.4 nm photometer (red) and LIS groups (green) with the shaded region corresponding to the duration of the ASIM camera frame.

Figures



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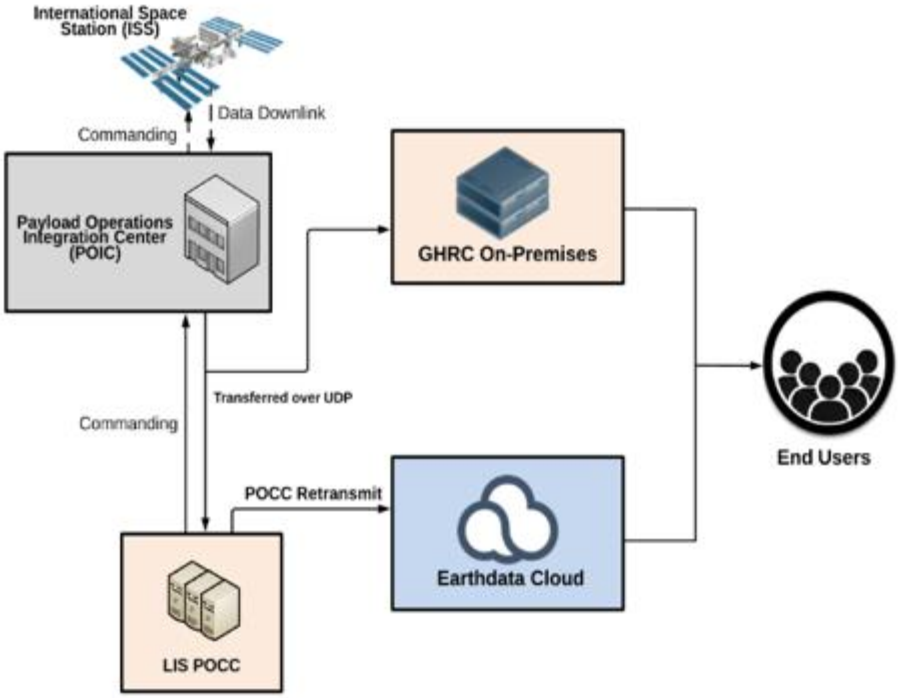

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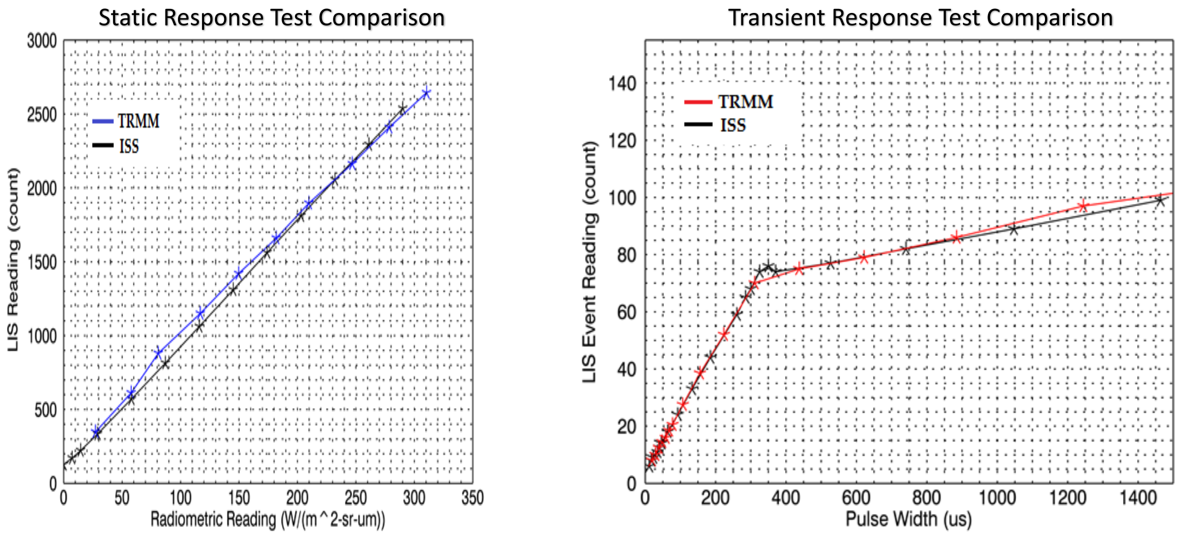

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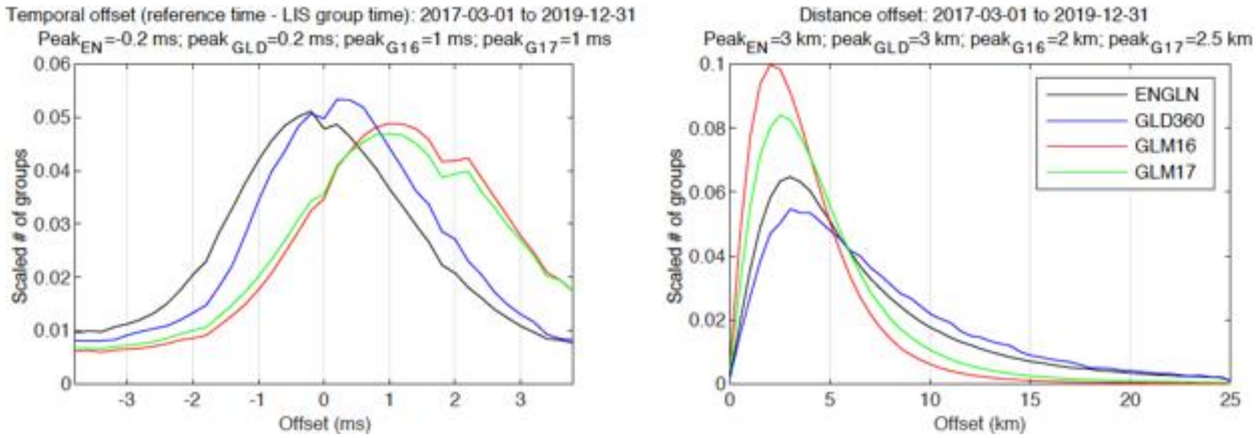

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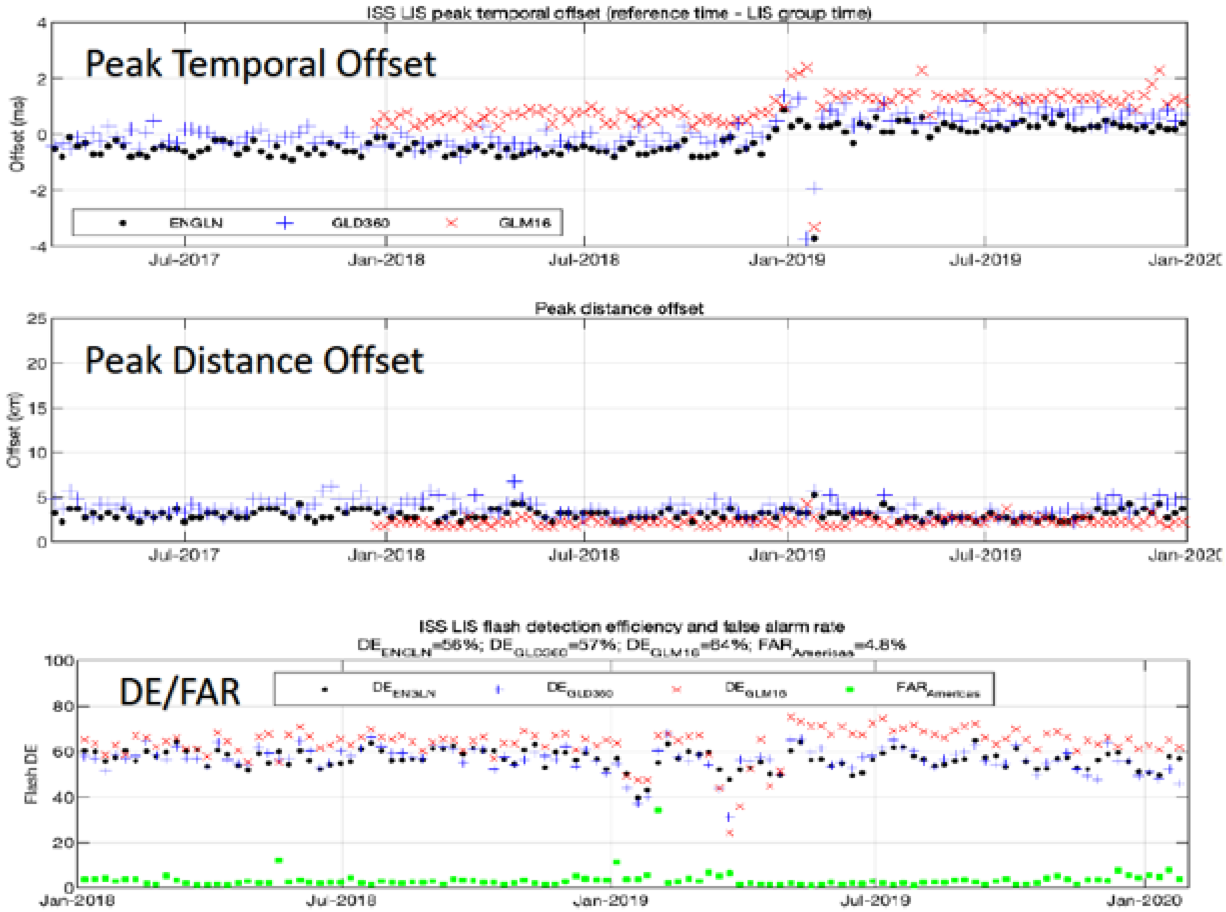

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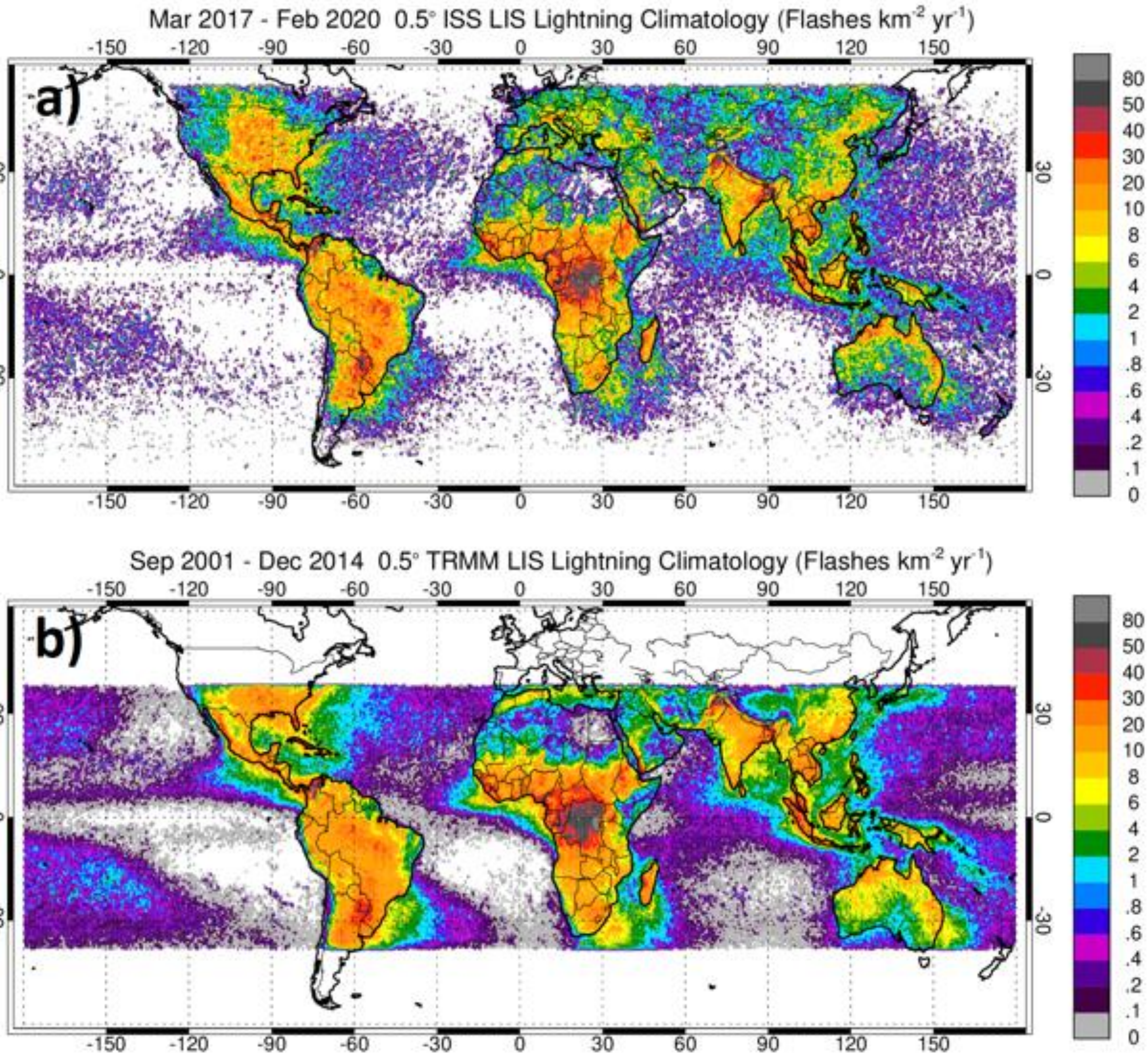

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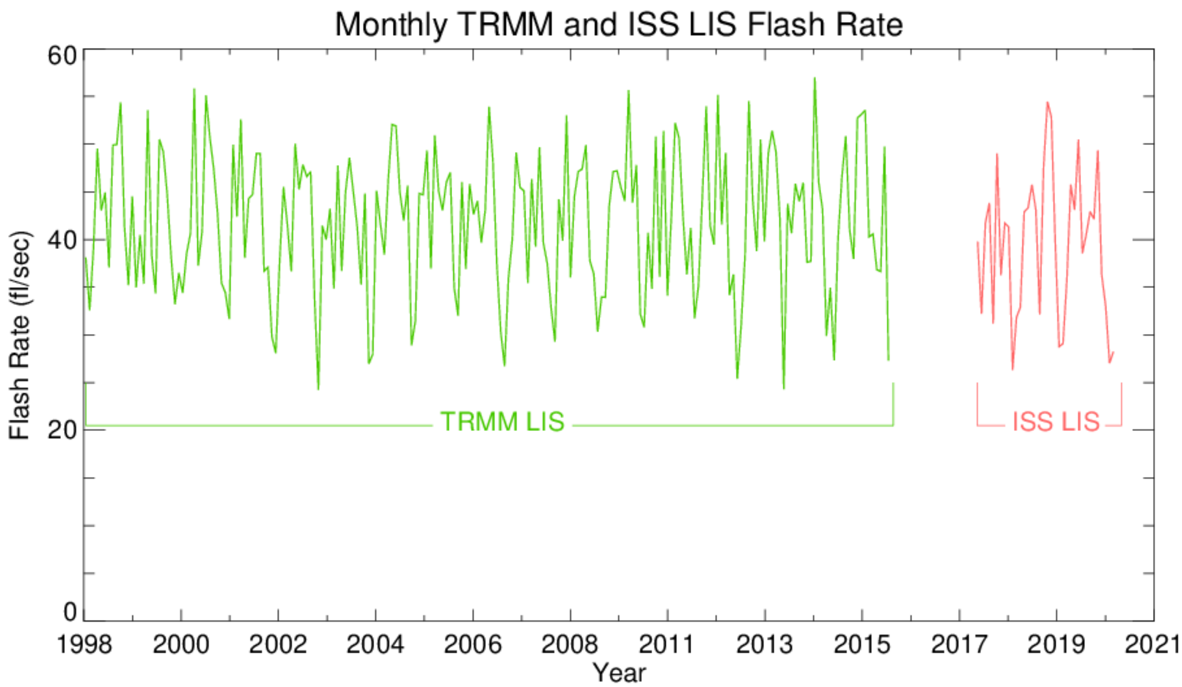

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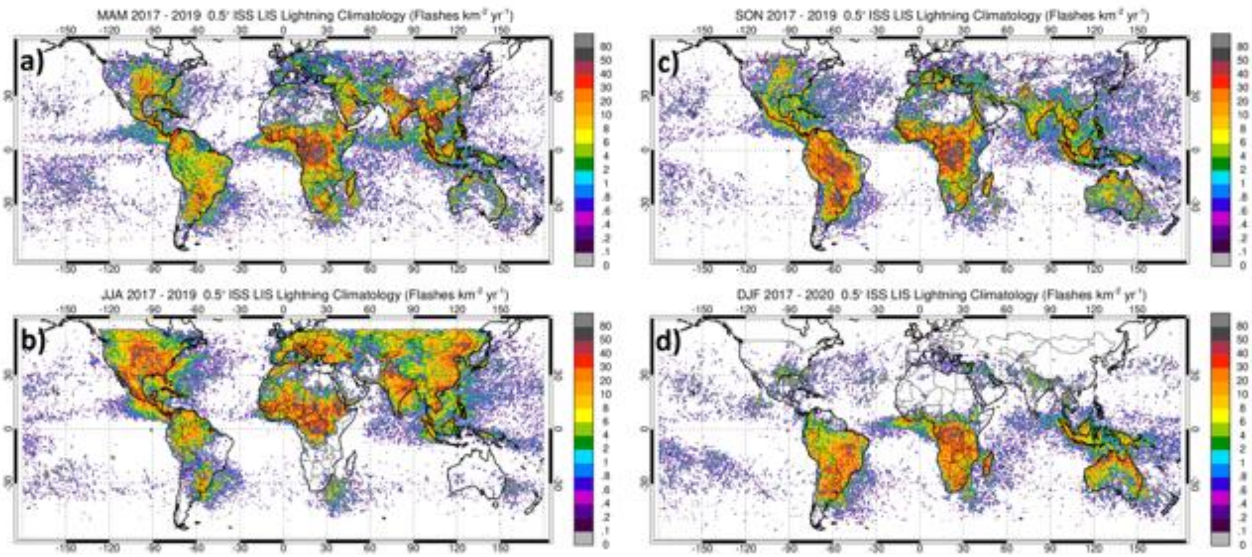

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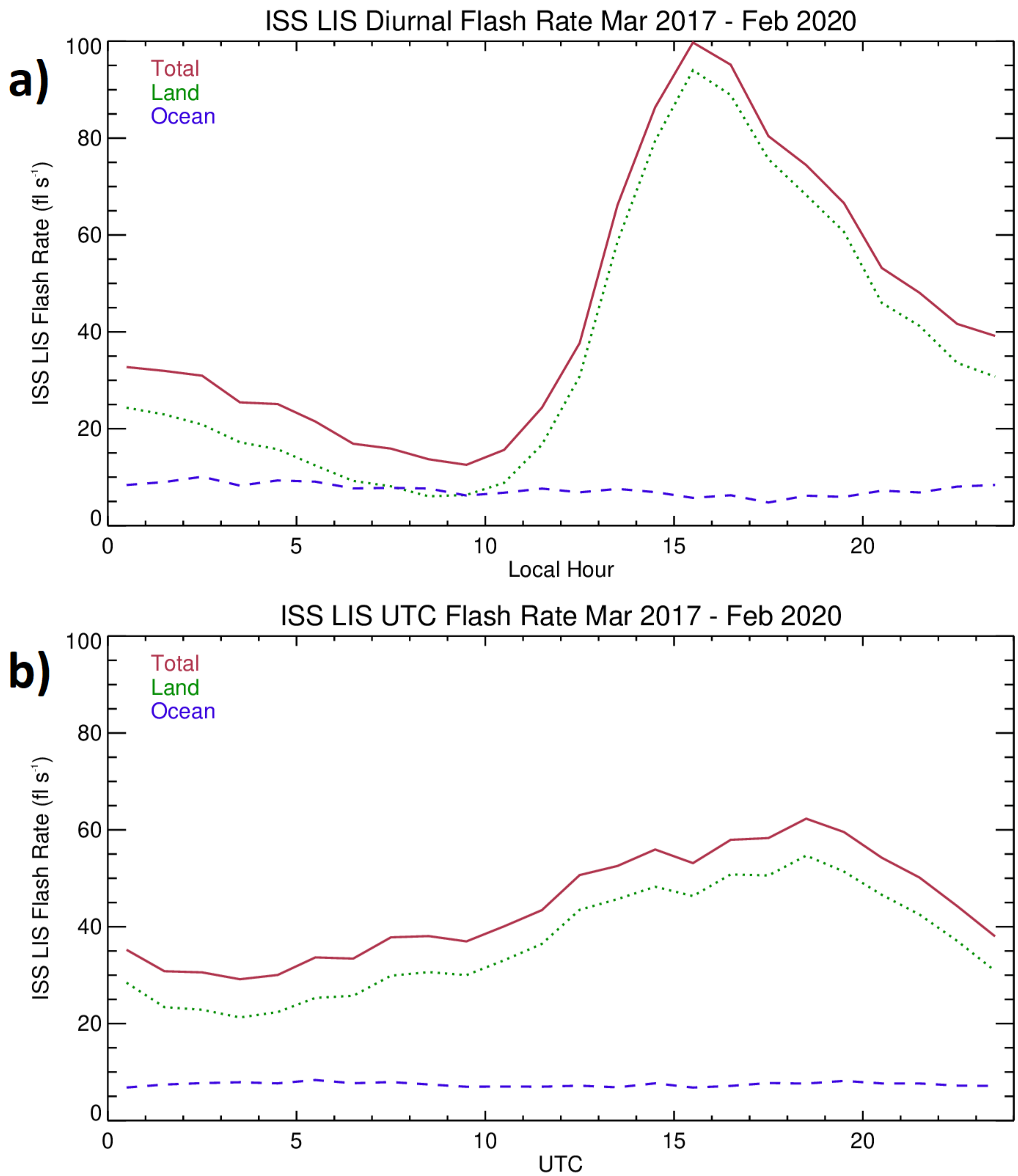
(Reviewers: Please see original figure to obtain full resolution)



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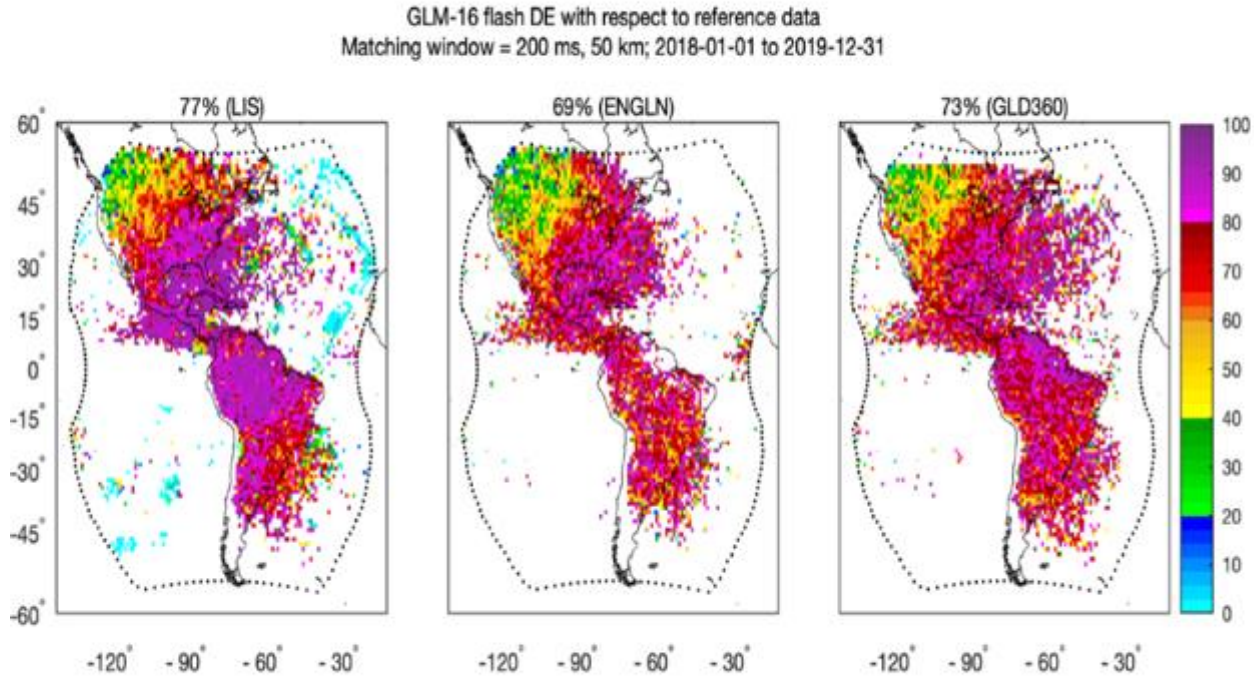

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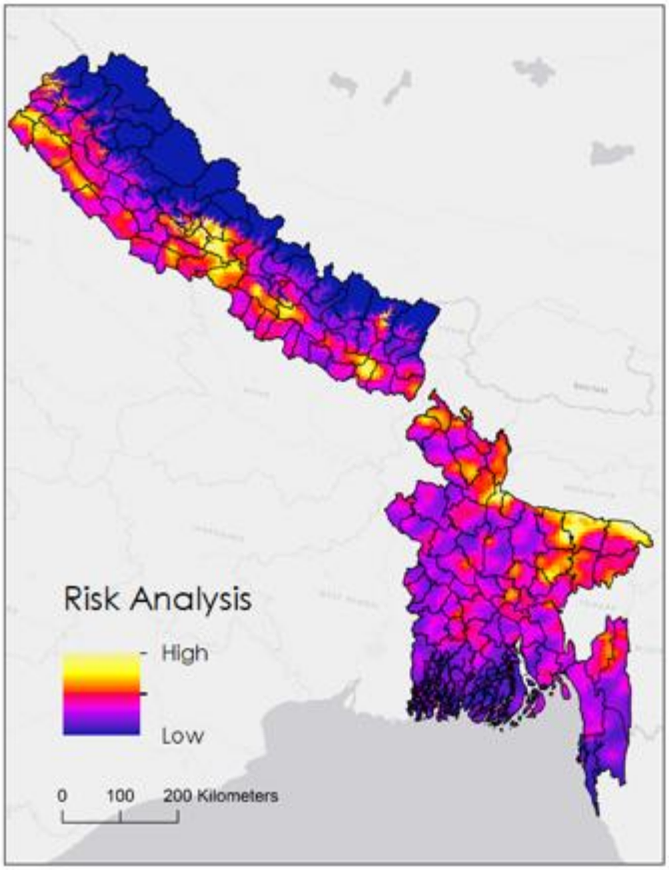

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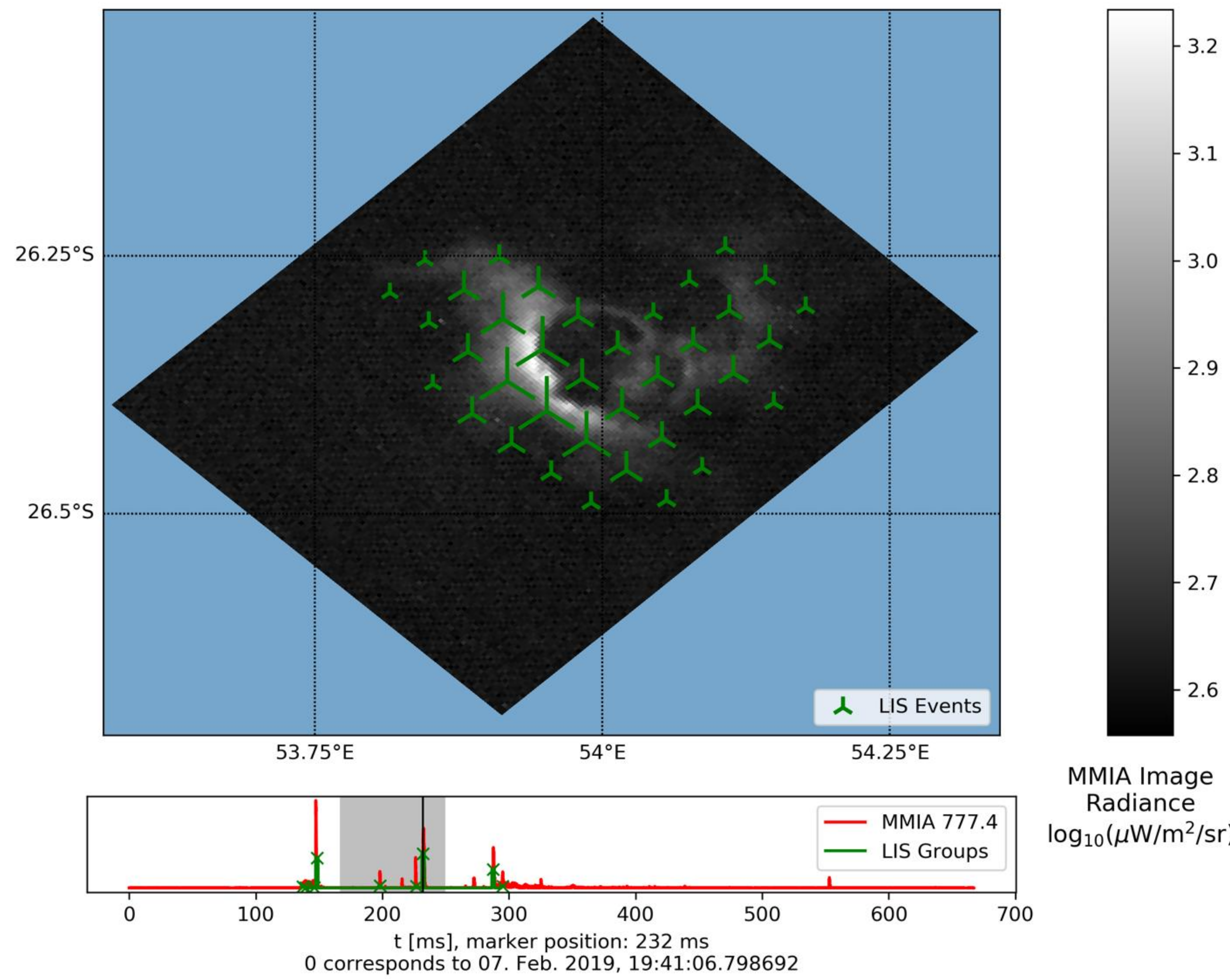

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Figure 1.

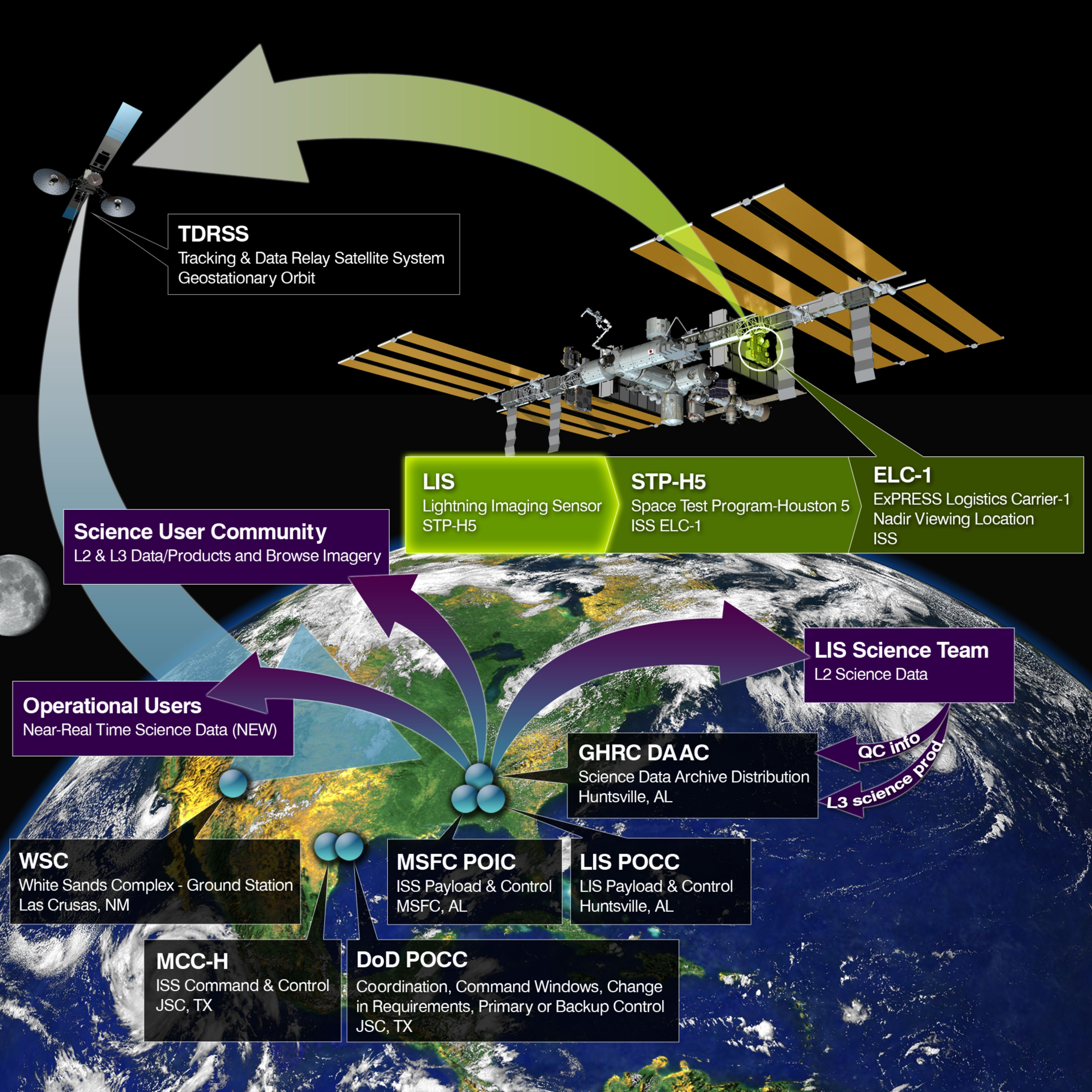

TDRSS
Tracking & Data Relay Satellite System
Geostationary Orbit
LIS
Lightning Imaging Sensor
STP-H5
STP-H5
Space Test Program-Houston 5
ISS ELC-1
ELC-1
ExPRESS Logistics Carrier-1
Nadir Viewing Location
ISS
Science User Community
L2 & L3 Data/Products and Browse Imagery
LIS Science Team
L2 Science Data
Operational Users
Near-Real Time Science Data (NEW)
GHRC DAAC
Science Data Archive Distribution
Huntsville, AL
QC info
L3 science prod.
WSC
White Sands Complex - Ground Station
Las Crusas, NM
MSFC POIC
ISS Payload & Control
MSFC, AL
LIS POCC
LIS Payload & Control
Huntsville, AL
MCC-H
ISS Command & Control
JSC, TX
DoD POCC
Coordination, Command Windows, Change
in Requirements, Primary or Backup Control
JSC, TX

Figure 2.

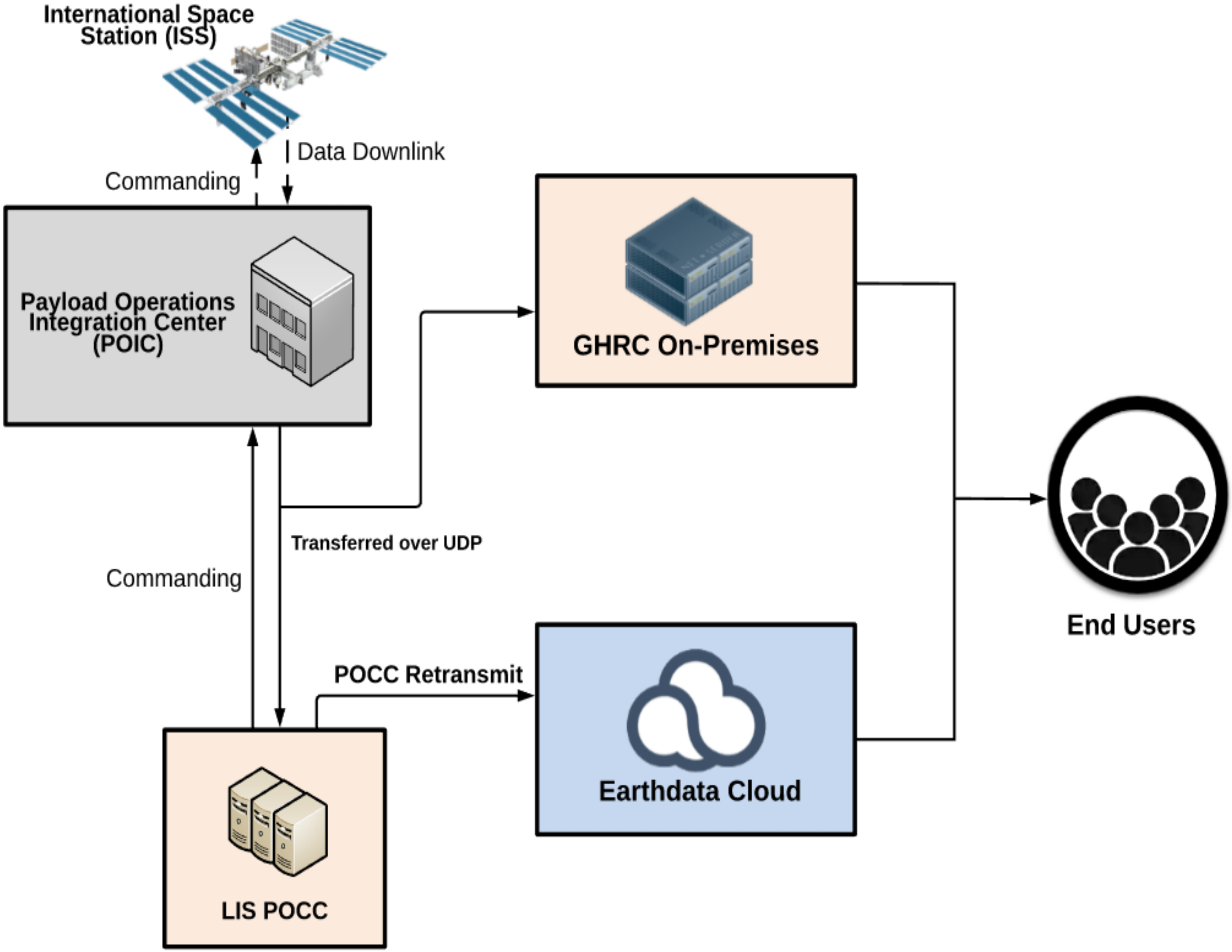
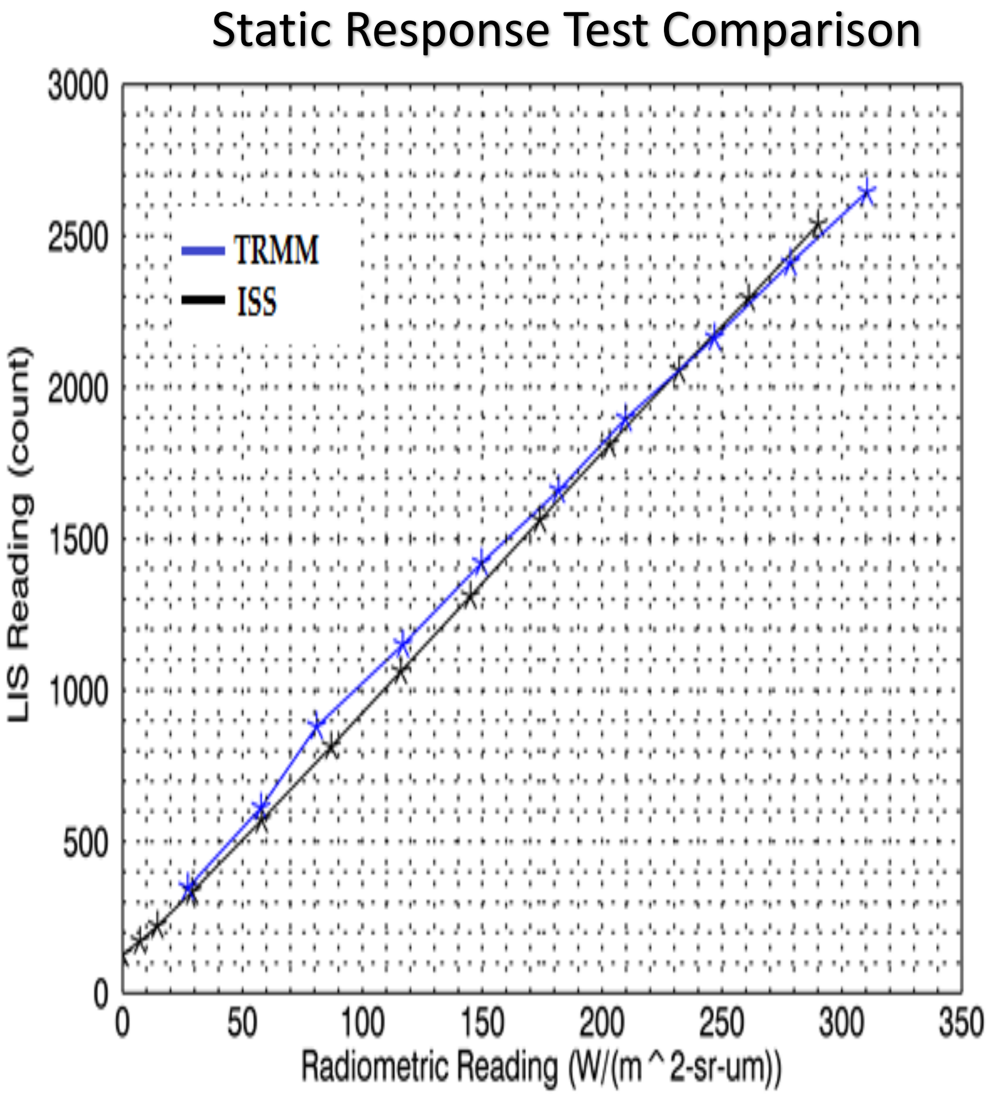
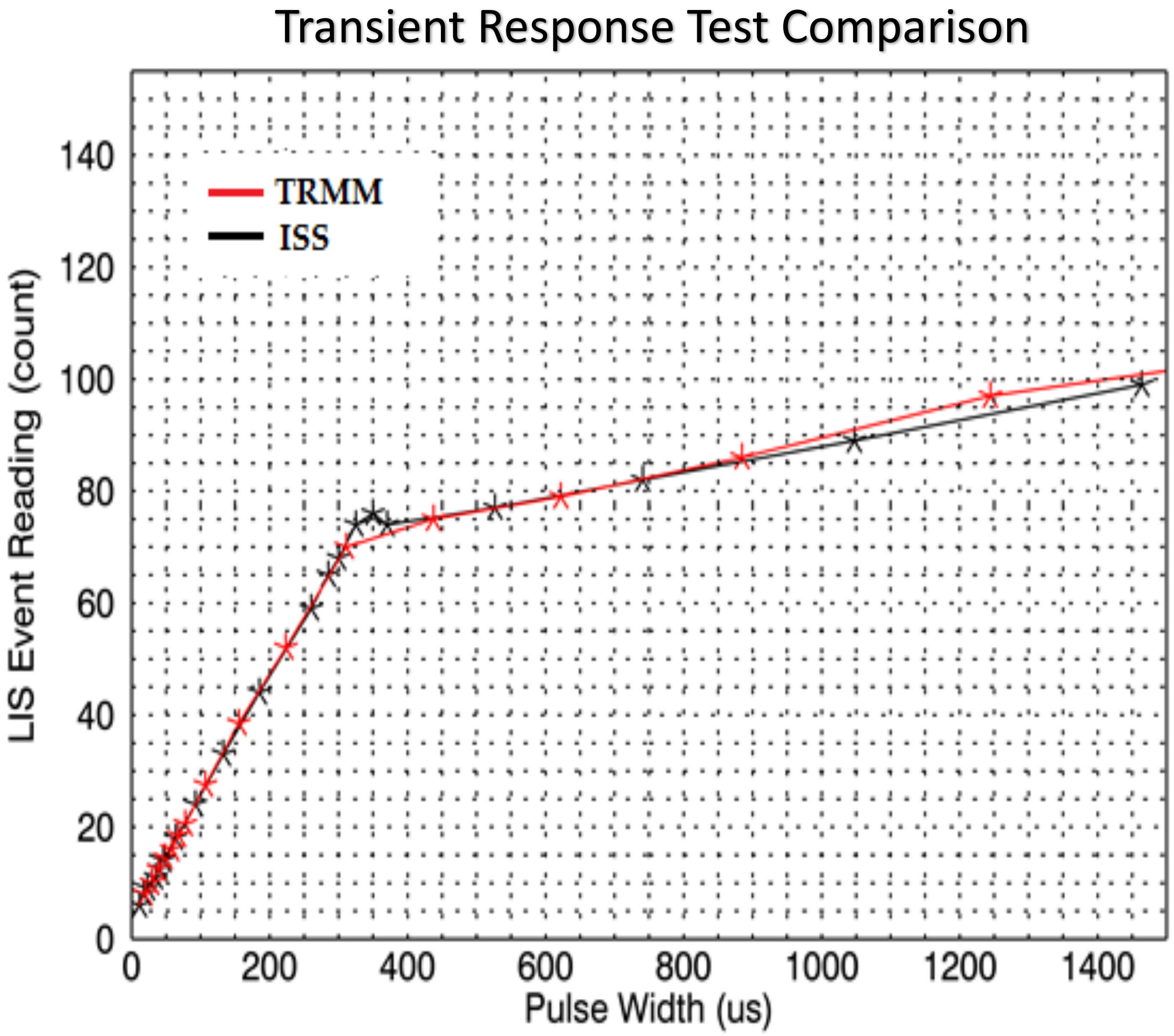

International Space Station (ISS)
Commanding
Data Downlink
Payload Operations Integration Center (POIC)
GHRC On-Premises
Transferred over UDP
Commanding
End Users
POCC Retransmit
Earthdata Cloud
LIS POCC

Figure 3.

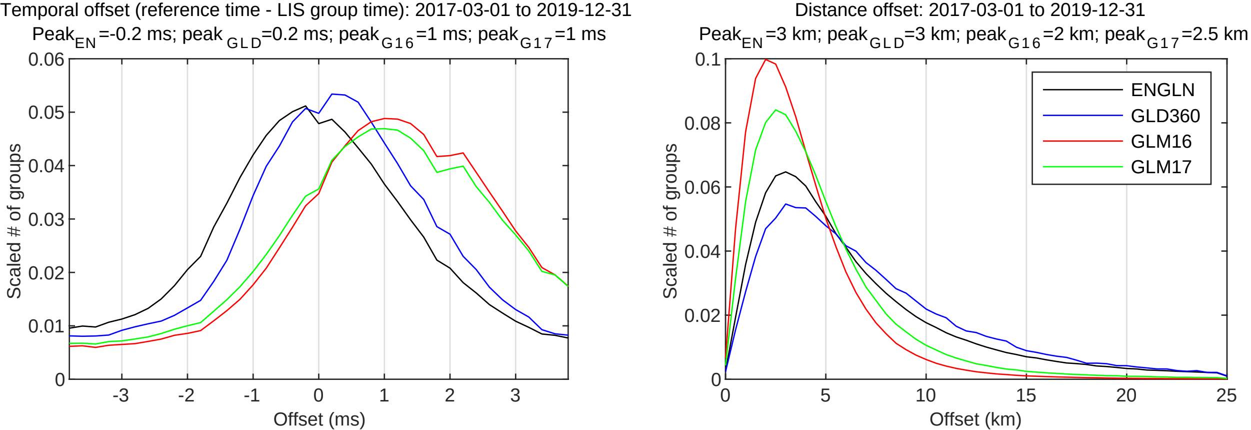


Static Response Test Comparison
TRMM
ISS
LIS Reading (count)
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
350
Radiometric Reading (W/(m^2-sr-um))



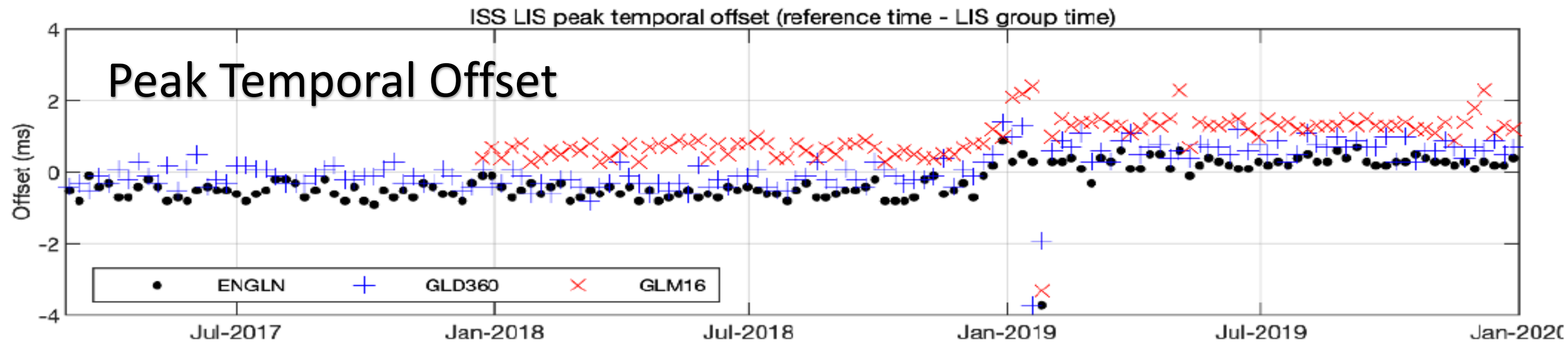
Transient Response Test Comparison
TRMM
ISS
LIS Event Reading (count)
140
120
100
80
60
40
20
0
0
200
400
600
800
1000
1200
1400
Pulse Width (us)

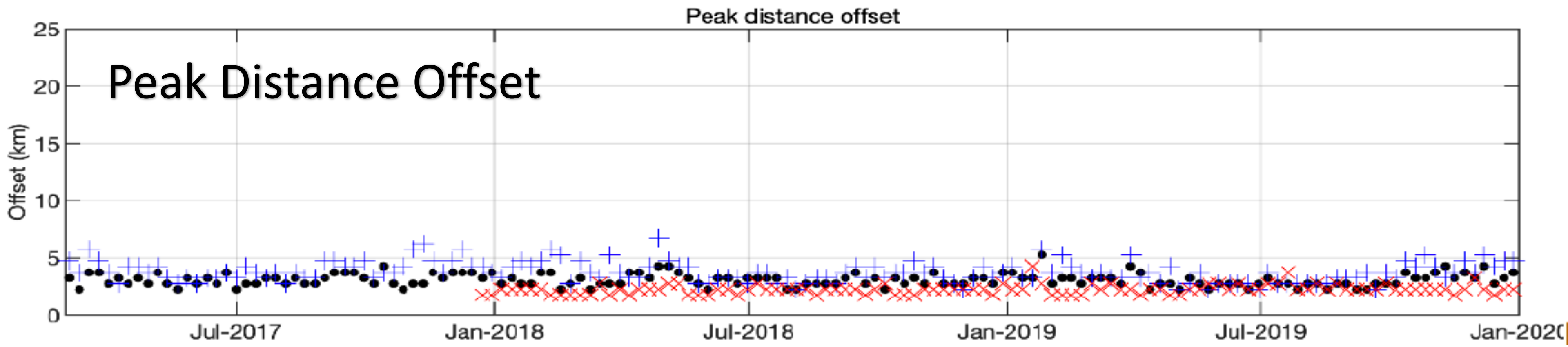
Figure 4.



Temporal offset (reference time - LIS group time): 2017-03-01 to 2019-12-31
Peak$_{EN}$=-0.2 ms; peak$_{GLD}$=0.2 ms; peak$_{G16}$=1 ms; peak$_{G17}$=1 ms
Scaled # of groups
Offset (ms)
Distance offset: 2017-03-01 to 2019-12-31
Peak$_{EN}$=3 km; peak$_{GLD}$=3 km; peak$_{G16}$=2 km; peak$_{G17}$=2.5 km
Scaled # of groups
Offset (km)
ENGLN
GLD360
GLM16
GLM17

Figure 5.


ISS LIS peak temporal offset (reference time - LIS group time)
Peak Temporal Offset
Offset (ms)
ENGLN
GLD360
GLM16
Jul-2017
Jan-2018
Jul-2018
Jan-2019
Jul-2019
Jan-2020


Peak distance offset
Peak Distance Offset
Offset (km)
Jul-2017
Jan-2018
Jul-2018
Jan-2019
Jul-2019
Jan-2020

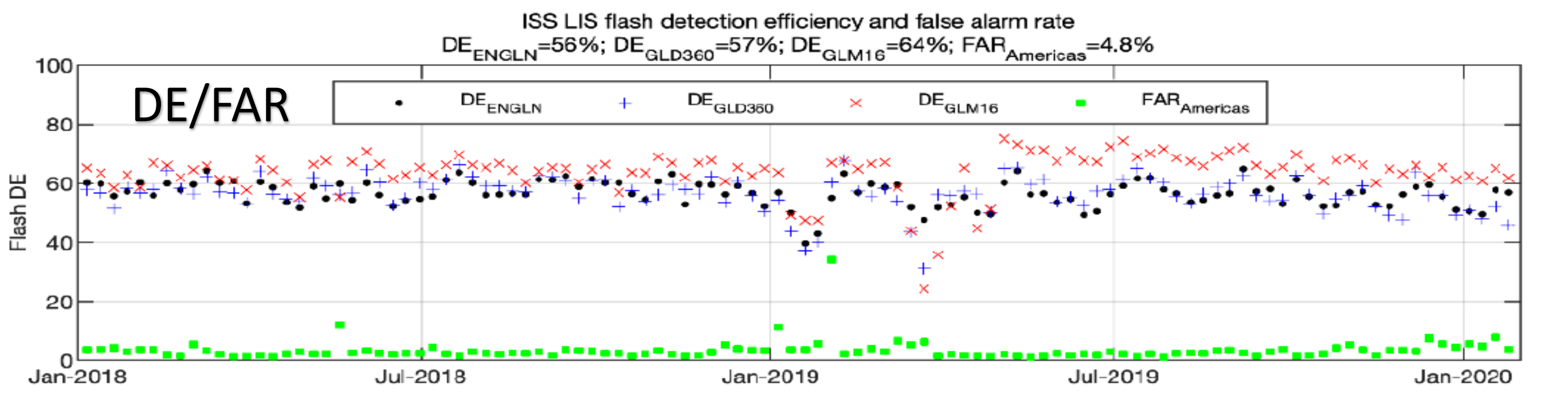
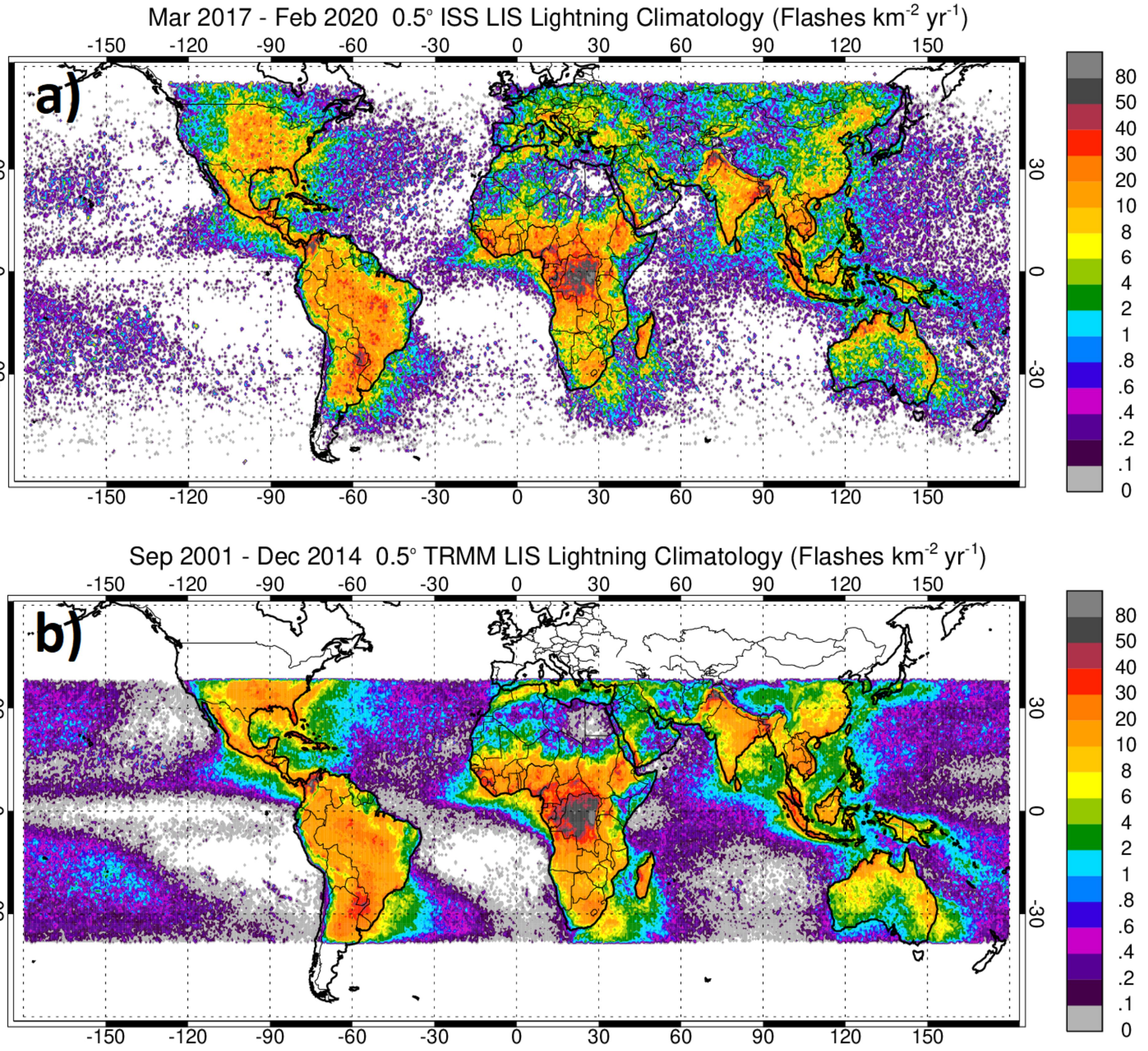
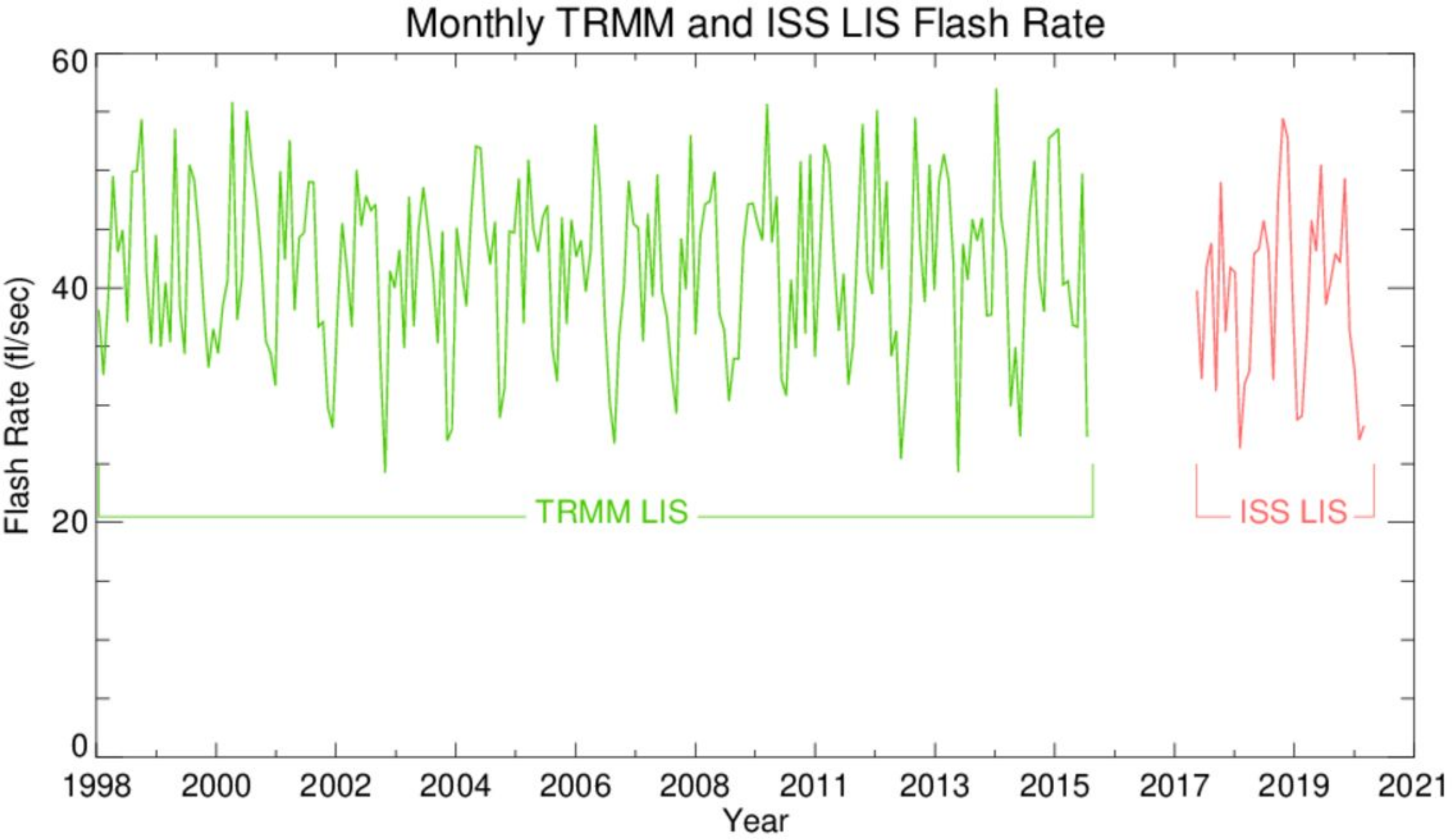

ISS LIS flash detection efficiency and false alarm rate
DE_{ENGLN}=56%; DE_{GLD360}=57%; DE_{GLM16}=64%; $FAR_{Americas}$=4.8%
DE/FAR
DE_{ENGLN}
DE_{GLD360}
DE_{GLM16}
$FAR_{Americas}$
Flash DE
Jan-2018
Jul-2018
Jan-2019
Jul-2019
Jan-2020

Figure 6.



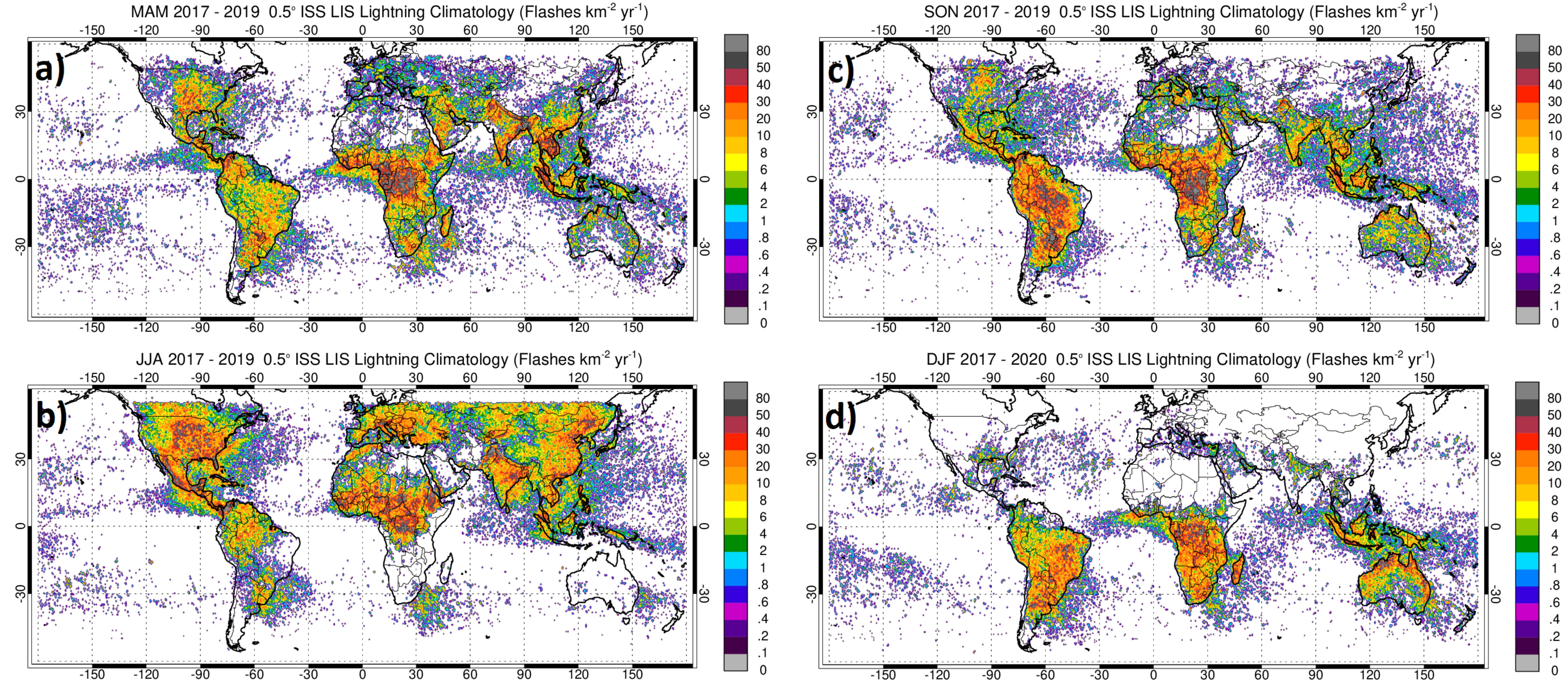
Mar 2017 - Feb 2020 0.5° ISS LIS Lightning Climatology (Flashes km-2 yr-1)
a)
-150
-120
-90
-60
-30
0
30
60
90
120
150
30
0
-30
80
50
40
30
20
10
8
6
4
2
1
.8
.6
.4
.2
.1
0
Sep 2001 - Dec 2014 0.5° TRMM LIS Lightning Climatology (Flashes km-2 yr-1)
b)

Figure 7.



Monthly TRMM and ISS LIS Flash Rate
60
40
20
0
Flash Rate (fl/sec)
TRMM LIS
ISS LIS
1998
2000
2002
2004
2006
2008
2011
2013
2015
2017
2019
2021
Year

Figure 8.



MAM 2017 - 2019 0.5° ISS LIS Lightning Climatology (Flashes km-2 yr-1)
SON 2017 - 2019 0.5° ISS LIS Lightning Climatology (Flashes km-2 yr-1)
JJA 2017 - 2019 0.5° ISS LIS Lightning Climatology (Flashes km-2 yr-1)
DJF 2017 - 2020 0.5° ISS LIS Lightning Climatology (Flashes km-2 yr-1)
a)
b)
c)
d)
-150
-120
-90
-60
-30
0
30
60
90
120
150
30
0
-30
80
50
40
30
20
10
8
6
4
2
1
.8
.6
.4
.2
.1
0

Figure 9.

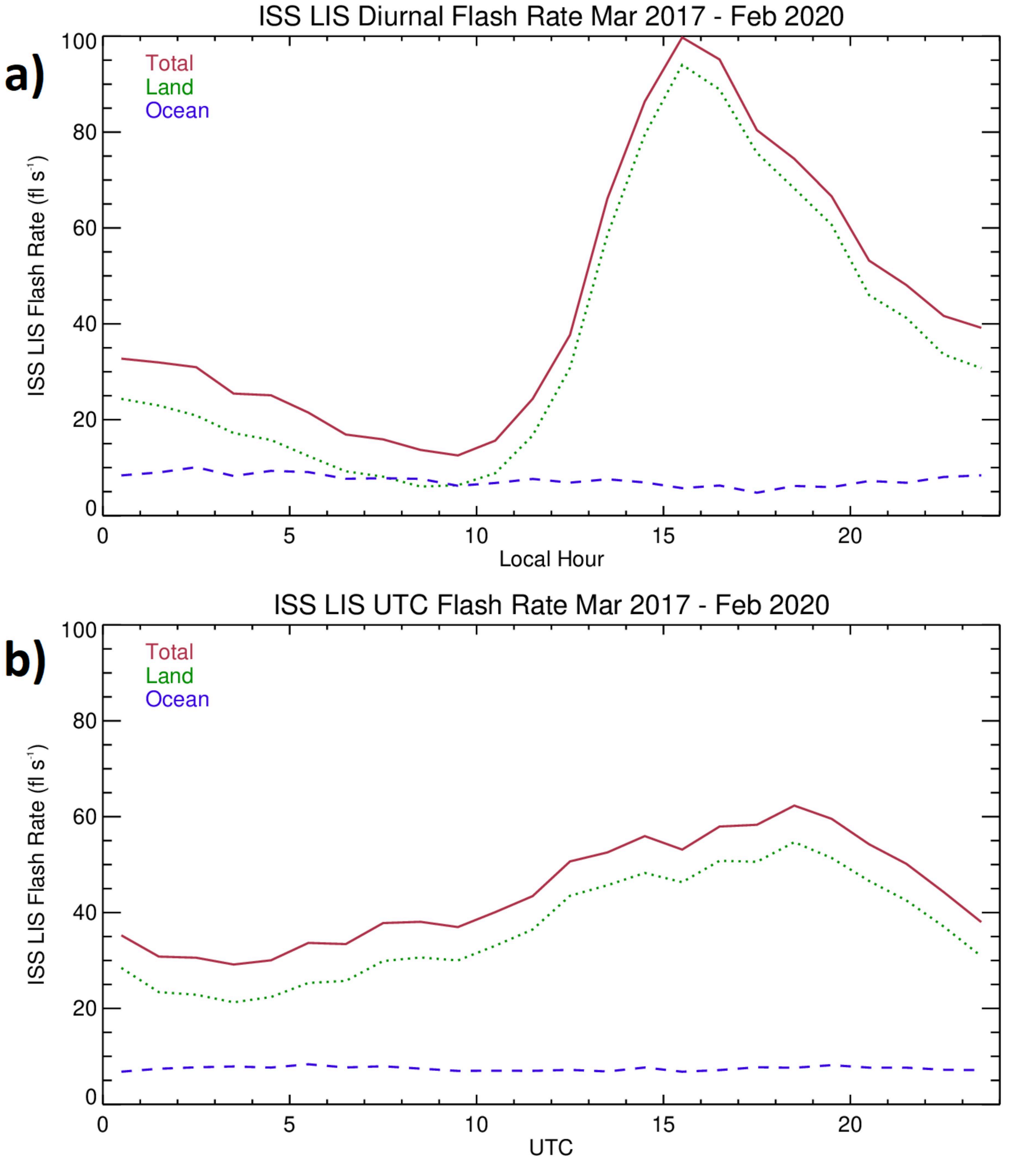

ISS LIS Diurnal Flash Rate Mar 2017 - Feb 2020
a)
Total
Land
Ocean
ISS LIS Flash Rate (fl s⁻¹)
Local Hour
ISS LIS UTC Flash Rate Mar 2017 - Feb 2020
b)
Total
Land
Ocean
ISS LIS Flash Rate (fl s⁻¹)
UTC

Figure 10.

GLM-16 flash DE with respect to reference data
Matching window = 200 ms, 50 km; 2018-01-01 to 2019-12-31

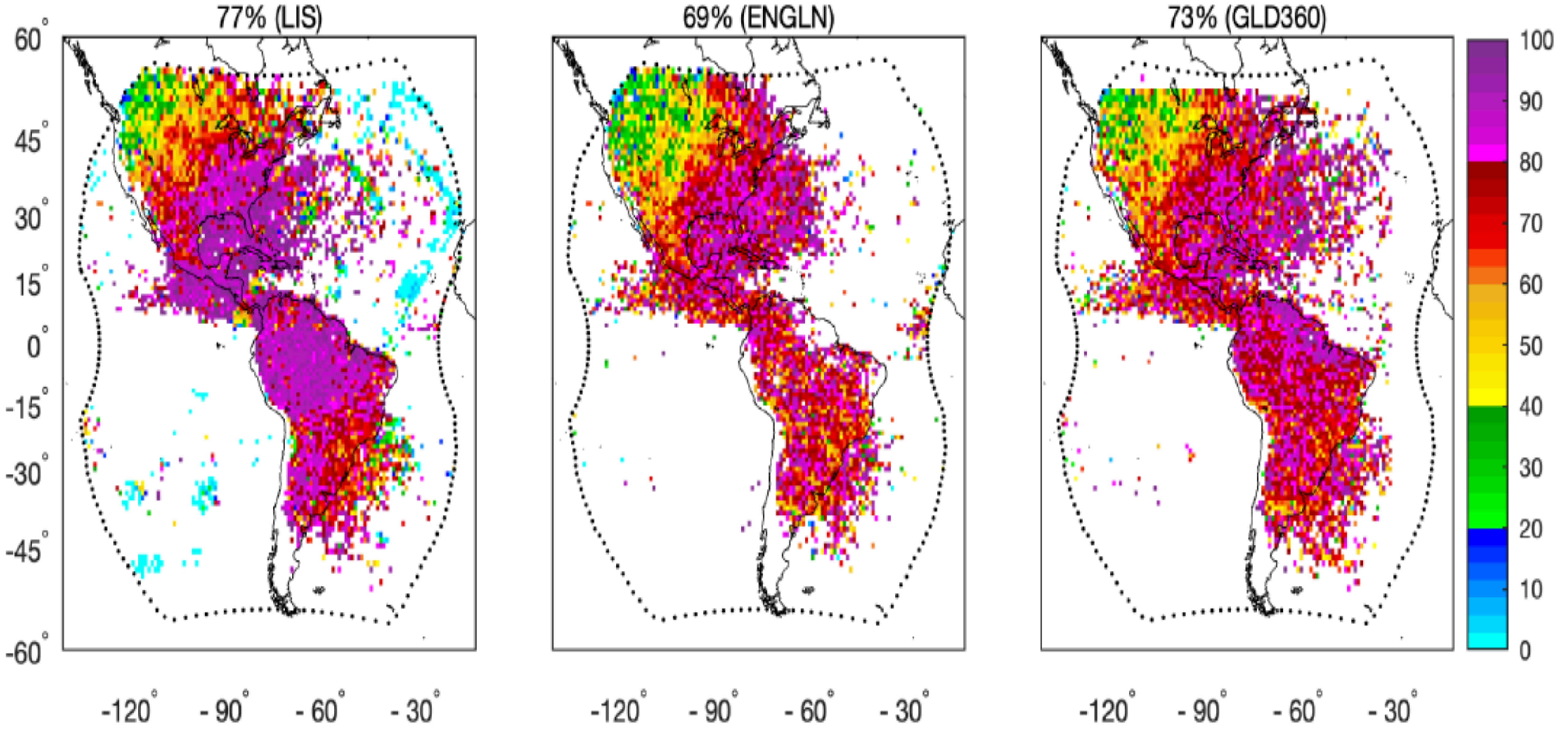
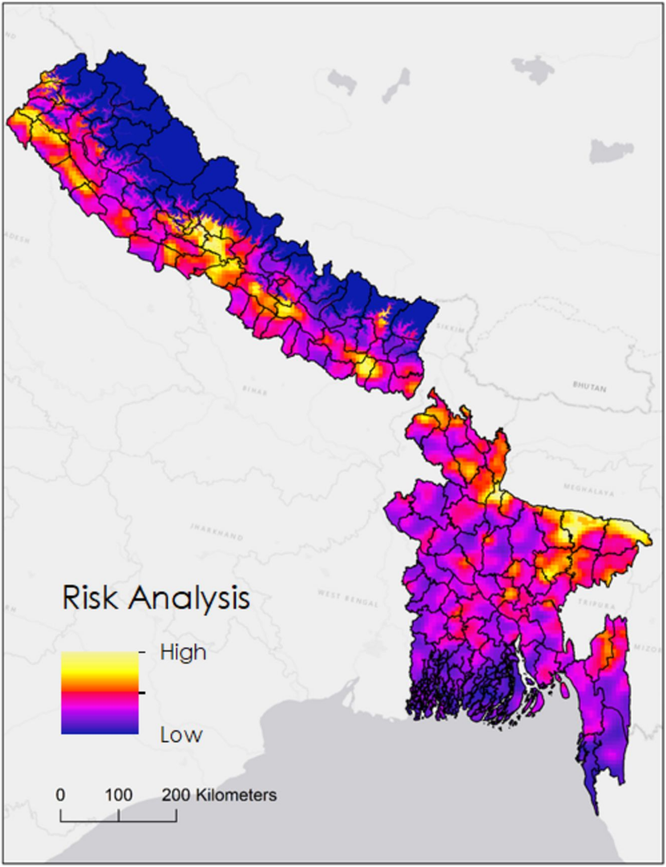
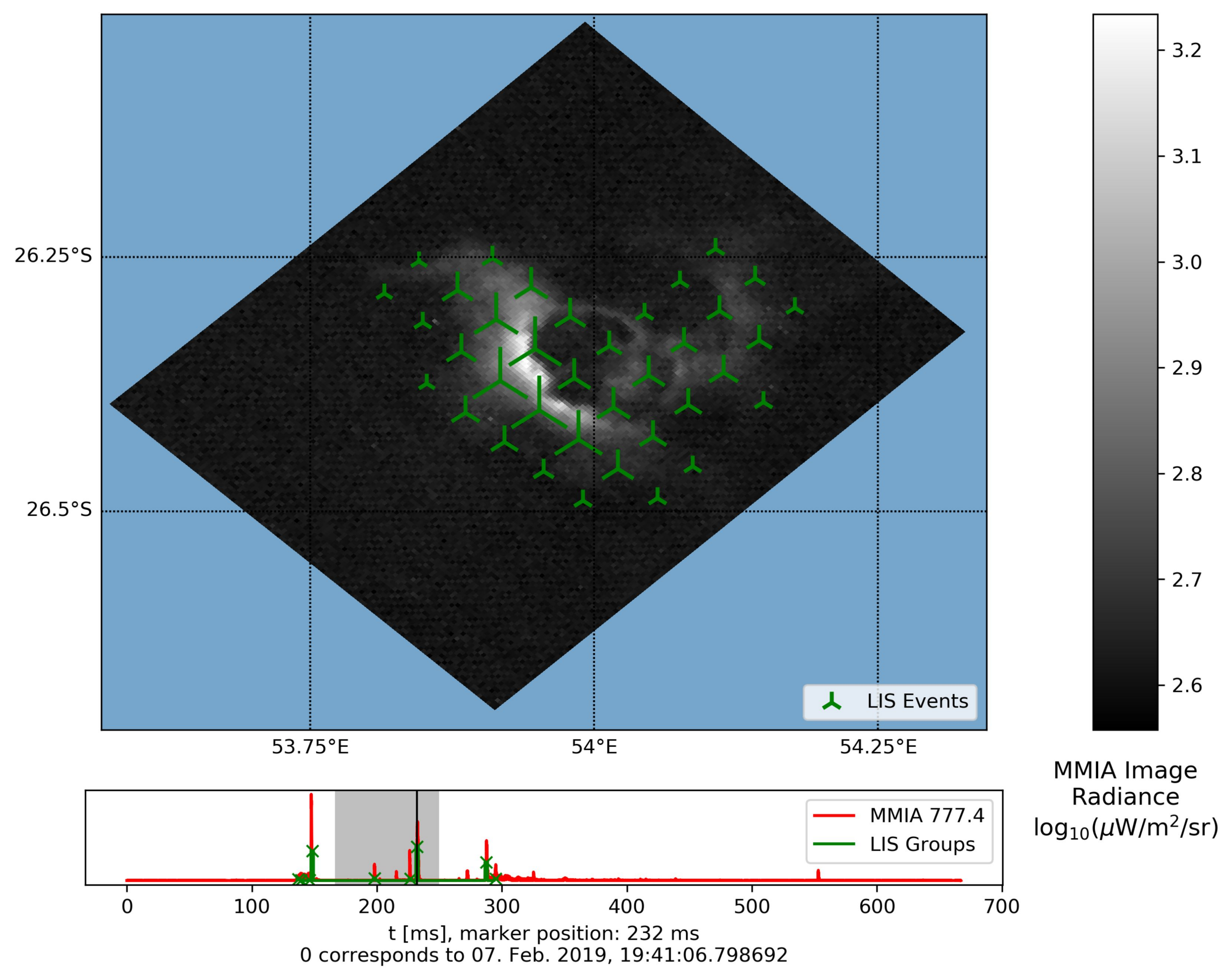


Figure 11.



Risk Analysis
High
Low
0
100
200 Kilometers
SIKKIM
BHUTAN
BIHAR
MEGHALAYA
JHARKHAND
WEST BENGAL
TRIPURA

Figure 12.


26.25°S
26.5°S
53.75°E
54°E
54.25°E
LIS Events
3.2
3.1
3.0
2.9
2.8
2.7
2.6
MMIA Image
Radiance
log$_{10}$(μW/m^2/sr)
MMIA 777.4
LIS Groups
0
100
200
300
400
500
600
700
t [ms], marker position: 232 ms
0 corresponds to 07. Feb. 2019, 19:41:06.798692