NRA-97-MTPE-03 : Cross-sensor Validation of the Lightning Imaging Sensor (LIS)

Progress Report : June 1998 – June 1999

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Summary. In the past year, considerable progress has been made on assessing LIS performance characteristics and optimizing data processing algorithms. Much of this progress has been made possible by improved understanding of key truth sensors, including VHF time-of-arrival (TOA) ground-based total lightning mapping networks. Preliminary estimates of LIS flash detection efficiency, spatial accuracy, optical pulse grouping algorithm errors, and noise filter effects are now available. Collection of other validation datasets has continued through the past year and efforts are underway to increase the truth data dramatically by installation of a long baseline TOA system near NASA/MSFC. Several journal articles and conference papers have resulted from this year's research.

Introduction. Most significant progress in this study has been made in the following three areas: (1) Development of new analytic and empirical methodologies for assessing the performance characteristics of both truth sensors and the target sensor (LIS). (2) Cross-sensor comparisons of LIS data with surface VHF/TOA total lightning mappers in Oklahoma and Florida. (3) Collection of further validation data in Brasil and during several aircraft (ER-2) campaigns of opportunity. We discuss each major category below.

1. **Methodology Development.**

   a. **Summary.** Quantitative use of data collected by lightning sensors over the last few decades has, in general, suffered from poor assessment of these sensors' biases, sensitivities and useful fields-of-view. While part of the limitations have been statistical (cross-sensor truth datasets being difficult to come by, and often requiring intensive field campaigns with low data yield), a significant part of the difficulty has been the lack of robust, well developed and widely applied methodologies for assessing sensor performance. A key example is total lightning mapping sensors such as VHF TOA or interferometric systems. These sensors have the potential to provide the only large database of total lightning data with which to truth the LIS. However, as with most electromagnetic lightning sensors, they have strong range-dependencies in their performance characteristics. Conventional wisdom has placed their effective range at one or two network baseline diameters wide; however, this is a conservative estimate yielding a very small radius of coverage – too small to build a statistically meaningful intercomparison dataset during the lifetime of the TRMM mission. Clear determination of these sensors' true maximum useful range is thus absolutely critical for validation (or science) studies, as modest gains in effective range yield significant gains in field-of-view overlap with satellite overpasses. We have developed a physically-based analytic and empirical methodology to assess this useful range, and applied it to the Kennedy Space Center LDAR TOA network, identifying a nearly threefold gain in maximum useful range over conservative conventional wisdom estimates.

Another difficulty with quantitative use of data from many lightning sensors is ambiguity in the determination of a "flash". Few sensors have adequate spatial, temporal and frequency resolution to completely and uniquely separate one lightning flash from another in high flash rate storms; there is thus always a sensor-dependent ambiguity in the definition of observed "flashes" based on the algorithm employed to cluster sub-flash level observations (optical pulses, VHF radiation sources, LF transients from return strokes). To skirt this issue, we employ a fairly straightforward (but to our knowledge, novel) technique in several studies: we 'bootstrap' estimates of true lightning flash characteristics (as observed by a given sensor) by examining the population of flashes which are clearly separable (clearly separated in space and time). This approach carries the hazard of small bias (if the properties of flashes in very high flash rate storms differ systematically from lower flash rate storms), but at least allows a zeroth order estimate with which to proceed. Direct benefits of this approach include the first-ever detection efficiency vs. range estimates for the LDAR network, and an assessment of the LIS pulse clustering algorithm performance.

b. **Framework for assessment TOA truth sensors.** A large historical database of LDAR TOA VHF source observations is archived at the Global Hydrology Resource Center. Recognizing that enough data has been collected to create a "climatology" for the Florida region, we created composite distributions of LDAR-observed VHF sources, and used the observed properties of these distributions (falloff of observations with range, spatial distortion in their locations, etc.) to infer properties of the "true" underlying lightning distribution. This analysis yielded the following results:

1. An analytic assessment of LDAR total lightning flash detection efficiency vs. range. The DE remains above 90% to 90-100 km range from the network centroid; this is a significant increase in demonstrated effective coverage for the sensor.
2. The location error distribution at each LDAR-relative ground range. This knowledge is critical for the construction of robust source clustering (flash identification) algorithms.
3. Properties of LDAR-observed flashes, including duration and observed number of sources. At close range, these are good estimates of "true" flash properties. In the case of duration, this provides an important constraint (based on a large number of statistics) for LIS data production algorithms.

4. **4.** Range-normalization schemes to make the observations at medium-far (>100 km) range quantitatively consistent. Skill improvement using these schemes has been confirmed by comparison with a large database of National Lightning Detection Network (NLDN) cloud-to-ground lightning observations. This may allow extension of the maximum useful range even further, albeit at the cost of additional statistical uncertainty.

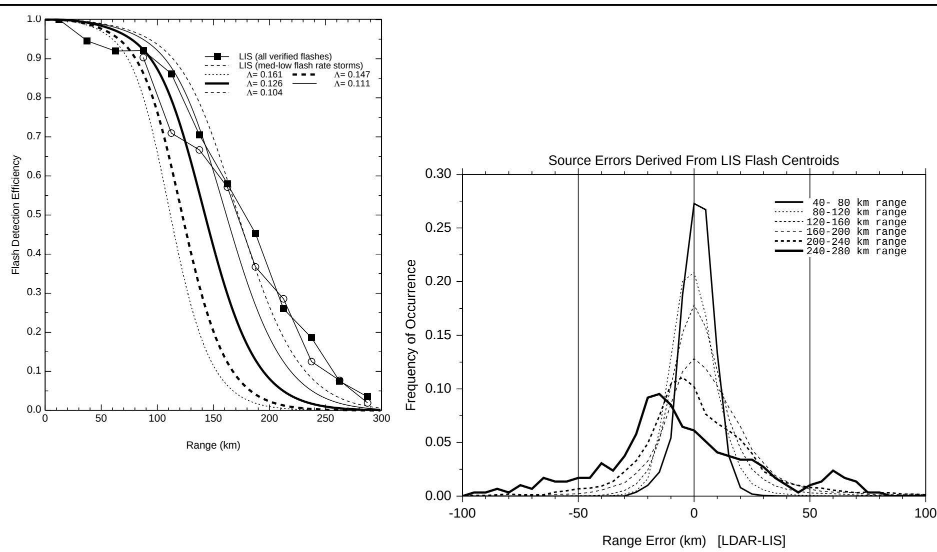

Fig. 1: Analytic and empirical LDAR flash detection efficiency vs range (left) and location error distributions vs range (right).

DE estimates have been confirmed at medium-far range with reverse-validation by the LIS sensor. The methodology is thus both internally consistent and validated by cross-sensor tests. More importantly, it is fully extensible to new TOA-network deployments, such as the one planned for the NASA/MSFC region in Fall 1999 (see below). Results of this analysis have been presented at the 11th International Conference on Atmospheric Electricity, and have been submitted as a pair of papers to the Journal of Geophysical Research.

c. **Framework for assessment of LIS grouping algorithm.** As described above, quantitative use of LIS data can be seriously compromised if the sensor does not properly assemble observed optical pulses into data corresponding to true flash channels. Assessment of how often the LIS is likely to fail in this task requires knowledge of the true occurrence of temporally overlapping flashes in nature.

As described above, we can bootstrap an estimate of this by examining temporal overlap of flashes which are widely separated in range (but still within the LIS field of view). At far (and decreasing) range, we find a continuous distribution with a slow increase in temporal overlap at smaller spatial separation (perhaps corresponding to a natural tendency of deep [electrified] convection to cluster at smaller spatial scales). At very short spatial separation, we observe discontinuities in the distributions coincident with spatial scales "hardwired" into the clustering algorithm. For the OTD sensor, fewer than expected temporal overlaps occur at small spatial scales, suggesting the algorithm incorrectly "merges" flashes too often. For the more sensitive LIS sensor, more temporal overlaps occur than expected, suggesting incorrect "fragmentation" of true flashes. (This behavior corresponds to known limitations in the first versions of both sensor's clustering algorithms). The difference between the observed distributions and 'expected' distributions (extrapolation from larger spatial scales) places bounds on how often algorithm failure occurs. For the OTD, at least 1% of all flashes are affected, and we do not expect the effect to be much larger. For preliminary release LIS data, at most 7% of all flashes are affected, a fraction deemed unacceptable for the final data release. A revised clustering algorithm has been devised by Doug Mach of the University of Alabama which should address the fragmentation issue, and will be incorporated into the second release reprocessing of LIS data in June-July 1999. The

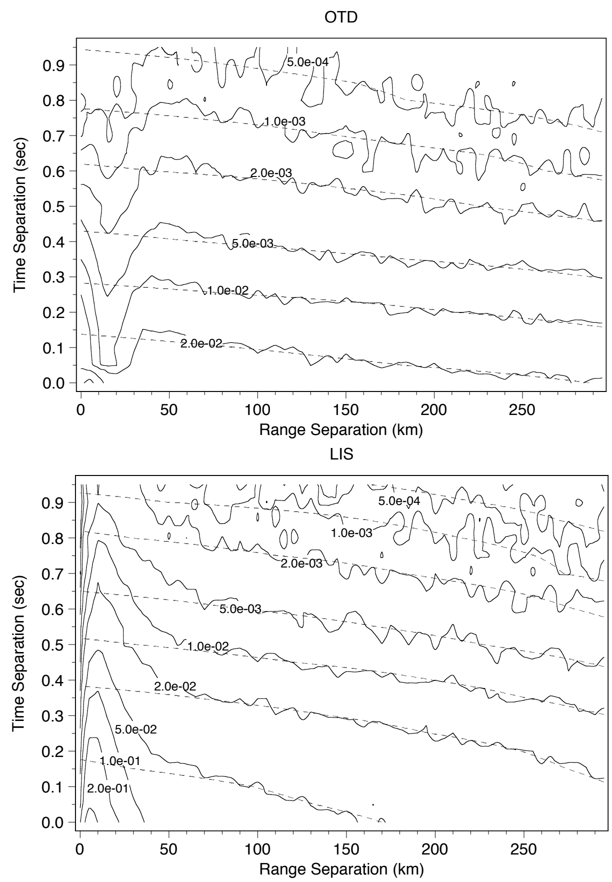

Fig. 2: Observed frequency of occurrence of temporally overlapping flashes. Distortions in the curves at small spatial scales indicate spurious algorithm merging (OTD) and fragmentation (LIS) of true flashes.

above technique will provide an objective technique to assess improvements from the revised algorithm. The approach described above is discussed in full detail in a recent paper accepted by the Journal of Atmospheric and Oceanic Technology.

2. Intercomparisons of LIS data with TOA systems in Oklahoma and Florida

In addition to the Kennedy Space Center LDAR described above, a higher quality TOA network built by Krehbiel, Rison and Thomas of the New Mexico Institute of Mining and Technology was deployed in Oklahoma during the summer of 1998. During one LIS overpass, joint observation of nearly 160 flashes was obtained by the two sensors. These flashes have been manually isolated in space and time, and a paired database constructed.

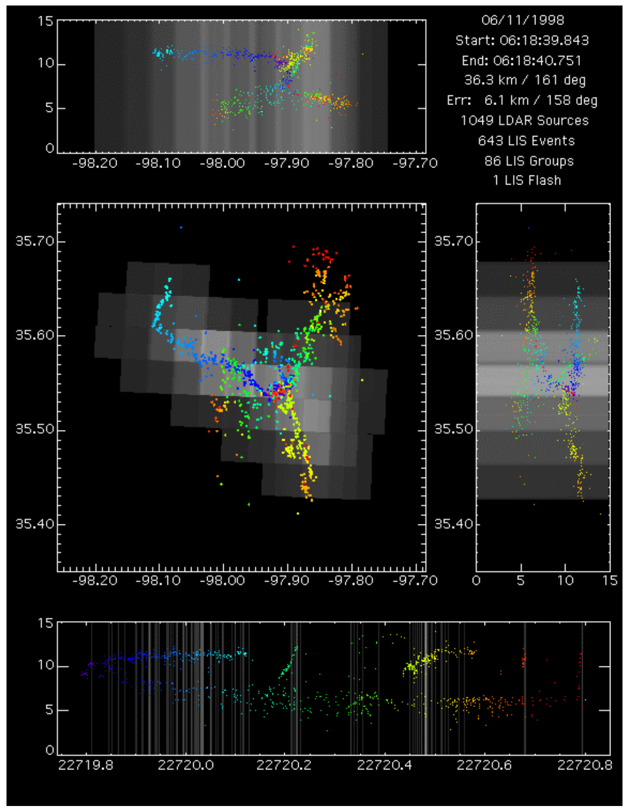

Fig. 3: A sample LIS / TOA system coincident flash observation (LIS = grayscale pixels, VHF sources = colored dots).

From this (nighttime) overpass, we obtain a preliminary estimate of LIS flash detection efficiency of 74-81%. This estimate is higher than prior estimates for the OTD (expected due to LIS sensor design improvements), but lower than expected from laboratory calibrations. This truth database is too limited to yield a robust DE estimate; observation of a wider dynamic range of storm flash rates (and hence intervening, optically attenuating cloud ice contents) is required for a full estimate. Nonetheless, this provides a working number for preliminary analyses.

Additional results from this case study are more relevant. Since the NMT TOA system locates flash components in altitude, we are able to confirm that the LIS detects significantly more optical pulses from the upper branches of IC channels than the lower branches, or from CG channels. This places strong constraints on the quantitative use of secondary LIS observables, such as flash optical footprint and total radiance, in science studies. These constraints are important, as statistically significant differences are observed between the optical flashes of, e.g., land and ocean flashes. Reexamination of the effects of multiple scattering and attenuation at the LIS optical wavelength are required before such observations can be interpreted.

A critical result from this case study is an assessment of the effects of the LIS noise filtering algorithm on low-information-content true flashes (i.e., those with few optical pulses). LIS level II data were produced for this overpass using the preliminary release production code, using a revised filter algorithm at various parameter settings, and using completely unfiltered data. It was determined that at most the production code removed 3-4% of all flashes during the overpass because their signal content was too low (too few pulses), and that tuning of the filter parameters had little effect. This is a significant result, as objective measures of the amount of true lightning removed by noise filters have previously been lacking. For the LIS, sensitivity is high enough that most flashes have sufficient spatial and temporal structure in their emitted optical pulses to be distinguishable from noise. Tuning of filter parameters can thus be guided more strongly by their effects in high noise regions (such as the South Atlantic Anomaly) rather than concern over their effects on true lightning in low noise regions (most of the rest of the world).

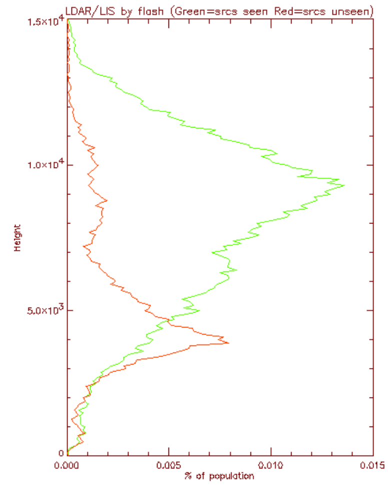

Fig. 4: Altitude distribution of VHF sources in flashes seen (green) and not seen (red) by the LIS.

Finally, differences between LIS and NMT TOA flash centroid locations were found to be less than 5-6 km on average. LIS location accuracy is thus significantly higher than OTD location accuracy, as expected from the better TRMM navigation and stabilization.

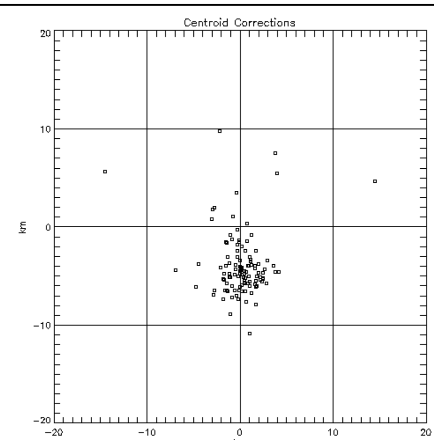

Fig. 5: Differences in the centroid locations of LIS and TOA observed flashes.

Results from the Oklahoma case study were presented at the 11th ICAE by Thomas et al, and submitted to Geophysical Research Letters for publication.

A similar analysis during an overpass of the KSC LDAR was presented by Ushio et al at the 11th ICAE. In this case, 122 flashes were examined. Similar results were obtained; the VHF source distributions of flashes seen and not seen by the LIS were high- and low-biased, respectively. During this overpass, location errors for intracloud flashes were about 4 km on average, while for cloud-to-ground flashes they were closer to 10 km.

These case studies provide preliminary estimates for key LIS validation quantities, and have identified key issues complicating bulk (statistical) assessment of these quantities using many overpasses. Using the results derived here, as well as the analytic methodology for TOA network performance assessment described above, the road is clear for such statistical determination. Deployment of a NMT-designed TOA validation system near NASA/MSFC will allow the assembly of a large intercomparison database; plans for such a deployment are described below.

3. **Collection of validation data – update.** In the original proposal, deployment of a TOA-type total lightning detection network during the TRMM-LBA campaign in Rondônia, Brasil was anticipated. Due to overcommitment of the NMT hardware and staff, such deployment was not possible (although an alternate CG-detection system was deployed by NASA/MSFC, as described below). Loss of this validation dataset somewhat compromises our ability to address one component of the original proposal: LIS performance in the South Atlantic Anomaly. We discuss ways of mitigating this loss below. Alternatively, we are now initiating contracts to build and deploy a large baseline TOA network near NASA/MSFC (within the LIS orbital coverage). This local network will have the benefits of easier data access, hardware maintenance, and most importantly, much longer duration deployment than in the Rondônia validation campaign. The additional validation and science gains from the revised deployment plan more than outweigh the data loss on the periphery of the SAA.

The MSFC TOA system is being designed as a long-baseline network. Based on the performance assessment of the (less sensitive) KSC LDAR system (described above), and field testing of the NMT TOA system by Krehbiel et al, we now know that network receivers can be operationally spaced many tens of km apart *and maintain nearly uniform total lightning detection efficiency*. The benefits of a long baseline system include not only a critical increase in effective coverage range (and hence useful overpass data), but significant improvements in flash location accuracy, needed for robust validation. The MSFC network is expected to be operational by Fall 1999. Dr. Bateman will be primarily tasked with assessment of network performance and analysis of network data during the next year.

In place of the TOA network originally slated for short-term deployment in Rondônia, the LIS team has deployed a four-sensor ALDF CG detection network in the TRMM-LBA domain

This network became operational during the second half of the TRMM-LBA campaign, and will continue collecting lightning data for at least one year. After this period, it may be redeployed elsewhere in Brasil, at the discretion of INMET. If the network is moved, NASA/MSFC will have continued access to network data. Dr. Rennó has been instrumental in the assembly,

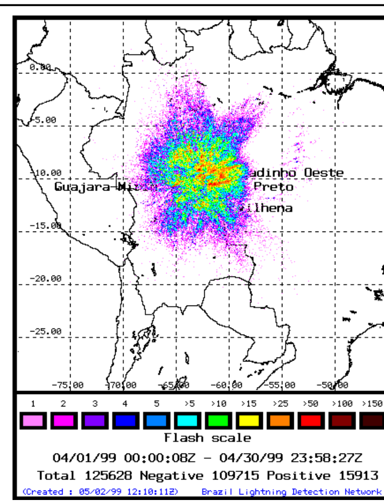

Fig. 6 : Sample 1-month lightning observations from the Rondônia network.

maintenance and continued operation of the network in the problematic Rondônia region, and in establishing and maintaining contacts with local and Federal Brasilian collaborators. With his assistance, and with the assistance of Dr. Osmar Pinto of INPE, we are also working to collect CG lightning data from previously-deployed and planned lightning networks elsewhere in Brasil. Together, these data streams should allow basic assessment of LIS performance in and near the SAA region, although such assessment is now expected to be completed closer to the end of the validation study.

A final validation database which has not yet been examined is aircraft (ER-2) measurements using the Lightning Imaging Package (LIP) during the CAMEX, TEFLUN and TRMM-LBA campaigns. Dr. Bateman has spent considerable effort in the past year refining the sensor hardware and collecting these data, and will serve as the key collaborator during data analysis. Data from the LIP provide crucial information on the *energetics* of flashes observed and not observed by the LIS; these data allow us to assess the importance of the small fraction (10-20%) of flashes undetectable by the LIS in the overall electrical budget of storms. (Studies which attempt to relate observed flash counts to storm convective properties proceed on the basis of this electrical energy budget to provide the physical linkage between lightning and storm kinematics and microphysics). Similar studies using the NASA/KSC electric field mill network and LDAR are being conducted by W. Koshak and P. Krider, funded through another NRA-97-MTPE-03 proposal. We are in close collaboration with this team and are sharing all preliminary results to assist their analysis.

4. **Activities for the final year (June 1999 – September 2000).** As described above, deployment of the NASA/MSFC TOA network, assessment of its performance, and statistical analysis of LIS / MSFC and KSC TOA network observations will be the major activities during the final year of this study. The bulk analyses will refine the preliminary estimates of LIS characteristics and guarantee that they are derived from a wide dynamic range of storm morphology (and hence a wide dynamic range of optical attenuation regimes, and thus LIS sensitivities). Reassessment of LIS algorithm performance using the methodologies developed this year and reprocessed data due in June-July, 1999 will complete our investigation of LIS data production code algorithms, since preliminary estimates suggest that algorithm issues are already at a manageable level, with impacts below the 10% level. We will repeat the NLDN-based CG detection efficiency study performed on OTD and recently accepted for publication in the Journal of Atmospheric and Oceanic Technology, as a large enough (2-year) database of LIS/NLDN observations is now available. Combining the TOA network (total lightning) and NLDN network (CG lightning) results, we will be able to determine the feasibility of merging data from the OTD and LIS to form a much longer baseline (7-year) tropical lightning dataset. Finally, if time permits, we will utilize LIP data to perform preliminary assessment of the energetics of flashes seen and not seen by the LIS.

5. Collaborators during 1998-1999

Steve Goodman, William Koshak, Richard Blakeslee, Hugh Christian (NASA/MSFC), Stan Heckman (USRA), Tomoo Ushio, Jeff Bailey (Global Hydrology and Climate Center), Doug Mach (Univ. of Alabama), Earle Williams (MIT), Paul Krehbiel, Ron Thomas, Bill Rison (New Mexico Tech), K. Cummins (Global Atmospherics, Inc.), Bob Boldi (MIT/Lincoln Labs), O. Pinto (INPE).