Modelling and Simulation of the GOES-R Geostationary Lightning Mapper (GLM) Instrument Performance

David Down[1], Susan P. Hagerty[1], Todd Updike[1], James W. Bergstrom[1], Steven J. Varlese[1]
[1]Ball Aerospace and Technologies Corp.

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Abstract

The Optical Transient Detector (OTD) and the Lightning Imaging Sensor (LIS) have provided optical detection of lightning from low-Earth orbit for over ten years. Due to the orbit limitations, OTD and LIS cannot provide continuous coverage of severe storm development. The objectives of the Geostationary Lightning Mapper (GLM) are to provide continuous, full-disk lightning measurements for storm warning and nowcasting; early warning of tornadic activity; and accumulate a long-term database to track decadal changes.

The fundamental requirement for GLM is to detect the occurrence of both cloud-to-ground and intra-cloud lightning flashes with a high detection efficiency and a low false alarm rate, 70% and 5% respectively at end of life. OTD and LIS have demonstrated the efficacy of the optical detection approach, which discriminates the optical pulses from the high-background daytime environment of sun-lit clouds. In order to accurately assess GLM performance, sophisticated modeling is required. Because lightning is a transient event, the GLM instrument is quite different from the typical remote sensing environmental instrument. In addition to radiometric modeling, which provides the usual signal-to-noise ratio, analysis of the "receiver operating characteristics" (ROC) is required to determine the probability of detection (P_D) or probability of a false alarm. These performance parameters are customarily used in certain military sensors.

Our approach to the analysis is twofold: a performance model has been generated that provides moderate fidelity and allows rapid trade-off of sensor characteristics, and another tool provides high-fidelity simulation of particular special cases.

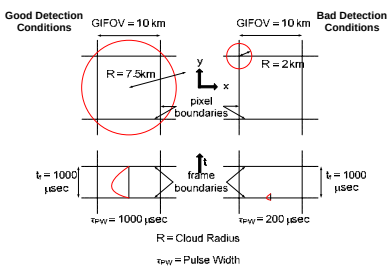
For both methods, a detailed understanding of the lightning optical pulse characteristics is required. Statistical models of the amplitude, temporal and spatial distribution of the optical emissions have been generated from the observations described in the literature. The particular detection algorithm has also been integrated into the detection analysis. Noise sources, including scene shot noise and sensor noise are included in the moderate fidelity model.

In the high-fidelity simulation, spacecraft jitter, edge effects and the radiation environment from cosmic ray and solar particle radiation (based on Ball Aerospace detailed models) have also been included. A Monte Carlo approach is used to incorporate radiation hits and lightning events. Finally, the high-fidelity simulation includes the effects of the varied and high radiance background by the inclusion of actual scenes from MODIS and other data.

Background

Why Use Statistics?

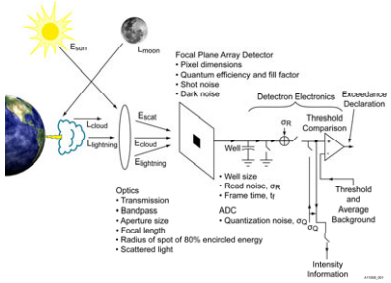
- **There is wide variation in lightning phenomena**
- **It is not possible to accurately determine sensor performance without modeling that takes account of lightning phenomena with statistical hypothesis testing**



Why a Model and a Simulation?

- Model is to derive sensitivities and performance trends
  - Uses simplifying assumptions about scene
  - Can use fast analytic formulas for P_D performance
- Simulation predicts real world End-to-end performance in the presence of
  - Structured scene, spacecraft induced LOS motion, radiation

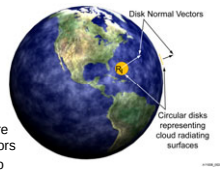
Model and simulation account for all sensor parameters that affect the number of signal and noise electrons

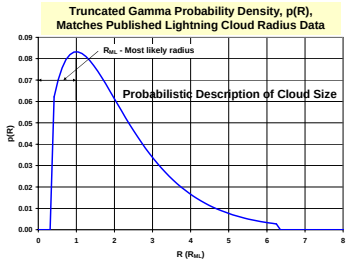


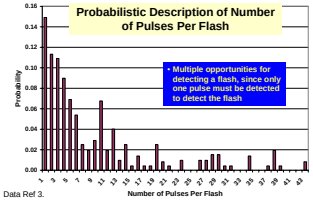
Model and Sim Share Core Statistical Description

Description of clouds must
- Capture the statistical properties that matter for detection
- Simple enough to fit within computing resources

Assumptions on cloud surfaces
- Cloud radiating surfaces are planar, circular, disk radiators
- Cloud planes are parallel to the Earth's surface







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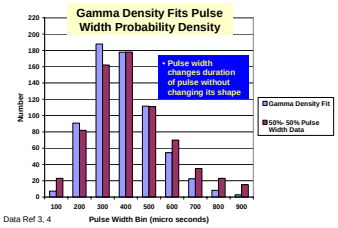

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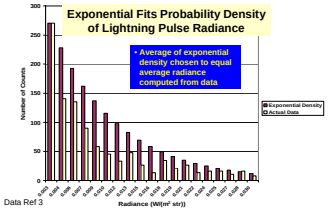

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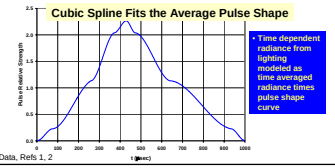
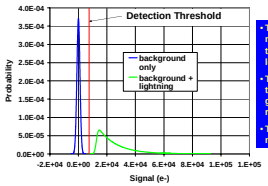


Data, Refs 1, 2

Model Uses Analytic Formula for Signal Electron Probability Density to Determine P_D

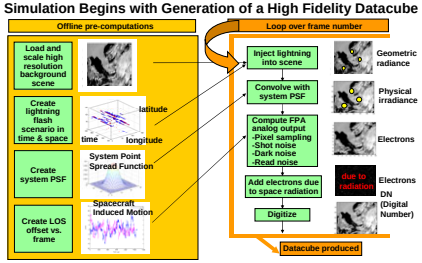
- The optimal detection threshold is computed from the background probability density
- P_D is the area under the background plus lightning density to the right of the threshold



- **To get acceptable P_{FA} most of the area under the blue curve must be left of the threshold**
- **To get good P_D most of the area under the green curve must be right of the threshold**
- **To get both, the areas must be well separated**

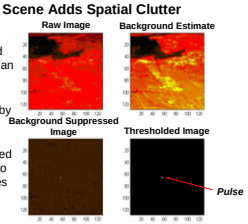
Sim Adds Statistical Descriptions of LOS Motion and Scene Background and Uses Monte Carlo Integration to Get P_D

Simulation Begins with Generation of a High Fidelity Datacube

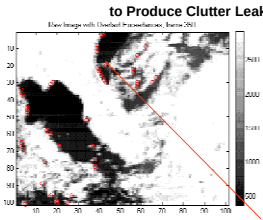


Structured Scene Adds Spatial Clutter

- GLM algorithms will average the structured scene radiance to get an estimate of the spatial clutter
- Clutter is suppressed by subtracting the background estimate
- Background suppressed image is thresholded to identify potential pulses



LOS Motion Interacts with Structured Scene to Produce Clutter Leakage



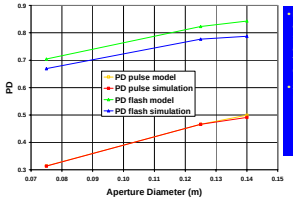
- Inter frame motion causes "clutter leakage", where structure from the background leaks into the background subtracted image. (See above)
- Clutter leakage is caused by sudden changes in the background scene from pixels close to high contrast edges whose positions are modulated by inter-frame LOS motion
- When the sudden changes in pixel signals exceed the threshold, a false event occurs
- Example of clutter leakage in simulated GLM image of Florida coast
- The red circles are exceedances – some due to lightning and some due to clutter leakage
- Our algorithms successfully suppress clutter leakage by using higher thresholds for high variance pixels

- **MODIS imagery with its proper spatial oversampling, adequate image size, similar spectral bands, and a wide latitude range provided the background scene for this simulated GLM image.**

References:
1. Mach, D.M., et al., "Lightning optical pulse statistics from storm overflights during the Altus Cumulus Electrification Study", Atmospheric Research, Vol. 76, 2005, pp 386 – 401
2. Goodman S.J., et al., "A Comparison of the Optical Pulse Characteristics of Intracloud and Cloud-to-Ground Lightning as Observed above Clouds", Journal of Applied Meteorology, Vol. 27, No. 12, 1988, pp 1369 – 1381
3. Christian H.J. and Goodman, S.J., "Optical observations of lightning from a high altitude airplane", Journal of Atmos. Oceanic Technol., Vol. 4, 1987, pp 701 – 711
4. Mach, D.M., et al., "Lightning optical pulse statistics from storm overflights during the Altus Cumulus Electrification Study", Atmospheric Research, Vol. 76, 2005, pp 386 – 401

Cross-validated Model and Simulation

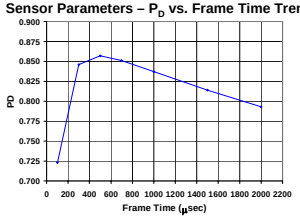
- In order to use the simulation to extend model predictions of performance trends to real world scenes we have to be sure model and sim predictions of P_D agree for the simplified scenes assumed by the model



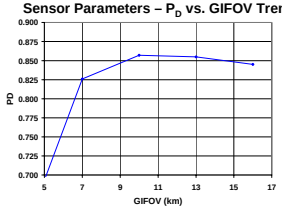
- **In this example the analytic model and simulation show their agreement on the PD trend for aperture diameter**
- **Simplified scene included**
  - **No scene structure**
  - **No LOS motion**
  - **No radiation effects**

Results

Interaction Between Lightning Parameters and Sensor Parameters – P_D vs. Frame Time Trend



Interaction Between Lightning Parameters and Sensor Parameters – P_D vs. GIFOV Trend



- **The optimal sensor parameters are functions of the lightning statistics and are constrained by spacecraft accommodation limits**
- **Modeling of the sensor-algorithm system leads to sensor parameters that are the best match to the system requirements**

Conclusions

- **The wide variation in lightning phenomena parameters requires a fully statistical treatment for accurate P_D predictions**
- **The large parameter space is best explored with an analytic model and examined in detail with a simulation**
- **Simulations offer a realistic assessment of expected sensor-algorithm system performance**

For additional information please contact:

David Down
Ball Aerospace & Technologies Corp.
(303) 939-4378
ddown@ball.com