GOES-R Geostationary Lightning Mapper Performance Specifications and Algorithms

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1. Introduction

The Geostationary Lightning Mapper (GLM) is a single channel, near-IR imager/optical transient event detector, used to detect, locate and measure total lightning activity over the full-disk. The next generation NOAA Geostationary Operational Environmental Satellite (GOES-R) series will carry a GLM that will provide continuous day and night observations of lightning. The mission objectives for the GLM are to:

- **Provide continuous, full-disk lightning measurements for storm warning and nowcasting**,
- **Provide early warning of tornadic activity**, and
- **Accumulate a long-term database to track decadal changes of lightning**.

The GLM owes its heritage to the NASA Lightning Imaging Sensor (1997-present) and the Optical Transient Detector (1995-2000), which were developed for the Earth Observing System and have produced a combined 13 year data record of global lightning activity.

GOES-R Risk Reduction Team and Algorithm Working Group Lightning Applications Team have begun to develop the Level 2 algorithms and applications. The science data will consist of lightning "events", "groups", and "flashes" (see section 5. "GLM Product Definitions" for the definitions of events, groups, and flashes). The algorithm is being designed to be an efficient user of the computational resources. This may include parallelization of the code and the concept of sub-dividing the GLM FOV into regions to be processed in parallel.

Proxy total lightning data from the NASA Lightning Imaging Sensor on the Tropical Rainfall Measuring Mission (TRMM) satellite and regional test beds (e.g., Lightning Mapping Arrays in North Alabama, Oklahoma, Central Florida, and the Washington DC Metropolitan area) are being used to develop the pre-launch algorithms and applications, and also improve our knowledge of thunderstorm initiation and evolution.

2. Lightning Applications Team

- **Chair:** Steve Goodman (NESDIS/STAR)
- **Stakeholders:**
  OFCM Agencies
  - National Weather Service (NWS)
    - National Centers
    - Weather Forecast Offices
  - FAA
  - NASA
  - USDA
  - BLM
  - Energy
  - Department of Defense (DoD)
  - EPA
  - NSF-Universities
  - Commercial
  - (Details below)

Product Development Team:
- STAR/CICS
- CIMSS
- CIRA
- NASA MSFC
- UAH
- USRA
- Application Team Partners:
  - Aviation
  - Clouds
  - Hydrology
  - Air Quality
  - Land
  - Proxy

- **Support and Collaboration:**
  - AIT
  - Proxy Data
  - Calibration
  - Product Validation
  - Visualization

- **AWG Team Members:**
  - »William Koshak (NASA MSFC; POC and co-Manager, Flash Type Discrimination Algorithm)
  - »Richard Blakeslee (NASA MSFC; co-Manager, Science Reviewer)
  - »Walt Petersen (NASA MSFC; Lightning Jump Algorithm, QPE Algorithm)
  - »Douglas Mach (UAHuntsville; Lightning Cluster-Filter Algorithm, Code Developer)
  - »Brian Farnell (UAHuntsville; Code Developer)
  - »Robert Boldi (UAHuntsville; Cell Tracking Algorithm)
  - »Dennis Buechler (UAHuntsville; Lightning Warning Algorithm)
  - »Larry Carey (UAHuntsville; Photogrammetry Algorithm)
  - »Monte Bateman (USRA; Proxy Data)
  - »Bill McCaul (USRA; Lightning Proxy Data, Lightning Forecast Algorithm)
  - »*UAH GRAs: Chris Schultz (UAHuntsville; Lightning Jump Algorithm); Yuanming Suo (UAHuntsville ECE; Photogrammetry Algorithm)*
  - »*Leveraged Support: Richard Solakiewicz (Senior NASA Post Doc; Flash Type Discrimination Algorithm et al.)*
  - »*Donald MacGorman, William Beasley (OAR/NSSL,OU/CIMMS; Proxy Data)*
  - »*Henry Fuelberg, GRA - Scott Rudlosky (FSU/NGI; Lightning Forecast, Warning Algorithm)*
  - »*Eric Bruning (CICS Post-doc; Proxy Data, cal/val, User Readiness, Proving Ground Coordinator)*
  - »*Rachel Albrecht (CICS Post-doc; Blended Multi-sensor Algorithms)*

3. GLM Stakeholders

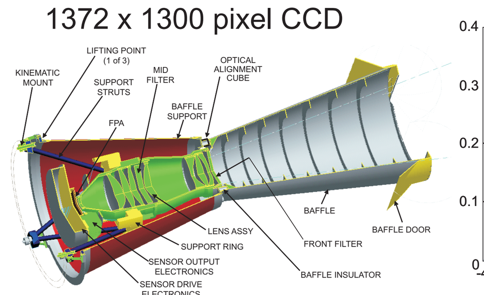
- **User Community**
  - National Weather Service
    - Weather Forecast Offices (WFOs)
    - National Centers for Environmental Prediction (AWC, SPC, EMC, TPC, NHC, HPC)
  - NESDIS Satellite Analysis Branch (SAB)
  - Department of Defense (DoD)
    - Air Force Weather Agency (AFWA)
    - Fleet Numerical Meteorology and Oceanography Center (FNMOC)
    - Joint Typhoon Warning Center (JTWC)
  - NASA
    - ESMD- space shuttle/Launch Commit Criteria
    - SMD- science
- **NOAA Mission Goal Supported**
  - **Weather and Water -** LFW: tornadoes, severe storms, flash floods, microbursts, lightning, nowcasting, data assimilation, QPE, QPF
  - **Climate -** thunderstorm and severe storm frequency/distribution and long term changes, El Nino
  - **Commerce and Transportation-**convective weather hazards en-route/terminal aviation, outdoor activities (e.g., construction) and recreation
  - **Ecosystems-**forest and rangeland fires

4. Hardware/Software (LMATC provided)

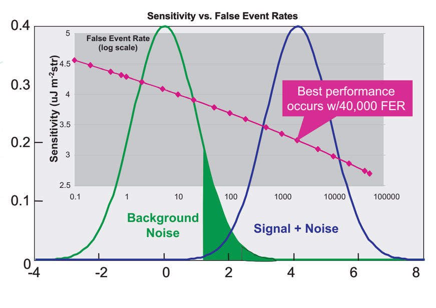
GOES-R GLM Mission Objectives

Provide continuous **Full-Disk** lightning measurements	Provide longer warnings of tornadic activity			Accumulate decadal lightning data
	False Alarm Probability <5%	Detection Probability >70%	Track lightning flash to storm cell; Calculate optical center over time	

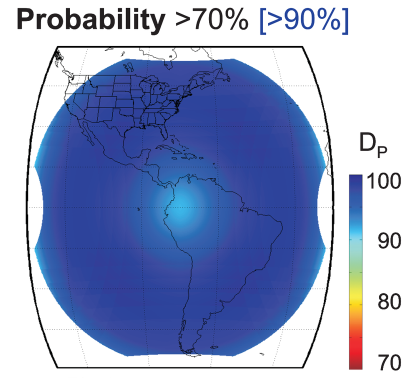
FOV = full-disk [16]
GSD = 8 km at nadir
1372 x 1300 pixel CCD



False Alarm Probability <5% [<3%]



Detection Probability >70% [>90%]

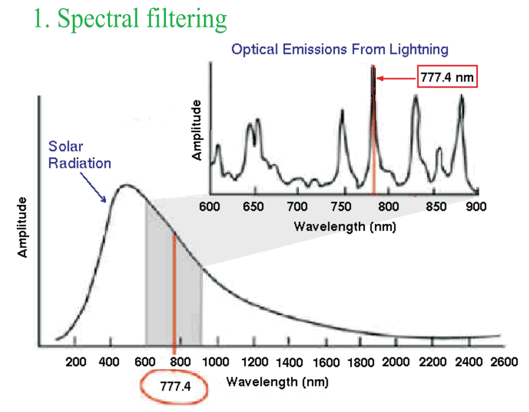


Robust performance through EOL with high sensitivity and detection probability results in longer warning of tornadic activity

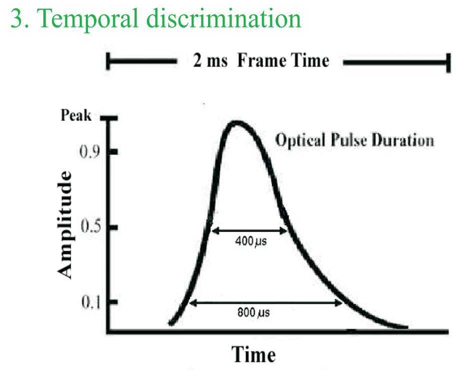
Black text = requirement
[Blue text] = capability

Key problem that OTD/LIS/GLM solves is the detection of dim lightning against a much brighter background during the day. Four techniques utilized:

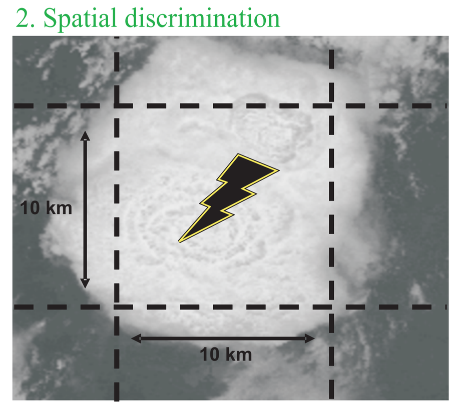
1. Spectral filtering



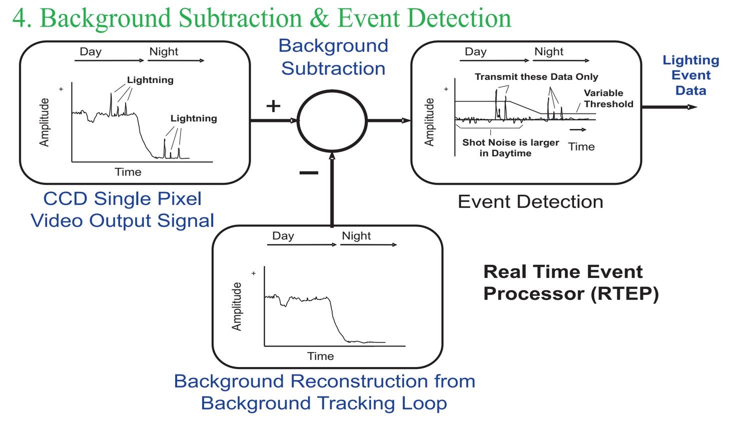
3. Temporal discrimination



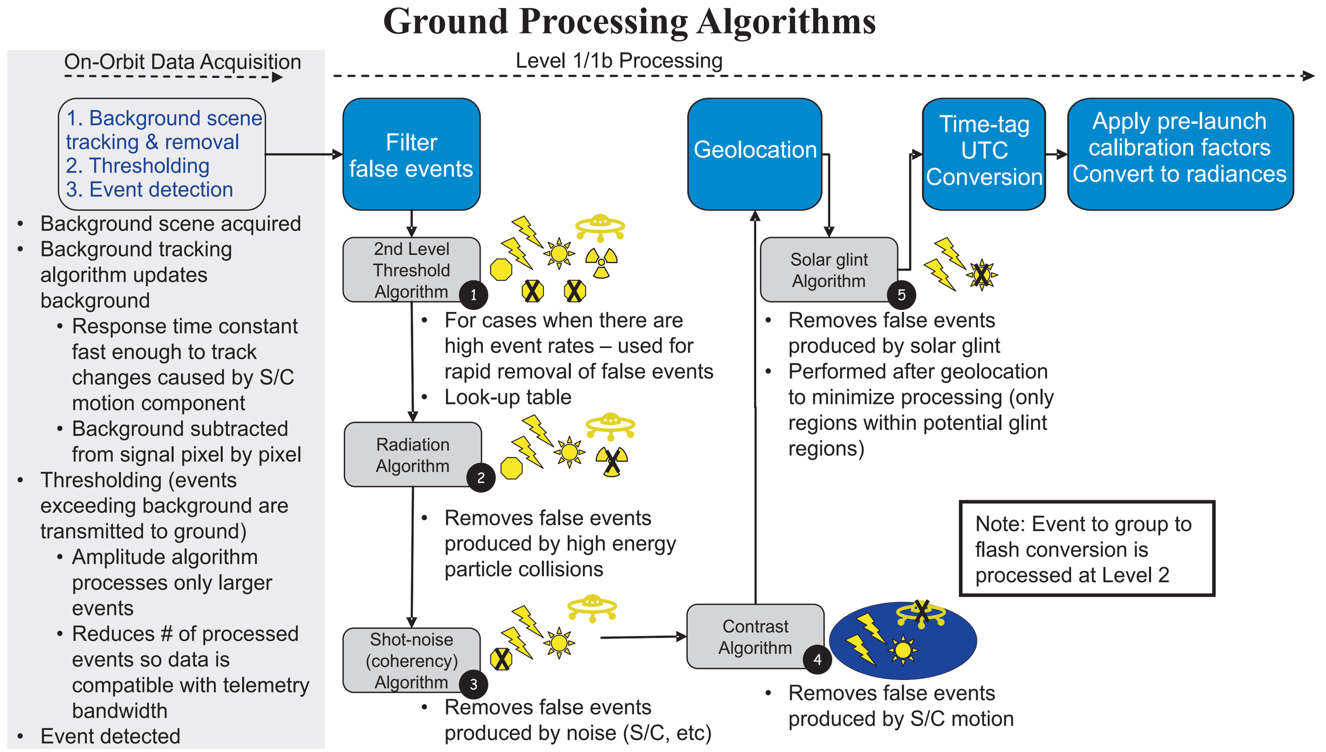
2. Spatial discrimination



4. Background Subtraction & Event Detection



Ground Processing Algorithms



Layered approach to false event removal results in high system performance

Courtesy LMATC

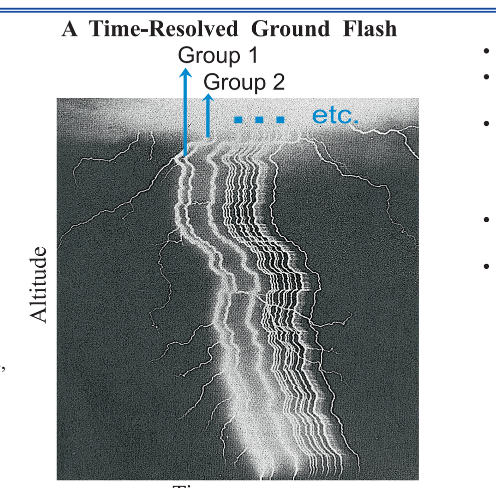
5. Product Definitions

Products: Events - Level 1B, Groups and Flashes - Level 2:
- Event = A single pixel illumination in one CCD time frame (~2 ms) and that breaks instrument threshold.
- Group = Multiple adjacent events that all occur at the same time.
- Flash = A cluster of groups; the groups must be within prescribed distance and time limits of each other (i.e., a connected sequence of groups occurring over one or more frames- initial criteria based on LIS uses within 16.5 km, 330 ms).
- Note that the group and flash temporal/spacial definitions may change

The GLM Lightning Cluster - Filter Algorithm initially will follow the same definitions applied with the heritage satellites (LIS, OTD):
- Flash Time = Time of the first detected lightning event in a flash.
- Flash Location = The optical radiance - weighted centroid of the flash. That is, one would use the radiance - weighted latitude (RWLAT) and the radiance weighted longitude (RWLONG) to characterize the "location" of a flash.
- Flash Footprint = Unique areal extent of the flash (measured in square kilometers). Note: some flashes, called "spider lightning" can extend hundreds of kilometers in the horizontal.

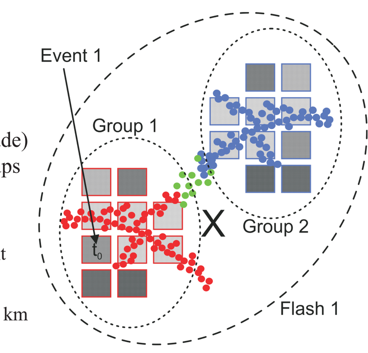
Level 2 Product Formats: netCDF4, McIDAS Areas

A Time-Resolved Ground Flash



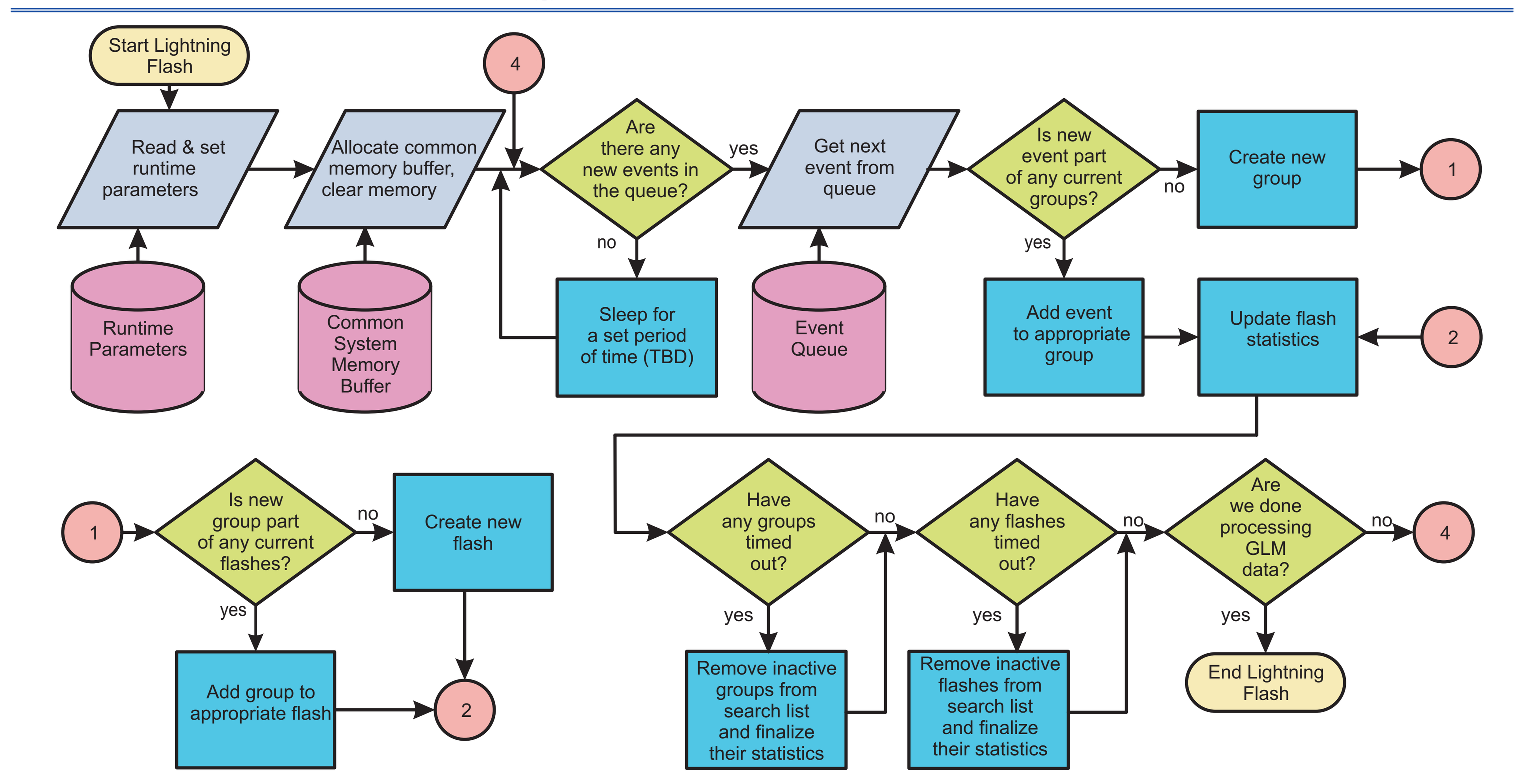
Groups Help Us Track the Strokes!

- Dots (red, green, blue) are LMA* data
- Gray squares are (simulated) GLM data
- Time is indicated by color
  - Red first
  - Green next
  - Blue last
- GLM radiance is indicated by greyscale (darker = greater amplitude)
- Shown is a single flash with 2 groups and 20 events
  - Amplitude weighted centroid is indicated by the large X
  - Time of flash is time of first event
  - The two groups (red & blue) are close enough in time/space to be clustered into a single flash (16.5 km & 333 ms)
  - In this example, the green LMA pulses did not create an optical signal large enough to be detected by the (simulated) GLM



* LMA: VHF Lightning Mapping Array (GLM Proxy Data source)

6. High Level Flowchart



7. GLM Clustering Example

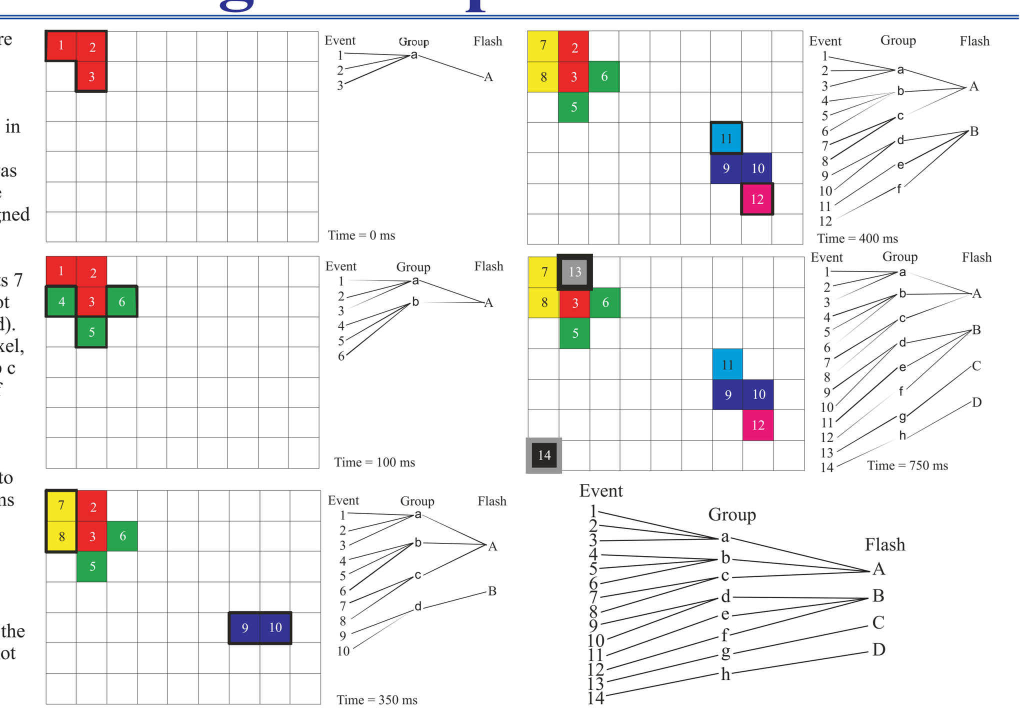
(Time = 0 ms) At the first time frame, three simulated events (designated 1, 2, and 3) occurred. They are collected into a single group (designated a) because the events were simultaneous and registered in adjacent (i.e., neighboring or diagonal) pixels. The group was assigned a new parent flash (designated A).

(Time = 100 ms) At the next frame with data, there were three more events (designated 4, 5, and 6). As in the previous case, these three new events were all assigned to a new group (called b). These events were not assigned to group a because they occurred at a different time. The time difference between groups a and b was 100 ms, and the minimum ground distance between these groups was 8 km (calculated from the center of the two nearest events from each group). This distance between a and b is small enough to have them both assigned to the same flash. As a result, group b was assigned to the first flash A.

(Time = 350 ms) At the next frame with data, four more events (labeled 7, 8, 9, and 10) occured. Events 7 and 8 were adjacent to each other and were assigned to a new group (designated c). Events 9 and 10 were not adjacent to events 7 and 8, but are adjacent to each other. They were assigned to another new group (called d). The time difference between group b and group c was 250 ms, and because events 4 and 8 share the same pixel, the minimum ground distance between these groups was 0 km. This distance is small enough to assign group c to flash A. Although group d also occurred within 250 ms of group c in flash A, its distance from any part of group c was approximately 40 km. As a result, group d was assigned to a new flash (designated B).

(Time = 400 ms) The next integration time with data is 50 ms after the last events. Two more events (labeled 11 and 12) occurred at this time. These two events were at the same time, but they are not adjacent to each other; they were assigned to two new groups (called e and f). The two new groups were less than 330 ms from the time of the last group of flash B and were within 16.5 km of flash B; thus, the two groups were assigned to flash B.

(Time = 750 ms) The last frame with events is 300 ms after the last events. There were two new events (designated 13 and 14) at this time. The events were not adjacent and they are assigned to two new groups (called g and h). Group g overlapped the parts of flash A; however, it has now been more than 330 ms since the last group associated with flash A. Therefore, group g was assigned to a new flash (labeled C). Group h is not within 16.5 km of any current flash; it is assigned another new flash (called D).

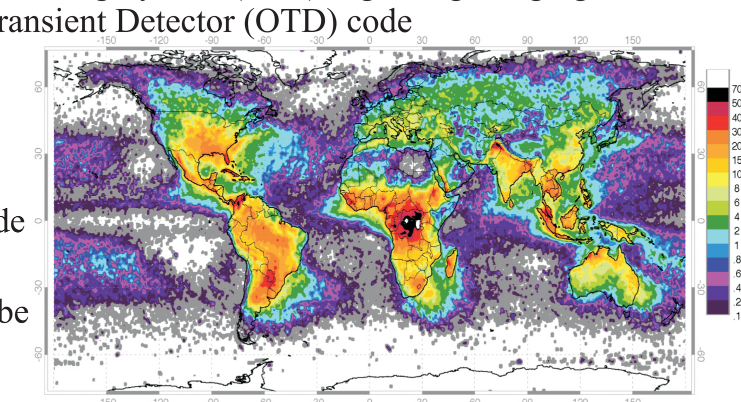


8. Code Optimization

1. Parallelization
   - Many of the subroutines are candidates for parallel processing
   - This allows for simple parallelization of the GLM code
     - To take advantage of modern computer architecture (e.g., multi-core processors and/or multi-threaded operating systems)
   - The tasks do not *require* parallelization, but are designed to accommodate it
   - Need to weigh the advantages of parallel processing against the extra code/memory overhead needed
2. Regionalizing GLM Code
   - Lightning in different sections of the GLM FOV are independent of each other
   - This allows for dividing the GLM FOV into flexible sub-regions for multiple processor assignment
   - Need to weigh the advantages of regionalization against the extra code/memory overhead needed

9. Algorithm Heritage: LIS/OTD

- NASA Earth Observing System (EOS) Lightning Imaging Sensor (LIS)/Optical Transient Detector (OTD) code
- V4 algorithm
- 6.5 x 10^8 events
- ~60000 SLOC
- Much of the code can be reused
- GLM data will be very similar to LIS/OTD data



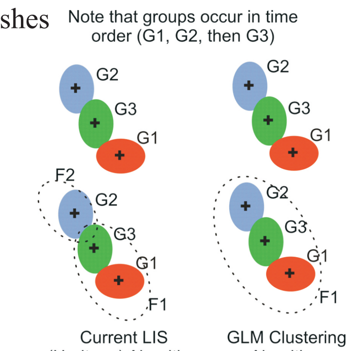
- http://thunder.msfc.nasa.gov/bookshelf/pubs/atbd-lis-2000.pdf

…We know what to expect…

10. Modifications to Heritage Code

1. Replace "first fit" with "full fit" clustering
   - Current LIS/OTD algorithm uses "first fit" to add new groups to flashes
     - Group is assigned to the first flash within range in the buffer
     - Does not check for more than one flash within range
   - GLM algorithm will use "full fit"
     - Group is assigned to ALL overlapping flashes in buffer
     - If the group can be assigned to more than one flash, all flashes it can be assigned to will be merged

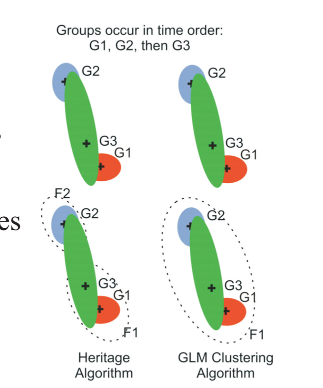
Note that groups occur in time order (G1, G2, then G3)



Current LIS (Heritage) Algorithm — GLM Clustering Algorithm

2. Replace clustering by centroids with clustering by total footprint
   - Current LIS/OTD algorithm uses centroids to cluster groups/flashes
   - GLM algorithm will use event footprints to cluster groups/flashes
     - Will prevent long/large groups from separating into multiple flashes
     - Create more accurate flashes
3. Remove LIS/OTD specific filters
4. Remove EOS specific code (PGS Toolkit, etc.)

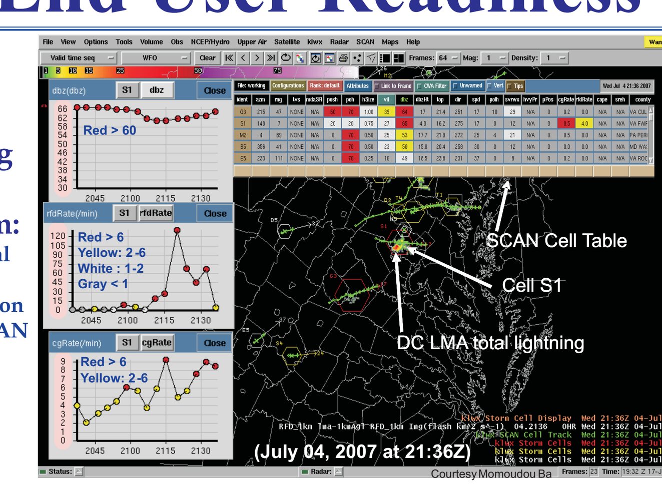
Groups occur in time order: G1, G2, then G3



Heritage Algorithm — GLM Clustering Algorithm

11. GOES-R Proving Ground and End User Readiness for GLM

Lightning Jump Algorithm: Experimental Trending Implementation in AWIPS/SCAN

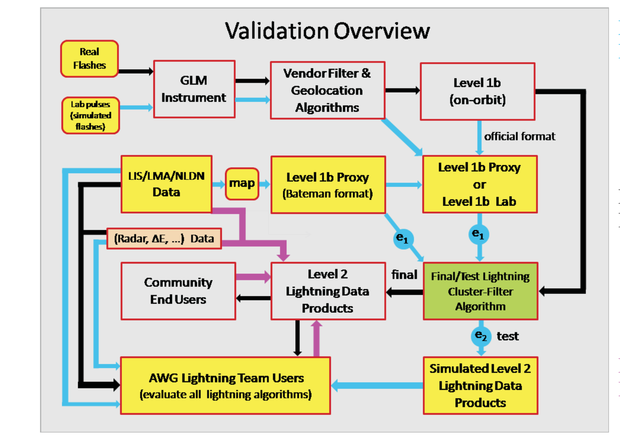


Courtesy Momoudou Ba

- Forecaster/AWIPS focused, to prepare for day-1 use of GLM end products
- Real-world experience by leveraging GLM proxy data to prepare for the GOES-R era.
- Product tailoring for NOAA Operations (group/flash density, flash rate trending)
- Coordination with the NWS WFOs and National Centers (SPC, AWC).

12. Testing and Validation

- Testing and Validation of the GLM Flash Detection Algorithm will consist of several major parts:
  - Testing of clustering code
  - Tuning of whole algorithm to best utilize computer cycles
  - Testing of alternative/fall back algorithms
- The idea of "testing" the code is really attempting to break it (find its limits)
- GLM clustering algorithm will be the LIS/OTD event/group/flash clustering algorithm (with enhancements)
- We already know the current clustering algorithm works, and works well (somewhat bullet-proof) [Mach D. M., H. J. Christian, R. J. Blakeslee, D. J. Boccipio, S. J. Goodman, W. L. Boeck, Performance assessment of the Optical Transient Detector and Lightning Imaging Sensor, *J. Geophys. Res.*, **112**, D09210, DOI:10.1029/2006JD007787, 2007.]
- Testing/Validation will concentrate on the new aspects of the algorithm (full clustering & total footprint) with a secondary emphasis on making sure the current algorithm will scale (with/without regionalization/fallback/parallelization) to the GLM footprint
- Also, testing code to determine tuning parameters of clustering code
- Validation is more of making sure the algorithm does what we think it should be doing (making sure what we *told* it to do is what we *want* it to do)



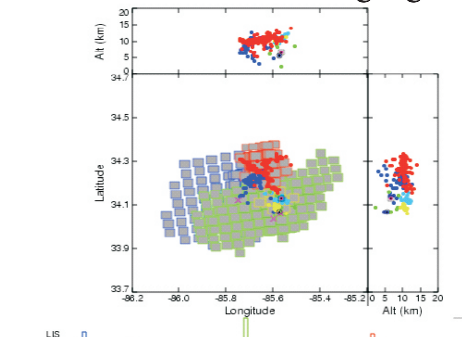
Pre-launch Algorithm Evaluation Phase: Cyan Arrows

Post-Launch Algorithm Evaluation Phase: Black Arrows

Post-Launch Level 2 Data Product Evaluation Phase: Magenta Arrows

GLM Proxy Data

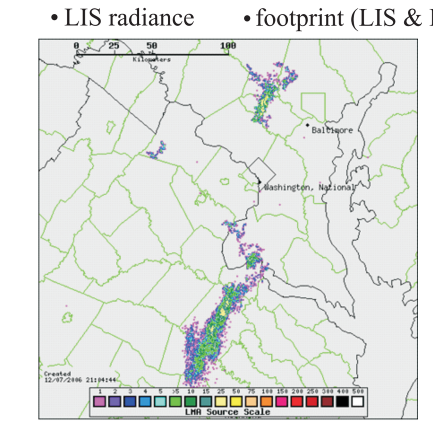
- First Proxy Dataset based on National Lightning Detection Network (NLDN) data to test regionalization
- Subsequent Proxy Datasets based on NLDN + LIS + LMA data to test clustering algorithm



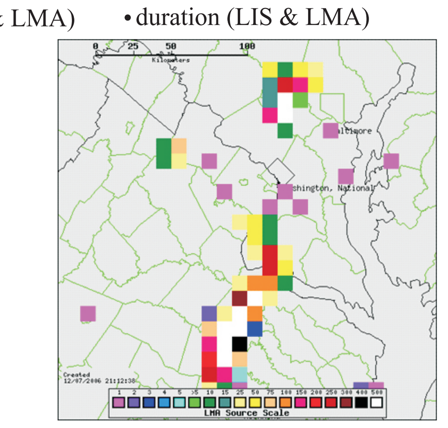
Example GLM proxy data development:LIS (squares), LMA (dots), and NLDN (Xs) Note that lightning is a very "burst -like" product (lots of data over short periods of time followed/preceded by almost no data)

*NLDN: National Lightning Detection Network, ground strikes only

- Other Proxy Datasets designed to "break" algorithm
- Also designed to help tune the various parameters of the clustering code
- Database compiled that contains all LIS overpasses of North Alabama LMA (2002-2007)
- Using a flash algorithm, LMA sources -> flashes
- These are compared with LIS flashes
- The algorithm also tries to assign a type (IC,CG), polarity, and # strokes
- NLDN data are also included
- From these, we are working to partition the dataset by flash type, and compute statistics (by flash type) for:
  - LIS radiance
  - footprint (LIS & LMA)
  - duration (LIS & LMA)



LMA 1 km resolution



LMA @ GLM 10 km resolution

- These should be all that we need to create a realistic, varied, and challenging proxy data set.

Conclusion

The GLM offers a new capability to observe total lightning day and night and with near uniform coverage of the US and adjacent oceans to improve NOAA's ability to issue forecasts and warnings that will save lives.