GLM – Level 1b Processing Algorithms

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What is a Lightning Flash? (cont.)

- No modern instrument measures a "lightning flash"
  - GLM and LI detect lightning strokes (~ groups)
  - LMA detects meter long sparks
- This makes GLM / LI validation and verification in terms of a "lightning flash" problematic
- Systems such as the HAMMA and FEGS also detect strokes and should be used as the definitive systems for evaluating GLM / LI performance

What is a Lightning Flash?

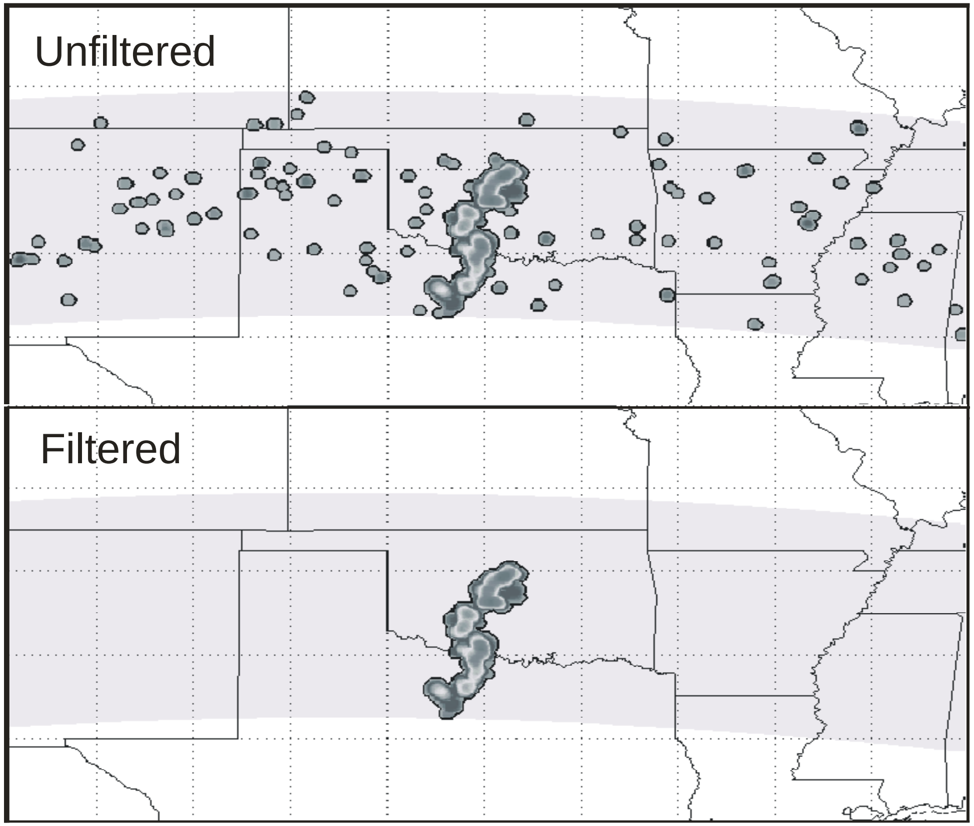
- It is not a specific physical process
  - unlike corona or steamers or leaders or strokes
- It is an ensemble of the above electrical discharges assembled in a ill defined manner with various summations over time and space
- It is an archaic term left over from observing lightning with the human eye and film cameras

What is a Lightning Flash?

- It can be argued that GLM / LI performance should be based on stroke detection ability, not flash detection
  - The severe weather lightning jump algorithms might be improved using stroke detection
  - Storm intensification is inferred by increases in the flash rate but the energy dissipated by flashes varies dramatically
    - Combining stroke detection with optical energy may provide a better indicator of the total energy generated
- Ultimately, the goal should be to determine the best approach for estimating the storm’s energy generation

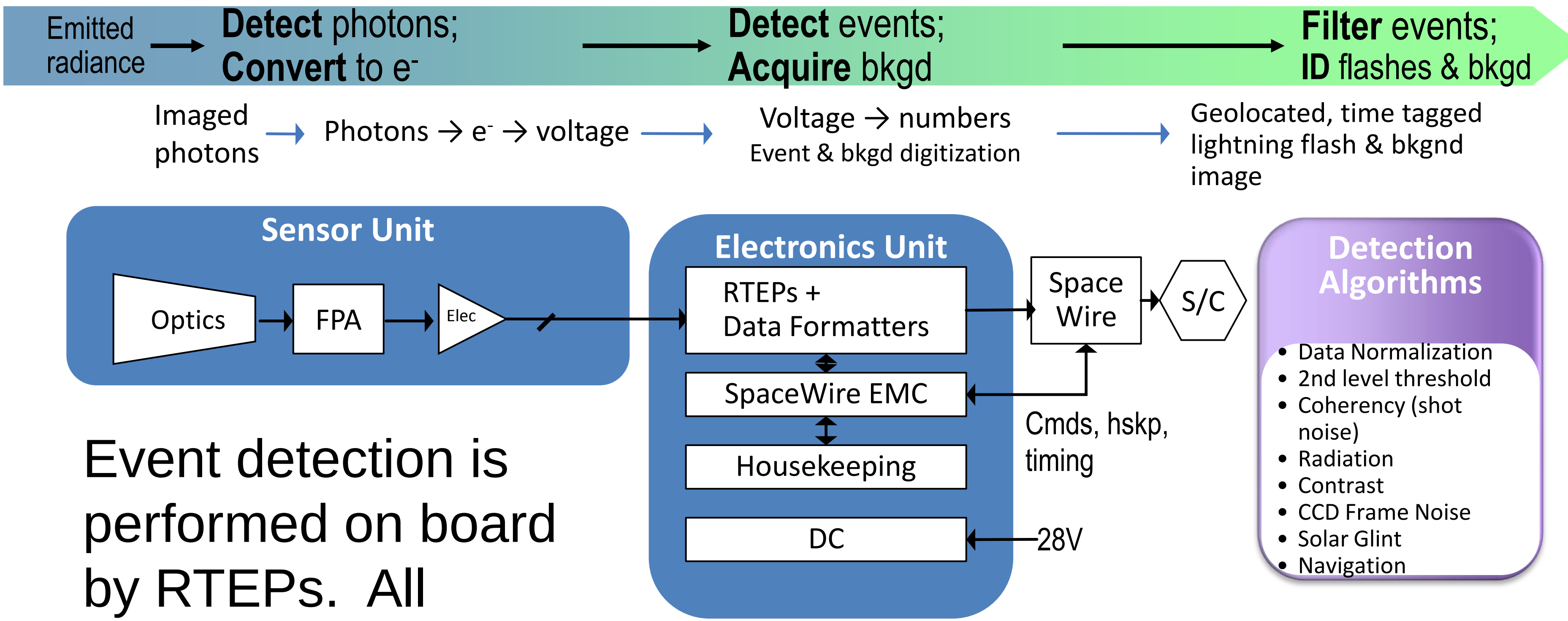
Lightning Detection and False Alarms

- To maintain high detection efficiency, GLM has high sensitivity and sends ***all*** events to the ground, including false events
- False Alarm Probability Requirement flows directly to the detection algorithms
- False events are removed during ground processing to maintain a false alarm rate << 5%
- Unfiltered data show many false events (non-lightning)
    - Some are due to energetic radiation
    - These events cannot be removed by amplitude thresholding alone - some are quite intense
- After filtering, lightning-only data shows coherency



GLM performance is optimized by making the detection thresholds as low as possible which results in many false events. The role of on-orbit processing is to detect as many lightning events as possible while maintaining compatibility between the total event rate and the telemetry bandwidth. The role of ground processing is to essentially remove all the false events while processing all the lightning events.

Ground Processing Algorithms Overview



Event detection is performed on board by RTEPs. All events, including false events are sent to the ground for processing.

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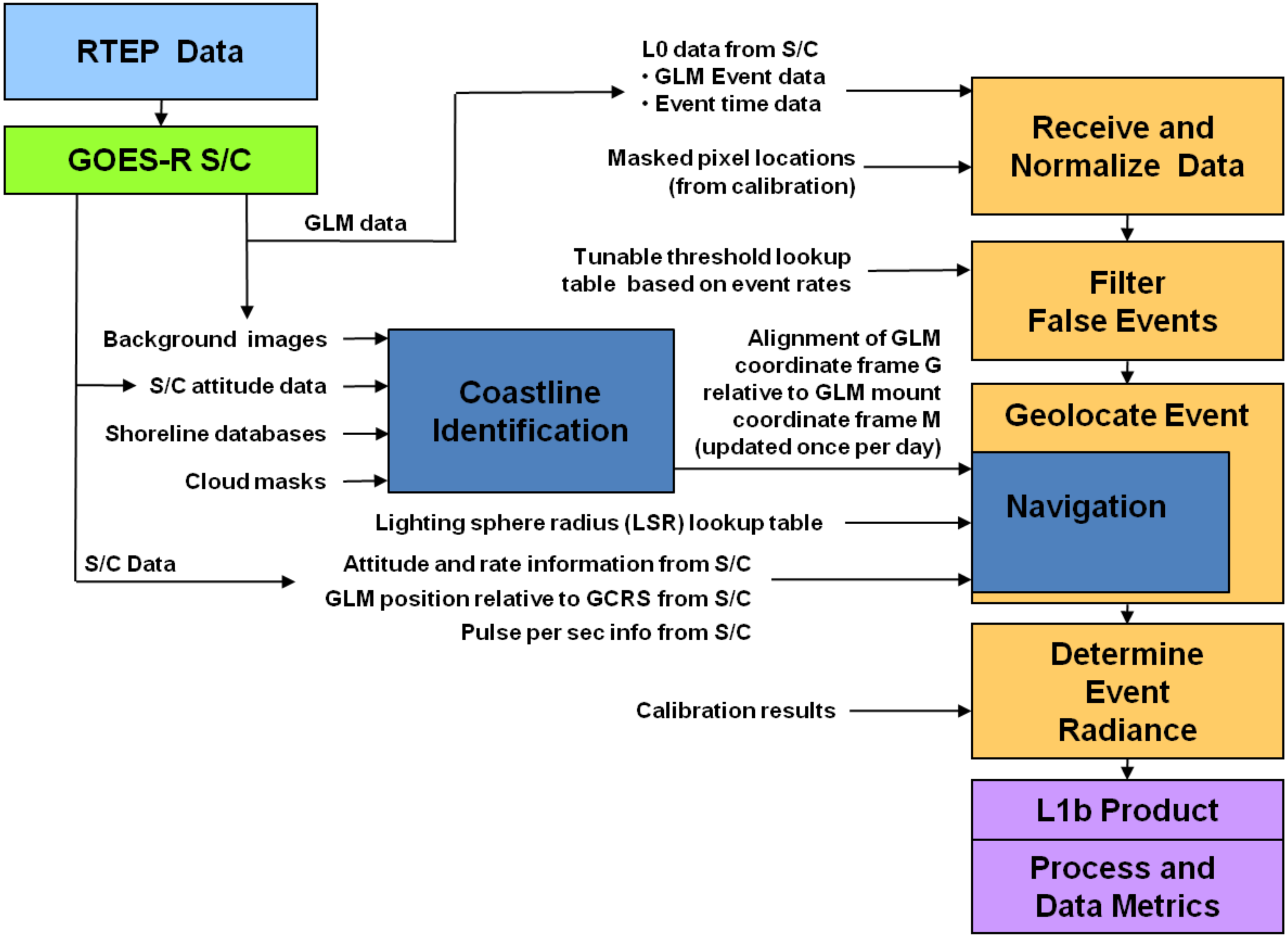
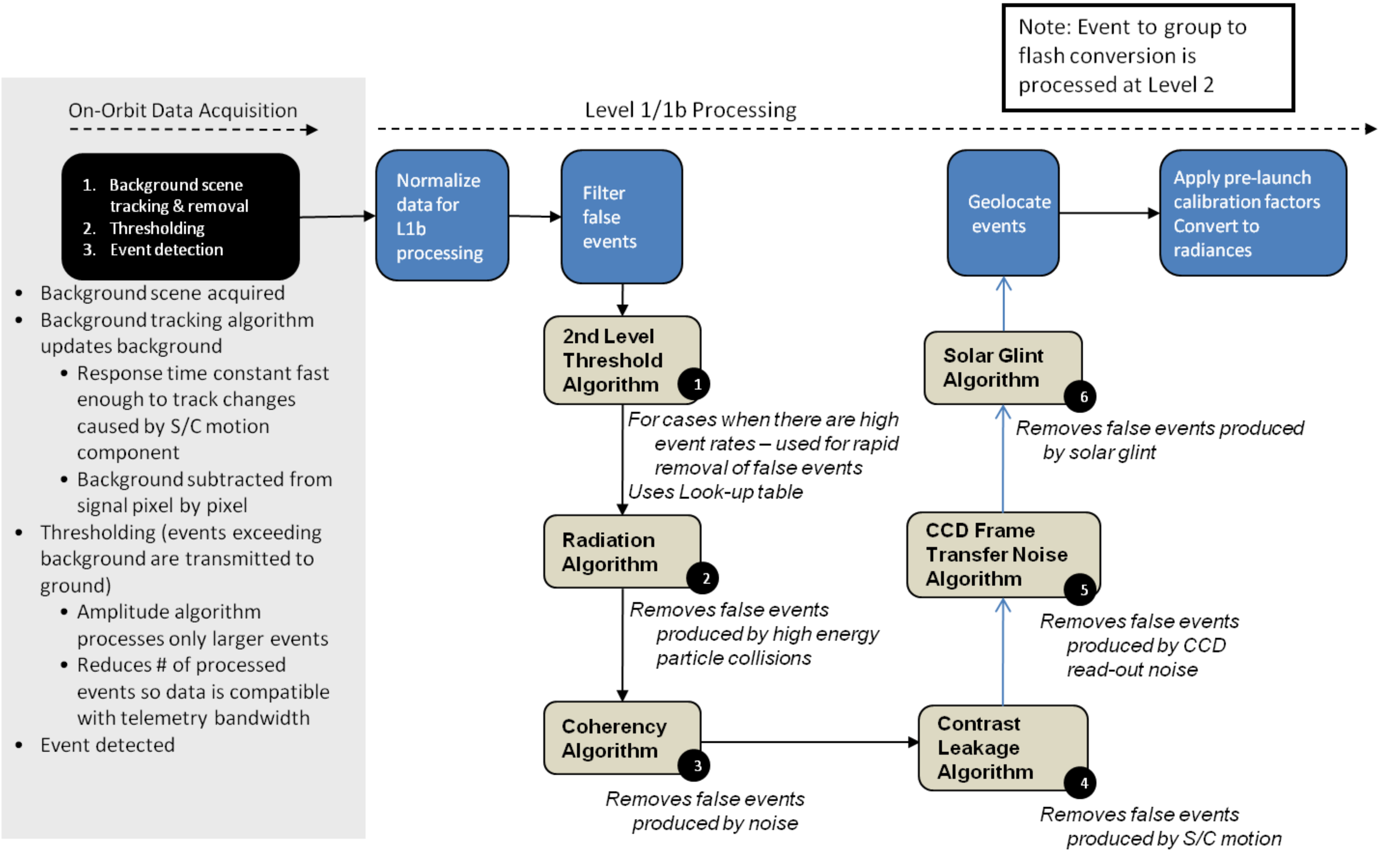
False events are filtered on the ground using level 1b detection algorithms. Detection algorithms allow high detection probability and low false alarm probability

GLM GPA Functions and Interfaces



Ground Processing Algorithm Block Diagram



False Alarm Rate Budget

Event Type	Expected number of false events (per second)	Expected number of events after filters applied (per second)	Requirement
Photon and Electronics Noise	> 600	< 0.05	N/A
Radiation	< 16	< 0.01	N/A
S/C motion (Jitter)	< 800	< 0.06	N/A
Solar Glint	< 1	< 0.01	N/A
Total	~ 1411	< 0.13	< 1 per second
False Alarm Rate		< 1%	5 %

False alarm rate calculation assumes a lightning flash rate averaged over 24 hours of 18 flashes per second.

False alarm rate calculation assumes that every false event that is incorrectly identified as a real event will become a lightning flash in L2 processing.

(Note: RTEP and L1b algorithms provide adjustments enabling user tuning of both false event rates and false alarm rates)

Estimated GLM Shot Noise Generated False Events

- Based on anticipated GLM Performance:

Energy Density	Energy (J)	# of electrons	Background	FE(805)	FE(500)	DE
4.7	300	6,340	801,000	64	0.33	90%
5	320	6750	801,000	9.9	0.026	88%
6	384	8,100	801,000	0.009	1.4E-10	85%
7	448	9,450	801,000	2.5E-6	2.5E-11	80%
8	512	10,800	801,000	2E-10	6.7E-17	75%

False event rates are very low when thresholds are set to nominal performance levels

Data Latency Budget

GLMPORD96 [ver. 2.2] → GLMSS90 Data Latency
The GLM shall contribute no more than 10 seconds to the total data latency from event detection through generation of Level 1b products.

Document		Req. ID	Allocated To:	Requirement (sec)	Comment
GLM00244, Rev. -	GLMSS	GLMSS90			
GLM00606, Rev. -	GLM SU Spec	GLMSU633	CCD & ADC	< 0.004	500 Hz Readout
GLM00554, Rev. -	GLM EU Spec	GLMEU982	Ser/Des	< 0.001	Transfer SU to EU
GLM00554, Rev. -	GLM EU Spec	GLMEU415	RTEP	≤ 0.25	Calculate background, extract events
GLM00554, Rev. -	GLM EU Spec	GLMEU812	Data Formatter	≤ 0.25	Take data from 4 RTEPs, send to SpaceWire
GLM00435, Rev. A	GLM SW Spec	SRS235	SW/CCSDS & GRDDP	≤ 0.25	Round-Robin extract of 14 FIFOs, reformatting into CCSDS/GRDDP packets
GLM00701, Rev. -	GLM NF Spec	GLMNF10	Ground Processing Algorithms	< 9.00	
			Total Allocated	9.755	
			Total	10.00	
			System Level Margin	0.245	

Ground Processing Algorithm Required Inputs

Data Required	Use	Location of Data	Frequency
GLM L0 Event & Time data	Event Filters	Provided to Ground Segment by Spacecraft	Each event
Calibration Table (Event)	Event Filters	Provided to Ground Segment by GLM prior to launch	Not updated
Gain Table	Event Filters	Provided to Ground Segment by GLM prior to launch	Not updated
Various lookup tables (see next chart)	Both	Provided to Ground Segment by GLM prior to launch	As required
RTEP settings	Event Filters	Provided to Ground Segment by GLM prior to launch	As required
GLM L0 Background data	INR	Provided to Ground Segment by Spacecraft	Every 2.5 min
Spacecraft Data (PPS, position, attitude, rate)	INR	Provided to Ground Segment by Spacecraft	1 Hz or 100Hz
Cloud Masks	INR	Provided to Ground Segment	Every 2.5 min
Shoreline Databases	INR	WVS and GSHHS databases	Not updated

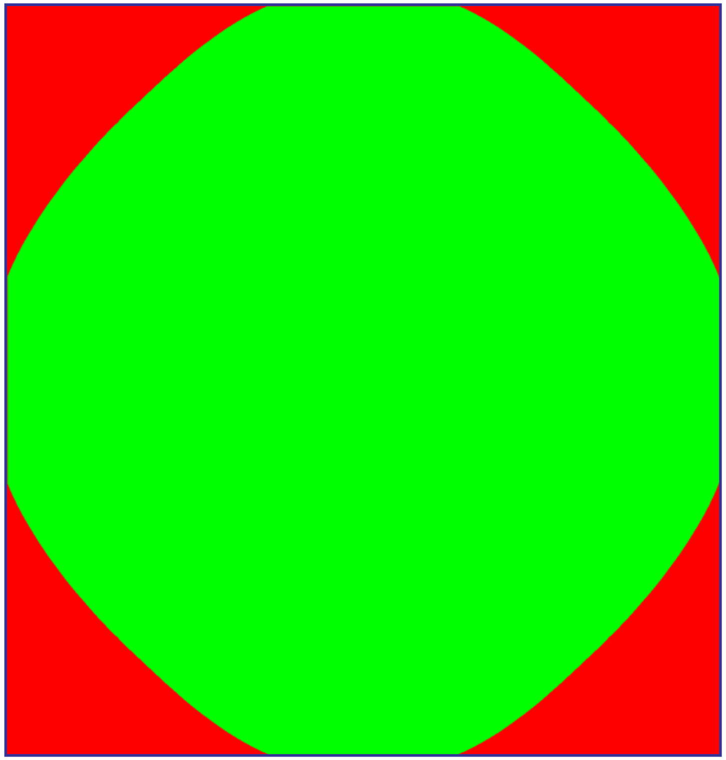
GLM GPA Lookup tables

Look Up Tables Provided By GLM at Flight Unit Delivery	Use
Masked pixel region	Event Filters
2^{nd} level threshold tables	Event Filters
Look up tables for coherency filter	Event Filters
Contrast leakage filter parameters	Event Filters
Solar glint (specular reflection) rejection region size	Event Filters
Lens Distortion and Calibration Factors	INR
Lightning Sphere Look Up Table	INR

Look Up Table Updated By Algorithms
Active region lookup table

- Lookup tables and stored parameters are used during L1B processing in order to reduce latency time.
- The values for these parameters are based on results from calibration and performance testing and may be modified on orbit

CCD Masked Pixel Filter Algorithm



1300 x 1372 CCD (masked pixel region in red)

Removed events will be used to determine the flux and energy distribution of high energy radiation particles

Events with pixel locations in the masked region of the CCD will be rejected during event data normalization. A lookup table will be utilized for this purpose. The masked pixel locations will be determined during instrument calibration. These masked pixel locations will be used to construct the masked region lookup table.

False event Removal Filters

In order of application, these filters are:

- 2nd level threshold algorithm
  - Pixel by pixel threshold optimization
- CCD frame transfer noise algorithm
  - Remove FEs caused by strong lightning occurring during frame transfer periods
- Radiation algorithm
  - Remove FEs caused by low angle of incidence high energy particles
- Coherency algorithm
  - Remove statistically random FEs
- Contrast leakage algorithm
  - Remove FEs caused by sharp cloud boundaries and S/C jitter
- Solar glint algorithm
  - Remove FEs produced by specular reflection of the sun off water (solar glint)

(After all false events are removed, the lightning events are geolocated and the amplitudes are converted to radiance values using the prelaunch calibration.)

Overview of Second Level Threshold

This filter's primary purpose is to remove excess events associated with "hot" pixels

During periods of special operations or very high event rates, a 2nd level threshold function can also be utilized.

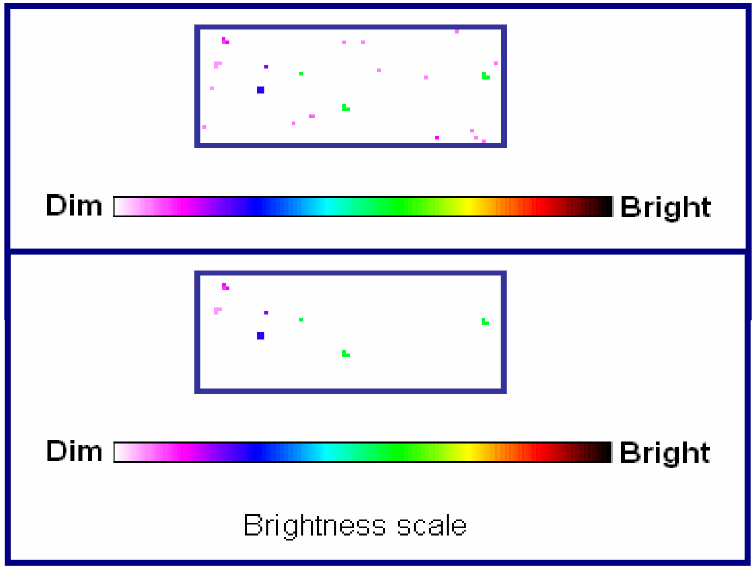
• The filter thresholds will allow for pixel specific low amplitude event rejection.

• A tunable threshold lookup table will be used for this purpose.

 • The event pixel x-y location will be used as the index to the threshold for the event.

 • The lookup table will be created or updated by specifying pixel x-y locations and the threshold value.

 • Initial values were established during instrument calibration and will updated during instrument on-orbit check out.



LIS events after 2nd level filter algorithm

•A frame of data from the LIS instrument with high events rates is shown in the top figure. This frame has many low amplitude single pixel event detections.

•The bottom figure shows the remaining pixels after amplitude thresholding

Performance of Second Level Threshold

- Second level threshold compensates for any anomalous pixels (~ 5 hot pixels on FM1)and is not expected to remove any false events under normal operations.

  False events from hot pixels varies as a function of the background – the filter compensates for this variation

Overview of CCD Frame Transfer Noise

- When a very bright optical lightning pulse occurs during the CCD readout phase, portions of the light appears to be deposited in trailing pixels forming the handle of a "lollypop".

- These are lightning produced events that are mis-located. They are easily corrected because of their spatial characteristics.

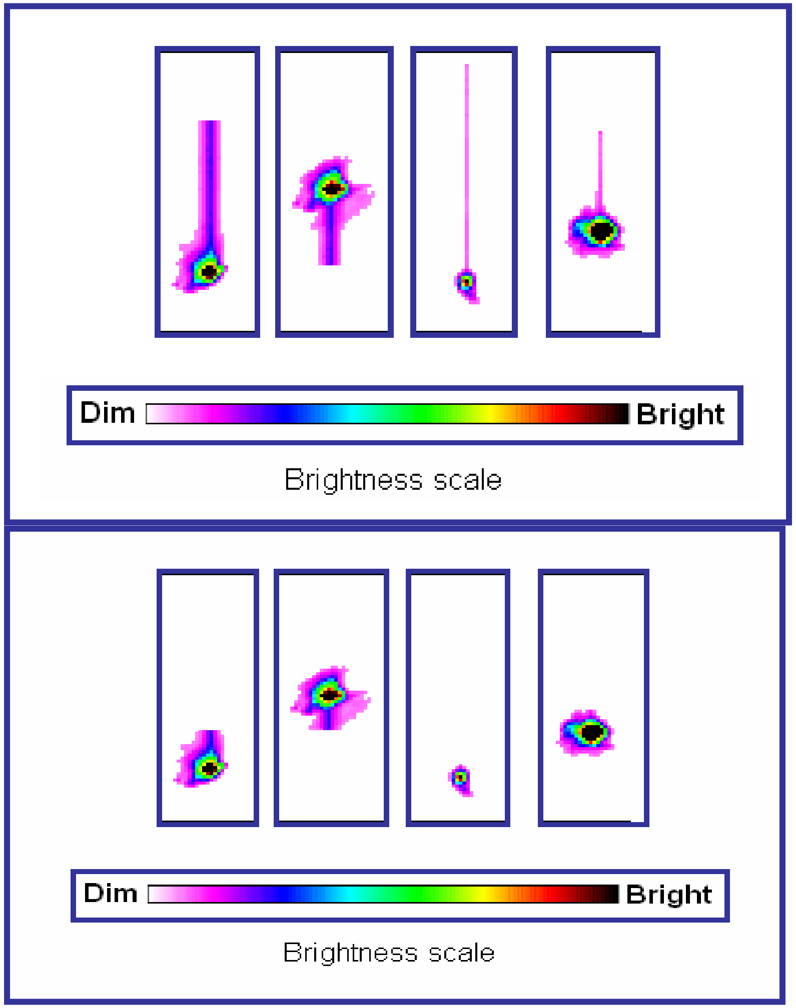


Figure LIS event cluster after readout FEs removal

Performance of CCD Frame Noise Filter

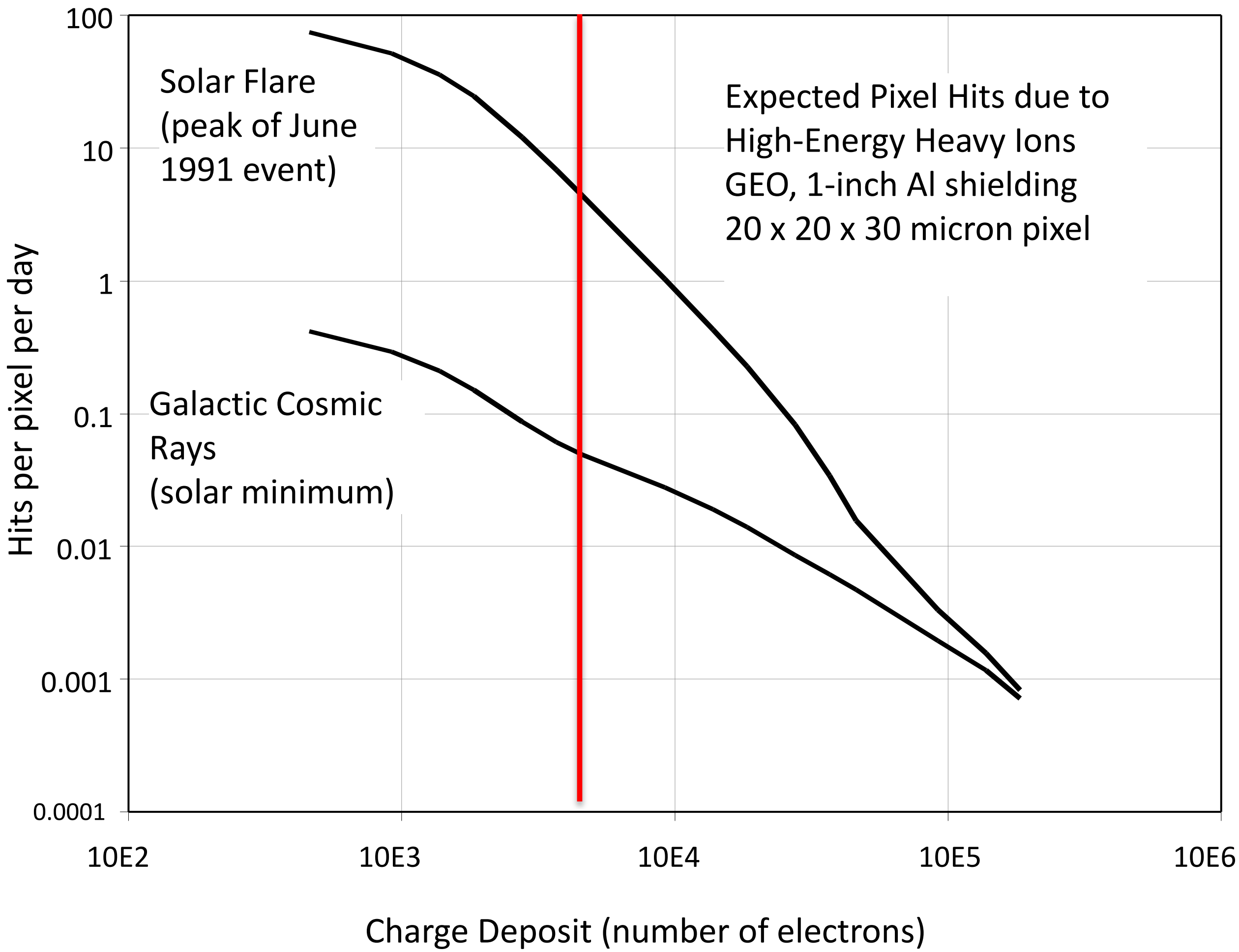
- With the rapid horizontal clocking rate of the GLM CCD (5MHz), lollypop effects are expected to be rare.
  - Maximum dwell on a pixel during clocking is 0.2 usec or 1/10000 of an integration period. If a 500,000 electron lightning event (100*minimum) occurs during clocking, only 50 electrons (100^{th} minimum) will be accumulated in the tail.
- The lollypop tail is easily identifiable. 100% removal is expected.

Overview of Radiation Filter Algorithm

When high energy ions strike the CCD or the background memory large false events will often be produced

- High energy particle impacts can produce large numbers of electrons – difficult to remove via amplitude thresholding
- Effect is the same for any silicon based focal plane (CCD, CMOS, etc)
- Events produced by high incident angle hits are removed via radiation track filter (streaks)
- Events produced by low angle of incidence hits (single pixel or single group) are removed using coherency (same as for shot noise)
- Hits on background memory can cause upset errors in the background estimate resulting in false events in successive frames until background tracking is reestablished
    - Characterized by decreasing event amplitudes in successive frames

Pixel Hit Rate from High Energy Ions



The GLM CCD will have at least 2 inches of shielding, thus reducing the hit rate to <5 hit per pixel per day

Expected Performance of Radiation Track Filter Algorithm

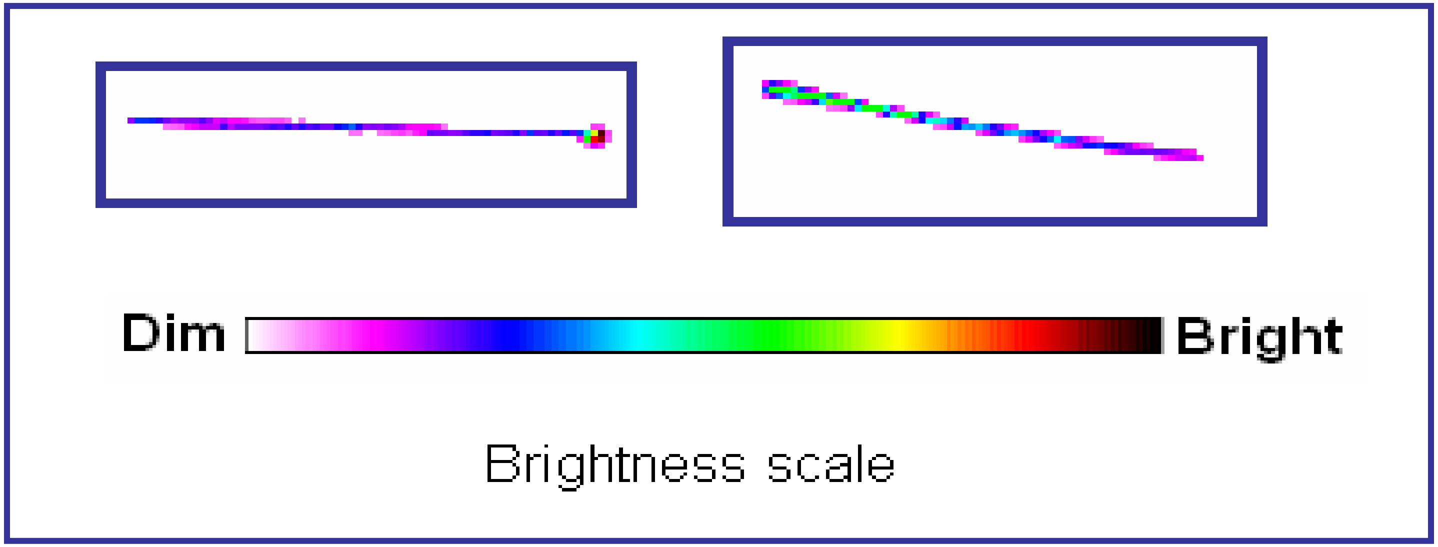


Figure Particle tracks

- Because of the excellent overall CCD shielding, the total number of radiation particle hit is expected to be < 5/pixel/day
- Less than 20% of the hits will produce streaks of 3 pixels or more, for a total of less than 10 streaks per second
- Streaks produce a unique signature – 100% removal efficiency is expected
- Radiation events that do not produce a track of 3 pixels or more are removed by the coherency filter.

Overview of Coherency

- The Coherency Filter removes false events caused by shot noise and radiation. Noise-produced false events are characterized by low amplitudes and random occurrences in time and location, whereas lightning events are characterized by high coherency in time and space (multiple pixels are illuminated in a single frame and the same pixels continue to be illuminated over the duration of the lightning flash).
  - Shot noise is characterized by a Gaussian distribution
  - Thresholding is used to control the false event rate – the higher the threshold (the larger the event amplitude), the lower the event rate
  - With the assumption of a Gaussian distribution, statistical techniques can be used to calculate false event rates for a given background intensity and threshold setting
  - Statistics are also used to calculate the probability that a given event is false and the probability that successive events are false.

- When successive events occur at the same or adjacent pixel locations but exceed a statistically derived programmable time interval the first event is rejected and removed from the processing queue.
  - The length of the time interval is dynamic and is a function of the event amplitude and background intensity of both events.

- An “active region” table is used to determine the events spatial and temporal compliance

Look Up Tables for Coherency Filter Algorithm

In order to minimize data processing latency and provide computational efficiency

- Look Up tables are used to determine the probability that an event is false
- GLM Radiometric Calibration parameters are used to generate these look up tables
- The current assumed GLM Radiometric parameters are shown in the next chart.

GLM Radiometric Parameters

	Constants	
R	**3.56×10^7 m**	**sensor altitude**
Ib	**375 Wm^{-2} sr^{-1} um^{-1}**	**background radiance at 777.4 nm**
h	**6.63×10^{-34} Js**	**Planck's constant**
C	**3.00×10^8 ms^{-1}**	**speed of light in vacuum**
	Variables	
As	**6.4 x 10^7 m^2**	**lightning illuminated source area (nom)**
Ab	**6.4 x 10^7 m^2**	**background area imaged by a single pixel**
D	**0.11 m**	**lens aperture**
Q	**0.9**	**FPA quantum efficiency (measured performance on LMS)**
Fill factor	**100%**	**CCD fill factor**
K	**0.8s**	**optical system transmission**
Kf(θ)	**Variable**	**filter transmittance as function of look angle (θ)**
λ	**777.6 nm**	**center wavelength of spectral filter**
$\Delta\lambda$	**1 nm**	**filter bandwidth (narrow band interference)**
Es	**4.7×10^{-6} J m^{-2} sr^{-1}**	**lightning radiant energy at 777.4 nm for 90% DE**
τ	**2×10^{-3} s**	**frame integration time**
α	**0.8**	**cloud albedo (used in radiometric equations to ensure performance margin)**
αg	**0.6**	**percent global cloud cover**
r	**30 μm**	**pixel size**

Probability of False Events and Lightning Detection

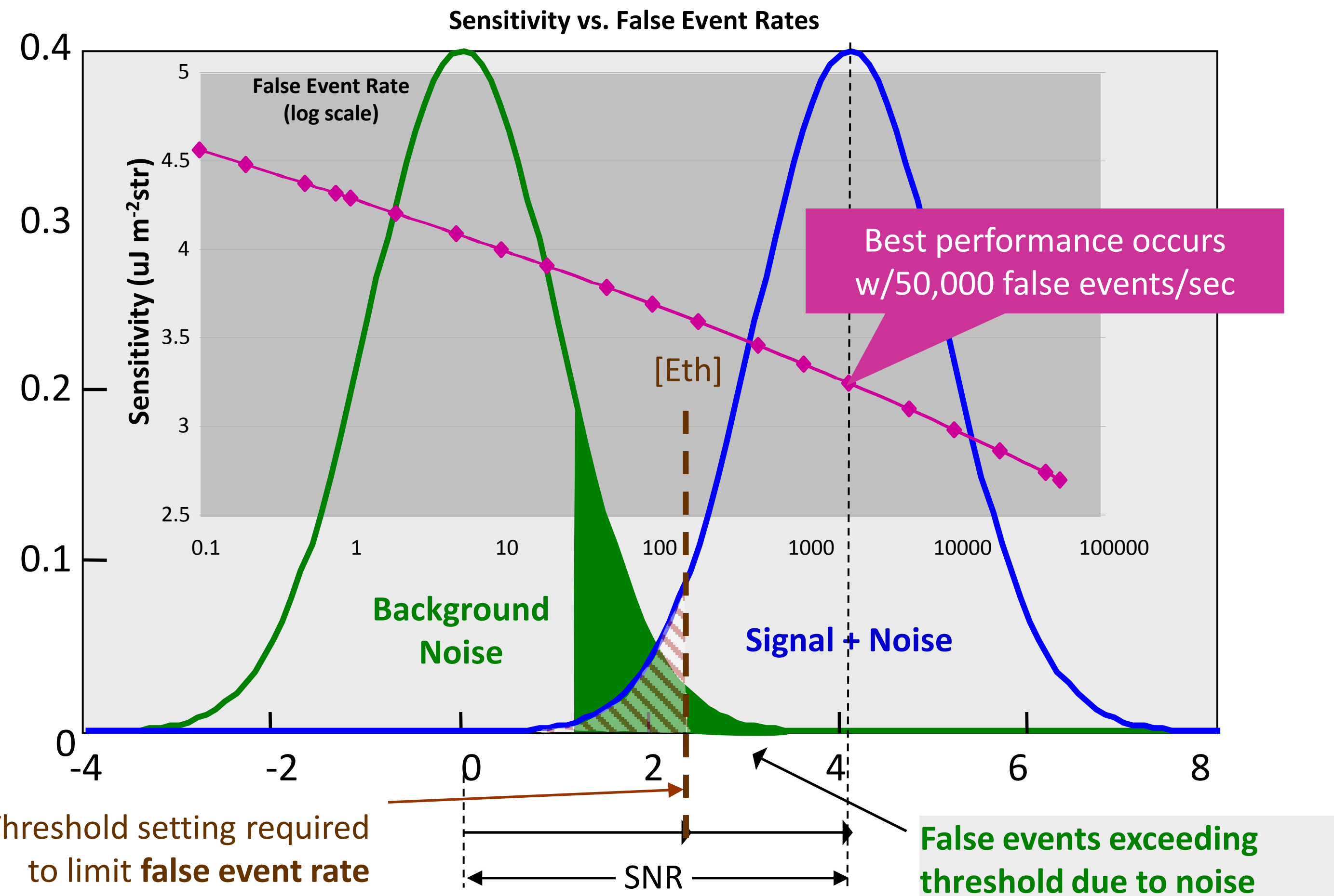
The coherency filter tests for spatially correlated event(s) that occur in two or more different frames within a given time interval. In order to determine whether as event is real or false, we define:

- **Probability of a false event (P_{FE})** = the probability that noise will exceed the specified threshold energy
  - P_{FE} decreases rapidly with increasing signal-to-noise ratio (SNR)
  - Due to the large number of pixels and high frame rate, the baseline GLM design specifies a SNR on the order of 5 to maintain reasonably low false event rate
- **Probability of lightning detection (P_D)** = the probability that a lightning event will be detected (i.e., exceed threshold) in the presence of noise, that is when the total signal from a given pixel exceeds the average signal for that pixel by a predetermined amount which we define as the threshold
  - P_D increases with SNR

Threshold Level Effect on False Event Rate and Detection Efficiency

SNR = Signal to Noise Ratio

Normalized Gaussian Distribution STD=1



As threshold (Eth) is lowered, the false event rate increases and more lightning signal is detected; false events are removed by robust algorithms in level 1b

Probability of False Events and Detection

Defining equations:

- Total number of electrons detected during an integration period:

  $n = \sqrt{(Ns + Nb + nr^2)}$

  where, nr is the rms electronic noise

- Signal to noise ratio is then defined as:
  - $SNR = Ns/n$
- and $P_D = 1/[\sqrt{(2\pi)}n]e^{-1/2(SNR)^2}$
- Probability that a random signal will break threshold is accurately approximated by the complementary error function:
  - $ERFC(SNR/\sqrt{2}) \sim 1/[\sqrt{(2\pi)}]e^{-1/2(SNR)^2}/(SNR/\sqrt{2})$
  - We define this as the Probably of a false event - $\mathbf{P_{FE}}$
- The total FER is the probability that noise exceeds threshold (i.e. ERFC) for a single pixel * number of pixels per frame (P) * number of frames per second (Fr) or

$$FER = ERFC * P * Fr$$

Coherency Test

- For an event to be labeled "lightning", a second event must occur in the same or an adjacent pixel within a coherency period, that is, two different frames must contain an event.
- The coherency test processes every event as an independent occurrence.
- It uses the event amplitude and background intensity to estimate the probability that the event is false.
  - The larger the event, the more likely that it is real (except for radiation events)
  - The brighter the background, the greater the likelihood for a FE occurrence
- P_{FE} is calculated (via lookup table) using the amplitude and background as variables and loaded into the active pixel table
- When a second event occurs, P_{FE} is again calculated.
- The product of the two P_{FEs} is then calculated and this number is multiplied by the total number of pixels processed during the coherency interval t (500*t*#of active pixels)
  - If the result is greater than a used selectable value, say 1%, then both the events are false

This is a test to determine whether both events are false

Coherency Test

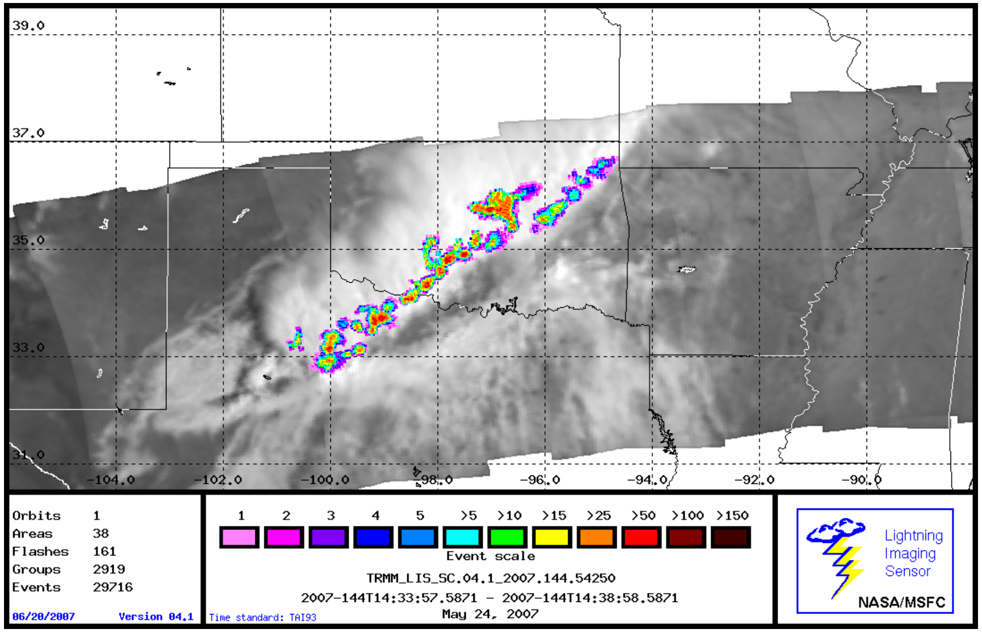
- To pass the coherency test, one or both of the events must be real
- Upon passing, only the later event is passed to the output queue (time sequencing and latency)
- Example of coherency test:
  - Event1 – amp=5,550 electrons (4.7uJ/m^2um), background=708,000 (80% albedo)
    - $P_{FE1} = 8.11*10^{-9}$
  - Event2 - amp=4130 electrons (3.5uJ/m^2um), background=708,000 (80% albedo)
    - $P_{FE1} = 1.32*10^{-5}$
  - $P_{FE1}*P_{FE2}*500*1,408,000*t = 7.5*10^{-4}t$
    - If t=10 sec., Test = $7.5*10^{-3}$ - one or more of the events is real
- Case 2
  - Event1 – amp=4130 electrons (3.5uJ/m^2um), background=708,000 (80% albedo)
    - $P_{FE1} = 1.32*10^{-5}$
  - Event2 - amp=4130 electrons (3.5uJ/m^2um), background=708,000 (80% albedo)
    - $P_{FE1} = 1.32*10^{-5}$
  - $P_{FE1}*P_{FE2}*500*1,408,000*t = 1.2t$
    - Test fails for any time interval> 80 milliseconds

Expected Performance of Coherency Algorithm

Description	Equation to Estimate	Estimate with SNR = 5
Probability of false event in one pixel in one frame	$ERFC(SNR/\sqrt{2})$	5.7×10^{-7}
Probability of two false events in the same pixel within 1 second	$(ERFC(SNR/\sqrt{2}))^2$ * Frame Rate	1.54×10^{-10}
Number of False Events per second not removed by this filter	$(ERFC(SNR/\sqrt{2}))^2$ * Frame Rate * Pixels per Frame	0.1 false alarms per second = 0.5 %

- Actual performance of the coherency filter is expected to exceed this estimate due to improving use of lightning properties.
- The coherency filter can be set to provide higher or lower false alarm rate at the expense or benefit of the detection efficiency.

Overview of Contrast Leakage



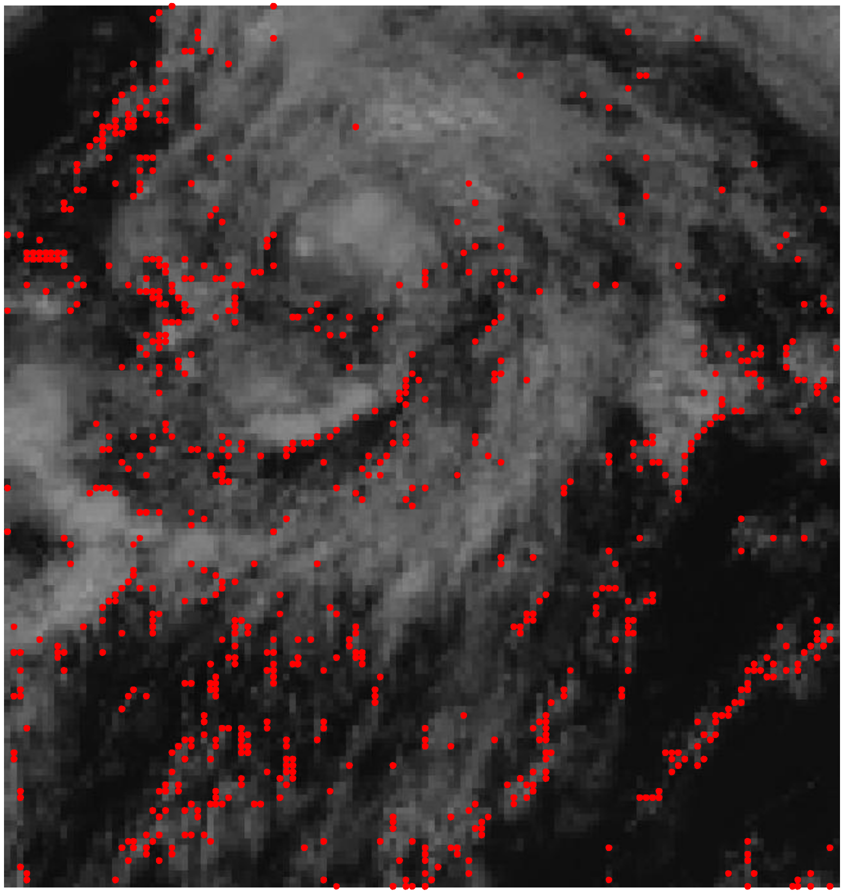
- Near the regions of cloud edges, coastlines, snowfields, or other bright/dark regions on the surface of the earth, contrast leakage FEs are possible due to spacecraft motion. The GLM instrument design and geo-stationary orbit will strongly suppress these types of FEs.
- The coherency filter will also be very effective in rejecting false events that fall in this category. Spatial filtering and background gradient tests provide removal of any surviving FEs from the processing queue.

Jitter Events on GLM

- The contrast leakage filter will remove false events caused by jitter in the GLM line of sight due to S/C disturbances at the cold plate and the GLM mounting deck.
- The contrast leakage filter performance is dependent on designing the filter to match the characteristics of the false events caused by jitter
- Contrast Leakage algorithm filter will be updated as better information on the expected S/C disturbances are available
  - The S/C damped, optical bench is expected to greatly suppress jitter produced events

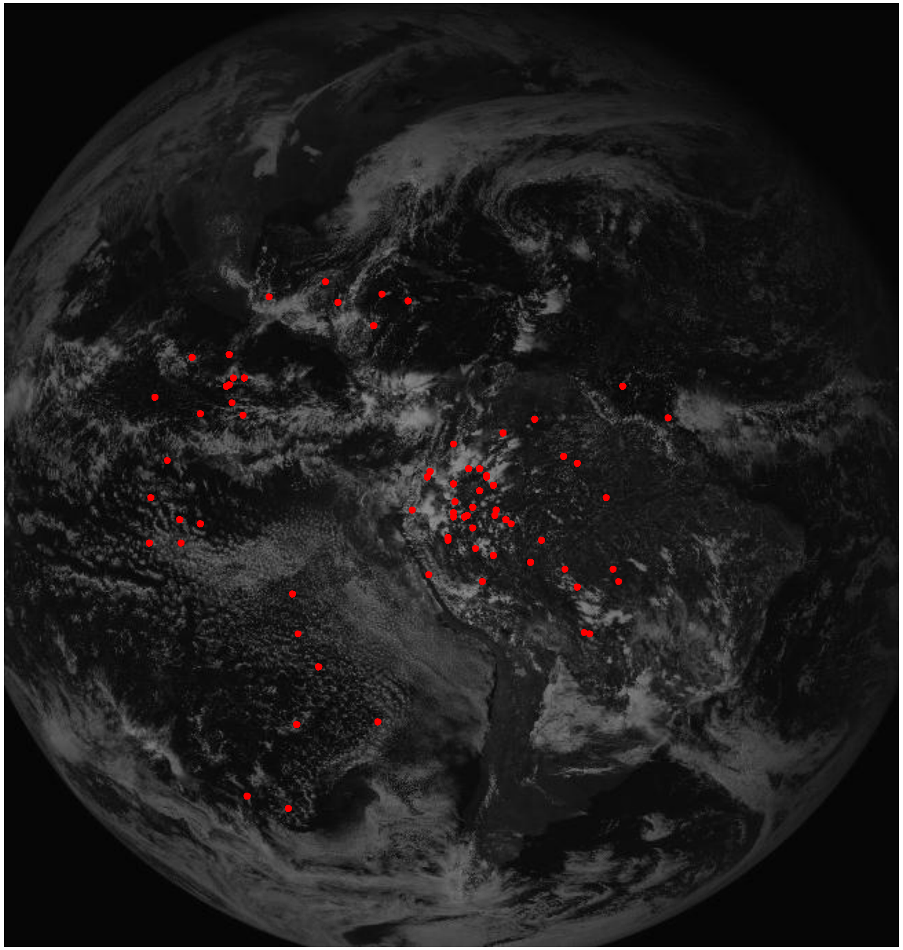
Characteristics of Jitter for GLM

- Jitter events occur on high-contrast boundaries
  - Typically, sun-lit clouds
  - No night-time jitter events
- Jitter is “fast”
  - Tens of Hz
  - Contrast with STOP analysis << 1 Hz
- Jitter events can be taken out by ground processing
  - However, jitter events still need to be downlinked, eating into the telemetry budget of 100,000 events per second
  - Jitter FER budget: 100 events/sec
  - System level margin: 8200 events/sec



Jitter Events Visualized

Note: most events repeat in same high-contrast pixels



Ground Processing Algorithms: Contrast Leakage

- Underlying Assumption: lightning occurs in thunderstorms that tend to be tall and bright and the vast majority of the activity tends to be in the active "core" regions, not the cloud edges.
- The contrast leakage filter tests for sharp gradients on the background intensity of adjacent pixels. When events occur in low background pixels, they are removed.
- As jitter characteristics are better characterized on orbit, additional features such as successive frame event removal may be implemented as necessary

Contrast Leakage Filter

The purpose of this filter is to remove false events caused by spacecraft jitter and bright cloud boundaries. The filter works by looking for relatively weak events that occur in pixels with low backgrounds that are adjacent to pixels with bright backgrounds. The filter parameters represent initial “good guest” values. They will be updated with higher fidelity data as quantitative data become available.

Input assumptions:

- Worst case jitter movement is 1 urad in 1 frame
- Brightest pixel = 800,000 electrons
- Dull pixel = 100,000 electrons
- Then, 1 frame leakage = 700,000/224 = 3000 electrons

Contrast Leakage Filter

- This filter has been redesigned to remove both “jitter” events and “drift” events

Jitter test logic

  - Test the background level of all adjacent pixels, select the pixel with the highest background.
  - Subtract the event pixel background from the background of the selected pixel.
  - If the result is negative, continue to the Drift Test.
  - If the result is positive, divide the value by 224 and multiple by a fractional value F (F is TBD via testing with initial value set to 1).
  - Add the residual to the event pixel threshold setting (Tj)
  - If event amplitude > Tj, go to Drift Test
  - If event amplitude < Tj, reject event

- In the case discussed above, 3000 electrons would be added to the threshold setting, thus maintaining the same threshold margin

Contrast Leakage Filter

- Drift test

  In the time interval between background scene updates, the pointing of the GLM may drift up to 3 pixels, thus the recorded background scene may on longer be representative of the actual event background. For this situation, a second CLF test has been developed. Named the "drift test" and it uses the 5 most significant bits of the event background to determine whether the static background has changed significantly since the last background update. If the background has changed significantly, the threshold setting is raised to a level appropriate for the static background and the event amplitude to compared to the higher threshold.

  Logic

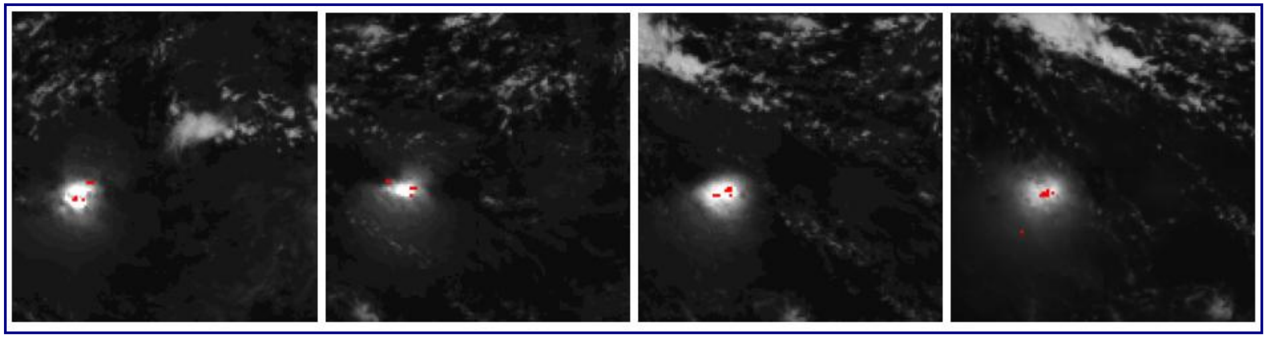
  – Subtract the event pixel's 5 MSB background from the 5 MSB if its static background.
  – If difference is < 0, event is alive, got to next filter
  – If difference is > 0, take the square root and multiple by K (K is an integer that requires tuning, default =3.5)
  – Add the calculated number to the event threshold = Td
  – If event amplitude > Td, go to next filter
  – If event amplitude < Td, reject event

- In the previous case, square root of 700,000 = 837, *3.5 = 2930 electrons

Overview of Solar Glint

The Solar Glint Filter removes solar glint induced false events.

1. Potential glint regions are identified by the solar angle relative to the S/C.
2. A spatial filter is applied only to these regions within the rejection zone (size is optimized during initial S/C checkout).
3. Background level is then checked. Any events within rejection cone and exceeding an albedo of 1 are removed.



Example from LIS of solar glint produced events

Ground Processing Algorithms: Solar Glint Filter

- Approach: Day of year and time of day are used to calculate the solar nadir point on the Earth, which together with the GLM nadir point and orbital position, is used to determine the centroid of the solar glint on the Earth's on the surface.
- An ellipse is drawn about this point, identifying the glint region.
  - Ratio of major to minor axis of ellipse is a function of solar angle
- Initially, all events in the glint ellipses will be removed.
  - With on orbit experience during GLM checkout, a refined algorithm will remove only events with a background intensity/cos (solar angle) exceeding A (initially A = 1).

Expected Performance of Solar Glint

The rate of solar glint produced false events is expected to be much lower for GLM than LIS because of the quasi-stationary orbit of GOES relative to TRMM in LEO.

  - With LIS, S/C motion modulated the bright glint scene causing events
  - However GLM will receive glint from lower incident angles, producing brighter glint
    - Waves and cloud boundaries will modulate the glint, causing events
- LIS used a 100% exclusion zone around glint resulting in a 100% glint event removal efficiency.
- GLM will use less restrictive criteria in order to detect lightning that may occur within the glint exclusion zone
  - These criteria will be tuned further tuned during initial on-orbit observations

Status of the Glint Filter

- The initial version will remove all events inside the elliptical exclusion zone.
  - Code has been written to pass low background associated events
    - This code will be activated and tweaked during initial GLM on-orbit check out

- The capability of glint filter has been fully demonstrated by OTD and LIS but there are sufficient difference between the orbits (lower expected event rates and potentially brighter backgrounds) that the GLM filter will benefit from on-orbit optimization.

Event Radiant Energy

- The event amplitude count is converted to a calibrated event radiance using an equation derived from instrument calibration. This calibrated radiance is stored as a member of the event data object in single precision.
- Event energy is specified in Joules