Algorithm Theoretical Basis Document (ATBD) for L2 processing of the MTG Lightning Imager data

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Document Change Record

Issue / Revision	*Date*	*DCN. No*	*Changed Pages / Paragraphs*
1A	13 July 2011	1	• System PDR RIDs #108 to #118 (for RID #109 also a new figure replacing the old one) • System PDR RID #119. Added new figure 3 with explanation in text. • System PDR RID #122 • System PDR RIDs #124 to #126 • System PDR RID #128 • System PDR RIDs #130 to #139 • System PDR RIDs #141 to #153 • System PDR RID #154, Figure 24 edited. • System PDR RID #155 (modified table).
1A	14 July 2011	2	• System PDR RIDs #15 to #16. • System PDR RID #17 (modified list in Section 2.2 instead of Table 8 as in the RID). • System PDR RID #45 (Table 3 modified). • System PDR RID #49 (note added to definitions). • System PDR RID #50 (note added to Section 2.3). • System PDR RID #51 (note on ASPKE added in Section 2.3). • System PDR RIDs #55 & #58 (timeliness requirements added in a new Section 2.3.4). • System PDR RIDs #56, #61, #82, #84. #86 (added product content description with an example illustration in Section 4.3) • System PDR RID #60, #99 (note added on flash definition and CHUVA campaign in Section 5.2.3) • System PDR RID #65, related to #154. The figure in 8.2.5.2 has been edited with accompanying text • System PDR RID #67 • System PDR RID #71 • System PDR RIDs #78 and #123: a misplaced bullet in Section 3.1 deleted. • System PDR RID #79: bullet list in Section 3.1 modified. • System PDR RID #85: cut-off rationale explained, taking into account the RID comment.

			• System PDR RID #94: L1b/L2 validation discussion in the text separated. • System PDR RID #96: Note added on prototype processor performance testing limitations. • System PDR RID #104: modified to explain isolated strokes. • System PDR RID #74: Word “spectrometer” omitted. • System PDR RID #91: Clustering distance discussion enhanced in Section 5.2.3. • System PDR RID #73: Section 2.2 (list of benefits) edited, so it is no longer a summary session. • System PDR RID #80: Table 2 modified to include jitter. • System PDR RID #106: Section 4.3 modified to include description on how group/flash locations are computed. • System PDR RID #87: Section 5.2.1 modified to describe baseline vs. future enhancement. • System PDR RID #107: Section 4.3 and 5.2.4 to better indicate that baseline processing is independent of auxiliary data sources.
1A	14 July 2011	3	• System PDR RIDs #1: availability estimate of operational processor related parts of the document (Section 7) added. • System PDR RIDs #2, #75, #76, #120: full rewrite of Section 2.3 parts dealing with system requirements, including explaining notes on issues brought up by review. • System PDR RIDs #72: modified Section 2.2
1A	12 August 2011	4	• Added the Product requirements table for lightning detection as Annex I as requested by PDR panel
1E	12 November 2012	1	• Modified Section 5.2.4 on Parallax correction to highlight that it is done on L2, not on L1b, and by removing references to ATDnet data usage.
1E	12 November 2012	2	Density product related changes: • Removed the density product from Section 9, on other potential MTG LI data products. • Changed wordings in the document from “baseline L2 product” to “baseline L2 lightning data product”. • Density product added to Table 5.

			• Added Section 4.4 on "L2 Lightning density products" • Added main Section 6 on "Algorithm description for lightning density generation", detailing the density products. • Removed obsolete prototype processor example images, which showed flash/group/event "densities" which have not been computed as defined for L2.
1E	31 January 2013	3	• Reworded the description on redundancy filtering and removed a note suggesting that it would not be baseline. It is baseline but the contents are still not defined as long as L1 processing has not been defined.
2Draft	11 February 2013	1	Density product modifications: • Products no longer called density products as no division with area is done in the computation, and is left for the users for any given area, with the help of detailed grid information. • In line with the above, three newly defined products are defined: accumulated flashes, accumulated flash index, and accumulated flash radiance. • Initially two periodicities were described (30 sec and 2.5 minutes). The latter was intended for direct comparison with FCI imagery. However, as the user can easily combine successive 30 sec products in order to reach any multiple of 30 seconds, the 2.5 independent product was regarded as unnecessary. • Describing the resampling necessary for the transition from the LI grid to the target IR grid (2 km) in a new sub-section.
2	12 February 2013	1	• New version for the system PDR (delta)
3	18 April 2013	1	• Updated based on LIST comments (editorial)
3	22 April 2013	2	• New Section 5.2.4.1 explaining the selected approach for parallax correction • New Sections 5.2.2.1 and 5.2.3.1 explaining the methodology for computing the group/flash locations. • New Section 5.2.3.1 describing the methodology for computing the X/Y distances for the WED-algorithm. • Editing parts of text mentioning LI integration time or spatial resolution to reflect the current state of design (1 ms and 4.5 km SSP).

3	25 April 2013	3	• Changing the WED algorithm from computing the direct distance between groups instead of (X, Y) distances. • Modified the description of filtering to be done at L2, consists now of: redundancy filtering (event level), 1st and 2nd level flash filtering (after L2 flash clustering and after accumulation product creation, respectively).
4	October 2013	1	Updates based on the Consistency Checkpoint Review (CCR) actions: • OBT added to list of acronyms (RID #135) • Definition of orbital radius (RID #172) • Typos corrected (RID #124, #132, #161, #164) • Added footnotes on references to other parts in the text (RID #133) • LI uses for other research purposes mentioned (RID #175) • Updated the MSG operational services timeline (RID #189) • Updated wording in the accumulated product definitions (RID #179) • Document chronology added (RID #209) • Terminology in Section 1.1 updated (RID #187) • Added a bullet on complementary use of ground-based observations (RID #191) • Timeliness definition added (RID #196) • Removing statement on using LI data alone for nowcasting of convection, as it would in reality always be used in conjunction with modelling or additional data sources (RID #213) • Footnote added on definition of the clustering distances (left open currently) (RID #185) • Footnote added describing the limited purpose of the prototype processor (RID #169) • Added a note on quality of products and the respective flags (RID #123) • Footnote added explaining the adjacency principle (RID #149) • “first fit” and “full fit” explanation expanded (RID #159) • Footnote added to explain the “N%” of the accumulated product processing of LI grids into the FCI grid (RID #162) • Spatial sampling definition and difference to LIS

			clarified (RUD #177) • Removed the text "...with the size of the grid box in km2, and in addition divided..." from the accumulated flash product description. The accumulated flashes are not density products (divided by km2) as the text would have indicated (RID #178) • Added a note that FCI grid information needs to be available to the accumulated product processing (RID #180) • Accumulated product conceptual examples (in Figure 26 to Figure 28) clarified to refer to the accumulated flash index product, with a note added how the corresponding accumulated flash product examples would be in comparison (RID #186) • Added a full Section on an up-to-date description of the LI instrument. Removing TBC and TBD throughout the document to reflect this major update (RID #130). Other changes: • Remove main section "Assumptions and limitations", which is now just a placeholder. It can be added later if needed. • Remove the current contents on the main Section "Synergy with ground-based observations", and add a note that these issues will be dealt with in the LI Cal/Val document in due time. • Updated Figure 10 on "Overview of MTG LI processing chain up to L2" to reflect the current status of the processing scheme, especially regarding the false event/group/flash filtering which will be encompassing both L1 and L2 processing. In relation, also modified the text introducing the image, to reflect the change in how false event filtering is now understood. • Added a reference to the follow-on study on the LIProxy simulator • Added an up-to-date picture of the LIProxy GUI • Removed Section 11 on "Other potential MTG LI data products" which is not considered relevant for the purpose of the document. • Significant changes in the LINET-based proxy data description on include the CHUVA-related new results and modifications to the method • Changed a note on whether IC or CG lightning is more easily observed by its optical pulse above clouds to reflect literature and LIST comments (Section 2.3.1).

4	6 March 2014	2	• Clarified statement in Section 6.2.2 on group clustering, in that integration time is not “fixed” at 1 ms but can be changed and shall be tested also during commissioning. This is leading to the need to have also the possibility to include temporally neighbouring time frames for group clustering (and not only events taking place in the same frame, which is the LIS approach). • Added a subsection 6.2.3.2 on “Flash clustering based on separate distance and time threshold criteria”. This means that two separate methods shall be available in the L2PF for flash clustering (WED and the separate distance/time criteria). The change is based on the L2 algorithm study outcome run as a LI MAG study.
5	7 May 2015	1	• Added a full description of the parallax correction issue with possible solutions and related analysis. This discussion is placed in Annex II. The note on parallax correction in Section 6.2.4 is changed to note the adding of the annex.
		2	• Added a full description of the training based filtering concepts in Annex III. Edited references to filtering throughout the text. Added section 6 to act as an umbrella for the filtering discussion, then pointing to Annex III.
		3	• Distribution list updated.
		4	• Equation numbering changed to start from #1 for each Section
5	6 Oct 2015	1	• Implemented changes according to MTG_DCR_84
	23 June 2016	2	• Edited the signature table to reflect the current organisation & review practices
6	20 February 2019	1	• A thorough rewrite of the document taking into account the definition of the LI Level 2 processing baseline with filtering, which was not available for the earlier versions of the document. The document then tightly related to the LI Level 2 Processing Specs (LIL2PS).
6	8 July 2020	2	• Included the full modification history (Section 1.6) to highlight the changes related to aligning the ATBD with the LIL2PS on the filtering algorithms. • Included the Annex with the Level 2 filtering settings derived in the assessment of the pre-flight Level 2 performances undertaken in March-June 2020 (LI MAG meeting #10 preparation; meeting focussed on RfDs) • Modified Figure 2 right panel with the correct LI

			FOV • Updated the list of Applicable documents • This version of the document is aimed for publishing on the EUMETSAT webpage. • The changes are according to DCR number MTG_DCR_728
6	24 September 2020		• Updated the signature table
6	15 October 2020		• Updated the distribution list table

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1 INTRODUCTION

1.1 Purpose

The Algorithm Theoretical Basis Document (ATBD) for the Level 2 processing of the MTG Lightning Imager (LI) encompasses four main parts:

1. The definition of lightning groups and flashes starting from the Level 1b events; this part of the processing has largely to do with clustering information in space and time.
2. The filtering of false events, and groups/flashes related to false events that were not rejected neither at Level 0, nor at Level 1b.
3. The accumulation over a certain time window of the Level 2 information.
4. The definition of Level 2 products (both archived and disseminated).

This document describes the scientific baseline for both the Level 2 algorithms and products.

1.2 Scope

This document is aimed at providing the ATBD for the Level 2 processing algorithms and provides the reference to the document describing both the content and format of the LI Level 2 products.

1.3 Applicable Documents

L2_PS	*MTG LI Level2 Processing Specifications*	EUM/MTG/SPE/10/0437
LI_22a	*Overall L1B processing ADD*	MTG-GA-LI-DD-013 Issue 3
L2_FS	*MTG LI Level 2 Format Specification*	EUM/MTG/SPE/10/0452
L2_PERF	*Meteosat Third Generation Lightning Imager Level 2 expected performances*	EUM/RSP/REP/20/1179001
SRD	*MTG System Requirements Document [SRD]*	EUM/MTG/SPE/06/0032

1.4 Reference Documents

CONV	*MTG Conventions & Terms Document*	EUM/MTG/DEF/08/0034

MACH07	*Performance assessment of the Optical Transient Detector and Lightning Imaging Sensor*	Mach, D., Christian, H., Blakeslee, R., Boccippio, D., Goodman, S., Boeck, W., J. **Geophys. Res., Vol. 112, 2007**
SINN0T84	*Virtues of the Haversine*	Sinnot, R. W. **Sky and Telescope, 68(2), 159**

1.5 Document Structure

Section 1 Introduction (this section)

Section 2 An overview of lightning detection from space

Section 3 Description of the LI instrument (Level 0/on-board detection and filtering) and of the Level 1b filtering

Section 4 Description of the LI Level 2 processing

Section 5 Description of the LI Level 2 products

1.6 Document evolution

The milestones of the Level 2 ATBD document evolution are described in Table 1.

Table 1. Level 2 ATBD significant milestones.

Date	**Version**	**Description**
May 2011	1	First release entering the system Preliminary Design Review
February 2013	2	As a result of discussions with the Lightning Imager Science Team (LIST), added the accumulated products as LI Level 2 baseline products.
May 2013	3	Final LIST reviewed update before the Consistency Checkpoint Review (CCR).
November 2013	4	Updates based on the CCR outcome.
April-May 2018	6	ATBD for the LI Level 2 processing baseline is defined; this is tightly related to the LI Level 2 Processing Specs (LIL2PS, see [L2_PS])
July 2020	6	Following the pre-flight assessment of LI Level 2 performances ([L2_PERF]); the Level 2 settings derived from the analysis have been included in Annex.

1.7 List of Acronyms

ADC	Analog-to-Digital Converter
ATBD	Algorithm Theoretical Basis Document
ATDnet	Arrival Time Difference network (Met Office ground based LLS)
CC	Cloud-to-Cloud
CDF	Common Data Format
CMOS	Complementary Metal Oxide Semiconductor
CG	Cloud-to-Ground
CL	Control Logic
CPU	Central Processing Unit
DE	Detection Efficiency
DT	Detected Transient
ELMA	Ebro Lightning Mapping Array
ENTLN	Earth Networks Total Lightning Network
EUCLID	EUropean Cooperation for Lightning Detection
FA	False Alarm
FAR	False Alarm Rate
FCI	Flexible Combined Imager
FEE	Front End Electronics
FOV	Field Of View
FPA	Focal Plane Assembly
FT	False (detected) Transient
GLD360	Vaisala Global Lightning Dataset
GLM	Geostationary Lightning Mapper
GEO	GEostationary Orbit
IADP	Instrument Average Detection Probability
IC	Intra-Cloud
LE	Lightning Event (caused by a real lightning optical pulse)
LEO	Low Earth Orbit
LF	Low Frequencies
LI	Lightning Imager
LINET	Nowcast lightning detection system
LIS	Lightning Imaging Sensor
LIST	MTG Lightning Imager Science Team
LLS	Lightning Locationing System
LMA	Lightning Mapping Array
LME	Lightning Imager Main Electronics
LOH	Lightning Imager Optical Head
LUT	Look-Up-Table
MTG	Meteosat Third Generation
NASA	National Aeronautics and Space Administration
NBF	Narrow Bandpass Filter
netCDF	network Common Data Format
NLDN	North American Lightning Detection Network
NWC	Now-Casting
NOx	Nitrogen Oxide
NWP	Numerical Weather Prediction

OC	Optical Channel
OTD	Optical Transient Detector
QE	Quantum Efficiency
RTPP	Real Time Pixel Processor
S/C	Spacecraft
SAETTA	Suivi de l'Activité Electrique Tridimensionelle Totale de l'Atmosphère
SRF	Solar Rejection Filter
SSP	Sub-Satellite Point
SZA	Sun Zenith Angle
TRMM	Tropical Rainfall Measurement Mission
TT	True (detected) Transient
VLF	Very Low Frequency
VHF	Very High Frequency
WED	Weighted Euclidian Distance

1.8 Terminology

Some basic MTG LI as well as data processing related terminology is provided in this section. These terms are in line with the document [CONV]. Many of the terms adopted in the MTG LI context are inherited from the Tropical Rainfall Measurement Mission-Lightning Imaging Sensor (TRMM-LIS), i.e., the key heritage mission for optical lightning detection from space.

Lightning optical pulse	Visible black body radiation from the hot lightning channel transported through the cloud up to its could top via scattering; the black body emission happens in about 50 µs and the released photons are transported to the cloud top surfaces by scattering. The resulting lightning optical pulse observable at the cloud top has a duration widened in time up to about 600 µs, distributed over an area ranging from 100 km^2 up to a maximum of about 10.000 km^2 depending on the number of scattering processes involved and the complexity of the flash "skeleton".
Triggered Event (or Detected Transient, DT)	Occurrence of an excess of radiance registered by a LI detector element on top of its background.
Trigger threshold	Threshold is used, per detector element, to detect a local excess of detected radiance with respect to the local background.
Background	The radiance from the Earth scene captured by the detector element.
Lightning event	LI DT caused by a lightning optical pulse.
Groups[1]	Groups are collections of DTs that are found in the same

[1] Groups are considered to be representative of lightning strokes, i.e., massive electrical discharge following the bridging of the conductive channel of ionized air between the negative charges in the cloud and the positive surface

	acquisition frame and are found in neighbouring detector elements. Groups are an intermediate product to obtain flashes.
Flash	Flashes are collections of groups based on their proximity in space and time.
Instrument Average Detection Probability (IADP)	The capability, at Level 1b, to have at least one DT in case of a weak and small lightning optical pulse.
Detection Efficiency (DE)	Capability, at Level 1b, to detect the DTs that exceed a minimum effective radiance.
False alarm	DT occurring in the absence of a lightning optical pulse which is not rejected at a certain filtering step (applies to on-board and on-ground processing).
False Alarm Rate (FAR)	The number of LI false alarms per second at Level 1b.

charges below. The stroke is the most luminous and noticeable part of the lightning discharge which is also detectable by instruments such as LI.

2 LIGHTNING DETECTION FROM SPACE

The LI instrument will complement existing ground-based and space-based capabilities for detecting, locating, and characterizing lightning. Lightning is an electrostatic discharge between electrically charged regions:

- of a cloud (intra-cloud lightning or IC);
- of two clouds (cloud-to-cloud lightning or CC);
- of a cloud and the ground (cloud-to-ground lightning or CG).

Moreover, lightning is a source of:

- Very High Frequency signals (VHF);
- Very Low Frequency signals (VLF);
- Low Frequency signals (LF);
- optical signals.

In Table 2 a compact description of the current lightning detection capabilities is provided.

Table 2: an overview of the main ground-based and space-based lightning detection capabilities.

Signal	Baseline[2]	Detected Type	Attributes	Instrument/Network
Optical	Space-borne	80%-90% of CG+CC+IC	2D mapping and radiance GEO/LEO Field of View	• Optical Transient Detector (OTD, 1995) • Lightning Imaging Sensor (LIS, 1997) • Geostationary Lightning Mapper (GLM, 2016) • Lightning Imager (LI, 2021)
VHF	10-20 km	100% of CG+CC+IC	3D mapping	• Ebro Lighting Mapping Array (ELMA) • Suivi de l'Activité Electrique Tridimensionelle Totale de l'Atmosphère (SAETTA)
LF	50-300 km	50%-90% of IC+CC > 95% CG	Waveform analysis	• European Cooperation for Lightning Detection (EUCLID) • North American Lightning Detection Network (NLDN)

[2] Indicating the typical distance between different detectors in Networks.

				• LINET
VLF	> 1000 km	10%-30% CC+IC 70%-80% CG	Global coverage	• Vaisala GLD360 • Met Office ATDnet • Earths Networks ENTLN

Feasibility of lightning detection from space by optical sensors has been successfully proven by the NASA instruments OTD (1995-2000) and LIS (1997-present) on Low Earth Orbit (LEO, see, e.g., [MACH07]). One of the main outcome of LEO acquisitions is the first instrumentally uniform collection of long-term lightning flash statistics within the coverage areas (see Figure 1).

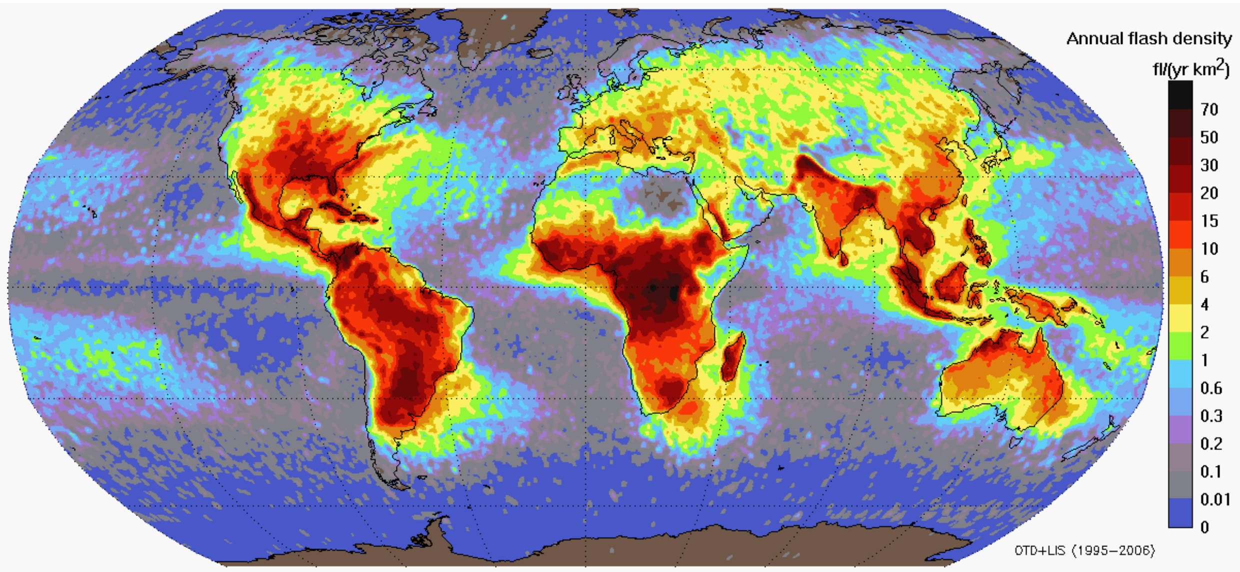

Figure 1: Annual flash density derived from NASA OTD and LIS observations (1995-2006).

The transition from LEO to GEO lightning observations is not straightforward, and certain elements need to be considered in order to understand the differences in, e.g., processing of the observed data. In some aspects the transition can be regarded as positive, for example:

- temporally, spatially and instrumentally uniform coverage of the visible disk over land and ocean;
- high temporal resolution;
- excessive radiation noise hampering LEO missions (from Southern Atlantic Anomaly, SAA) less problematic for GEO observations.

In other aspects the transition implies the following issues:

- the larger distance target-satellite affects radiometric sensitivity and resolution capabilities with an important impact on instrument requirements and complexity;

- fixed observation geometry with location dependent distortions and observation angles (affecting for example northernmost member states);
- the spatial resolution does vary across the full disk coverage area of more than in the case of LEO instruments, for example for LI the requirement is a 10 km spatial sampling at 45 deg latitude and SSP longitude, which is achievable with the 4.5 km spatial sampling at SSP;
- finally, noise conditions (e.g., S/C external noise, solar glint, S/C attitude effects, cloud vs. S/C movement) are different to LEO[3].

Based on currently available total lightning data from LEO satellites and ground-based systems, it has been estimated that CG cases count only roughly 15% of the total lightning activity (although this fraction varies during a storm lifecycle). This means that a global network such as Vaisala GLD360 which is particularly sensitive to CG lightning is missing a large part of the total lightning activity. The key advantages of lightning observations in the Visible from GEO location are:

1. the capability of observing continuously the whole lightning activity, and
2. the capability of observing a large fraction of the Earth disk visible from GEO position, i.e., the capability of covering global scales.

Within its Field of View (FOV), LI observations will reveal the “space counterpart” for the different ground based lightning observation systems, and it will serve as an essential point of comparison for all lightning systems (ground- and space-based). The main benefits of the MTG LI mission can be described as:

- LI measurements of total lightning activity complement the global/regional measurements of CG lightning as provided by ground based systems and will improve the quality of information which is essential for air traffic routing and safety.
- Error characterized (i.e., post-validation) total lightning activity information can be assimilated to improve very short range forecasts of severe convective events or used to verify/validate other satellite-data-based NWC algorithms to forecast time and location of initiation of lightning in a new storm cell.
- Information on lightning can also serve as proxy for adiabatic and latent heating to be assimilated in global/mesoscale NWP models.
- The information on the total lightning activity will allow to assess the impact of climate change on thunderstorm activity by monitoring and long-term analyses. In cooperation with the two NOAA GLMs on GOES-R and GOES-S a major part of the globe will be covered by a long term committed GEO total lightning activity observation systems.
- Providing total lightning activity information on a global scale will be a prerequisite for studying and monitoring the physical and chemical processes in the atmosphere regarding NOx production, which plays a central role in the ozone conversion process and acid rain generation.
- Use of total lightning activity information as a convective/stratiform separator for rain classification and rain retrieval.
- In high latitude boreal forests lightning is a major cause of forest fires; LI data can be used to issue warnings of high risk areas in affected regions.
- Lightning observations can be used to help diagnose the intensification of tropical cyclones over oceans.

[3] Both type of observations are subject to such effects and should be properly taken into account in processing

- Lightning observations can be used to identify active convection for over-ocean air traffic.
- LI will provide a link to TRMM LIS science and climatological datasets for the tropics that have been developed since 1998. LIS climatology is based on very long term observations due to the short view-time available from the instrument. Verifying and complementing/improving the climatology obtained with OTD and LIS from GEO observations will be an important task in the future.
- Some ground based system operating in the LF/VLF and VHF regions are more suitable for monitoring utilities, airports and such, which require very high location accuracy down to hundreds of meters. However, observations from space offer a complementary data source by identifying, tracking and extrapolating electrically active areas with a uniform observation quality.

3 MTG LIGHTNING IMAGER

3.1 Main characteristics

The LI instrument consists of the following main elements:

- A Lightning Imager Optical Head (LOH) consisting of four identical Optical Channels (OCs), each one covering a different part of the visible Earth from GEO position. The covered percentage of the total visible Earth from GEO position is about 84% and includes the European territories of all EUMETSAT Member States as shown in Figure 2. OCs are counted clock-wise from 1 to 4 starting from the one pointing at west (i.e., the OC pointing over EUMETSAT member states is OC2). Each OC is equipped with:
  - A protective cover on the baffle aperture to prevent baffle and optics contamination during launch and pre-launch activities.
  - Baffle for stray light suppression.
  - A telescope with a FOV to cover about ±5.1 degrees. The entrance aperture is 110 mm in diameter.
  - A Solar Rejection Filter (SRF) that is designed to block as much as possible all sun light outside the wavelength range of interest 770-785 nm. Within the wavelength range of interest the filter transmission is as high as possible: >0.95. The performance of this filter is critical, because all unwanted light entering the system after the filter may cause thermal problems, stray light problems and optical degradation problems.
  - A spectral Narrow Bandpass Filter (NBF) with an equivalent band width of 1.9 nm centred on the main atomic oxygen triplet lightning emission line at 777.4 nm. The performance of this filter is critical, because it determines to a large extent the signal-to-noise behaviour of the LI instrument for lightning occurring over bright clouds. If selected to broad, the filter transmits the white light from the cloud, whilst the lightning signal itself is not increased. The cloud background signal will introduce significantly more shot-noise and the overall instrument signal-to-noise is reduced, which in turn reduces the LI lightning detection efficiency. If the filter band width is selected too narrow, the lightning spectral signal may be cut off by the filter response (also as function of incidence angle of the filter), which also reduces the signal-to-noise and the LI lightning detection efficiency. The NBF filter band width has to be carefully optimised. The transmission of the NBF at 777.4 nm is >0.90.
  - Imaging optics to image the Earth on the detector(s).
  - Backside illuminated CMOS detector(s) of 1170x1000 pixels with on-chip ADC. The detector performance characteristics are critical for the overall LI performance. The quantum efficiency (QE) is required to be >0.70. The ADCs have 11 bit resolution (goal 12 bits) in order to meet the radiometric accuracy requirements. The 24 µm x 24 µm detector pixel pitch corresponds to a 4.5 km x 4.5 km ground sample at the sub-satellite point. The detector pixel full well capacity is required to be >450000 electrons in order to cope with the radiometric dynamic range.
  - The proximity electronics, also referenced as Front End Electronics (FEE), consisting of electronics boards and relevant frames and covers, are supported by the Focal Plane Assembly (FPA) structures.

- A LI Main Electronics (LME) box located 1-2 meters away from the LOH. The LME box takes care of processing all DTs, both True Transients (TTs) and False Transients (FTs) and packaging the data for downlinking to fit within the allocated 30 Mbps bandwidth.
- LOH to LME interconnection harness.

The LI mass is about 93 kg (including 15% contingency margin; required ≤93 kg), the average power consumption is about 194 W (required ≤320 W) and the data rate is 16.9 Mbps (required ≤30 Mbps).

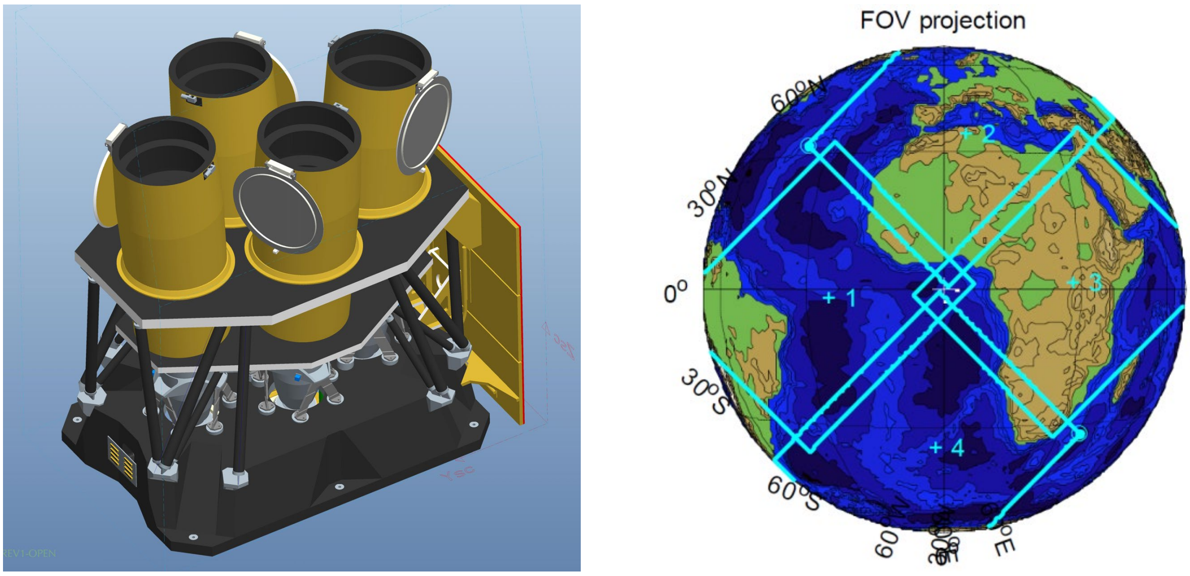

Figure 2: The LI imager and its FOV. Left image: schematic picture of the LI optical bench. Right image: LI FOV for the four OCs (sky-blue solid rectangles).

3.2 Lightning detection concept and functional description

The concept adopted for the lightning detection drives the overall architecture of the instrument, including the selection of the CMOS detector architecture, of the hardware and software needed to manage the detector and to process the measured images. The detection philosophy implemented in LI is based on the following functional and performance aspects:

1. Image acquisition for continuous detection of the lightning pulses in the FOV.
2. Calculation of pixel-by-pixel adaptive background to cope with non-uniformities within the image (e.g., oceans, clouds, area in night conditions and areas with daylight conditions).
3. Use of an adaptive threshold, to fully exploit the detection capability over portions of the image presenting different illumination conditions.
4. Achievement of the maximum flexibility in the detection method, to allow fine tuning of the key parameters to improve the instrument performances during operations.
5. The system must allow on ground testing and characterisation of the key parameters needed to improve the instrument performances.

The request to perform continuous detection of lightning pulses (bullet 1), combined with the typical lightning pulse duration of 0.6 ms, leads to set the exposure time as close as possible to the pulse duration, and continuous readout of the detector. An exposure time of 1 ms and image rate of 1 kHz have been selected as trade-off between the lightning duration and the time needed by the electronics and software to perform the functionalities reported in bullets 2 to 4 in real time. In addition, the high frame rate, combined with the large amount of data to be processed, requires a high computational throughput that could not be achieved via the software architecture only. For this reason the detector processing is implemented in a hardwired logic. The necessity to perform adaptive background computation (bullet 2) requires a dedicated logic that computes for every detector pixel the background level: this calculation is performed through a dedicated filter that washes out noise effects and spurious events, but retains low frequency information to take into account local background changes and different illumination conditions during the day. The subtraction of the background component from the pixel measurement provides the net signal (e.g., the signal from the lightning). To fully exploit the LI detection capability (bullet 3), the Real Time Pixel Processor (RTPP) uses different thresholds for background scenes: low thresholds can be used for dark scenes (with lower shot noise, e.g., ocean scenes), and high thresholds for the bright ones (with high shot noise, e.g., cloud scenes during the day). Finally, to enable the maximum flexibility of the system, the transfer function associating a threshold level to the estimated background is stored in the software and commanded to the hardwired logic (bullet 4): changes to the thresholds can be performed in flight, on the basis of the measured operational conditions.

3.2.1 Background level determination and Real Time Pixel Processor (RTPP)

The full frame digital video signal is processed by RTPP that performs the following tasks (see also Figure 3 A to C):

- Background level estimation for each detector pixel: performed in real time by averaging the continuously acquired background with the aim of increasing the signal-to-noise ratio of the background evaluation and retaining low frequency information to take into account the local background scene.
- Definition of the detection threshold for each pixel. This is implemented by means of a Look-Up-Table (LUT) mapping the threshold as a function of the background level. This LUT can be modified by the software running in the LI CPU.
- Pixel thresholding and detection: each pixel net signal is compared against the defined detection threshold, when the threshold is exceeded a DT is found.
  - DT address identification: the address of each detected pixel is transmitted to the Control Logic (CL).
  - Storage of DT net signal of each detected pixel and of the surrounding pixels: 3x3 pixel window around the DT.
  - Storage of the background level for each DT and of the surrounding pixels: 3x3 pixel window around the DT.

As represented in Figure 3 D, DTs can be originated by lightning optical pulses (in this case True DTs, or TTs) as well as noise (in this case False DTs, or FTs). The main noise sources of DTs are well known:

- local fluctuations of the radiometric (shot) noise;
- micro-vibration of the platform;
- particle impacts on the focal plane;
- Sun glint, Sun intrusion.

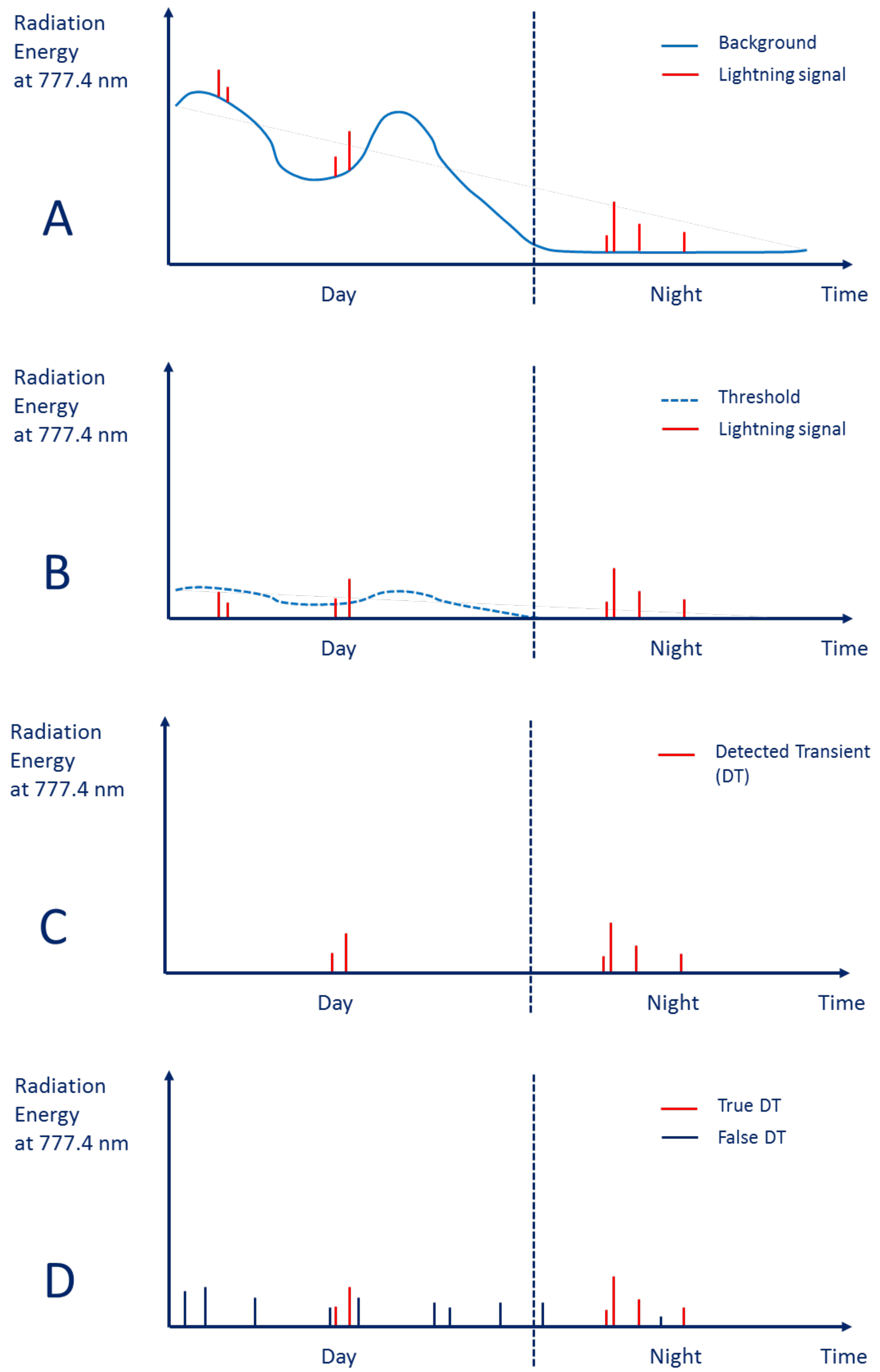

Figure 3: Schematic representation of the RTPP detection principle of one pixel within the LI FOV. A) representation of the lightning signal on top of the background (variable from day to night); B) threshold computation from background and comparison of the threshold against the net lightning signal; C) DTs selected from the time sequence; D) Representation of both

TTs and FTs generated by noise sources (from A to C the impact of the noise was not taken into account).

3.2.2 On-board filtering

The noise sources listed at the end of Section 3.2.1 are capable of generating a large amount of the DTs. For this reason, in order to *i)* "clean" the acquired data from FTs and *ii)* reducing the total amount of data to be broadcasted to the ground due to limitation of the band, two on-board filtering steps are employed. These have been designed to handle the FTs generated by the fluctuations of the radiometric (shot) noise (i.e., the Single Detected Transient Filter, SDTF) and the FTs generated at locations of sharp transition of the Earth scene by the micro-vibration of the LI instrument (i.e., the Micro-Vibration filter MVF), respectively. It is very important to stress that such filters apply in real time to the information acquired per frame (i.e., every millisecond); in fact, the hardwired implementation logic performs also the filtering analyses.

3.2.2.1 Single Detected Transient Filter (SDTF)

The FTs produced by radiometric noise are known to have an important characteristic: in the 3x3 window of the net signal these are expected to have a strong central signal (at the location of the DT) and a low total signal from the 8 neighbour pixels due to the fact that the fluctuating noise ads up in a non-coherent way. The SDTF computes the total net signal from the DT neighbours and compares this against a threshold derived from a LUT which is function of the average value of the background computed over the DT neighbour pixels. If the total net signal is above the threshold the DT is considered (at this filtering step) to be a TT; if the test is not passed the DT is rejected and lost.

3.2.2.2 Micro-Vibration Filter (MVF)

The FTs produced by the micro-vibrations of the satellite are known to be generated at the locations where specific properties of the background are found: in detail, in the 3x3 pixel window, one expects to have a strong variation of the background (a large gradient). The variation of the background within the window is measured by means of the Sobel gradient which describes, in a single figure, the overall variation of such quantity, with particular weight given to the along-X and along-Y components. This (absolute) gradient is compared against a threshold which is function of the total net signal. If the Sobel gradient of the background is higher/lower than the threshold the DT is considered (at this filtering step) to be a FT/TT. This method has the aim of finding those cases in which the local gradient of the background is high enough to generate a DT. As in Section 3.2.2.1, FTs are lost while TTs are kept for further processing.

3.2.3 DTs to be processed at Level 1b

The RTPP-SDTF-MVF (see Sections 3.2.1, 3.2.2.1, and 3.2.2.2) processing sequence defines the main steps of the LI Level 0 processing. Level 0 data (to be processed at Level 1b) are defined form the DTs that have passed both the Level 0 filtering steps (i.e., SDTF and MVF). In Figure 4 the impact of the Level 0 filtering on the total amount of information detected over 10 sec at RTPP is shown.

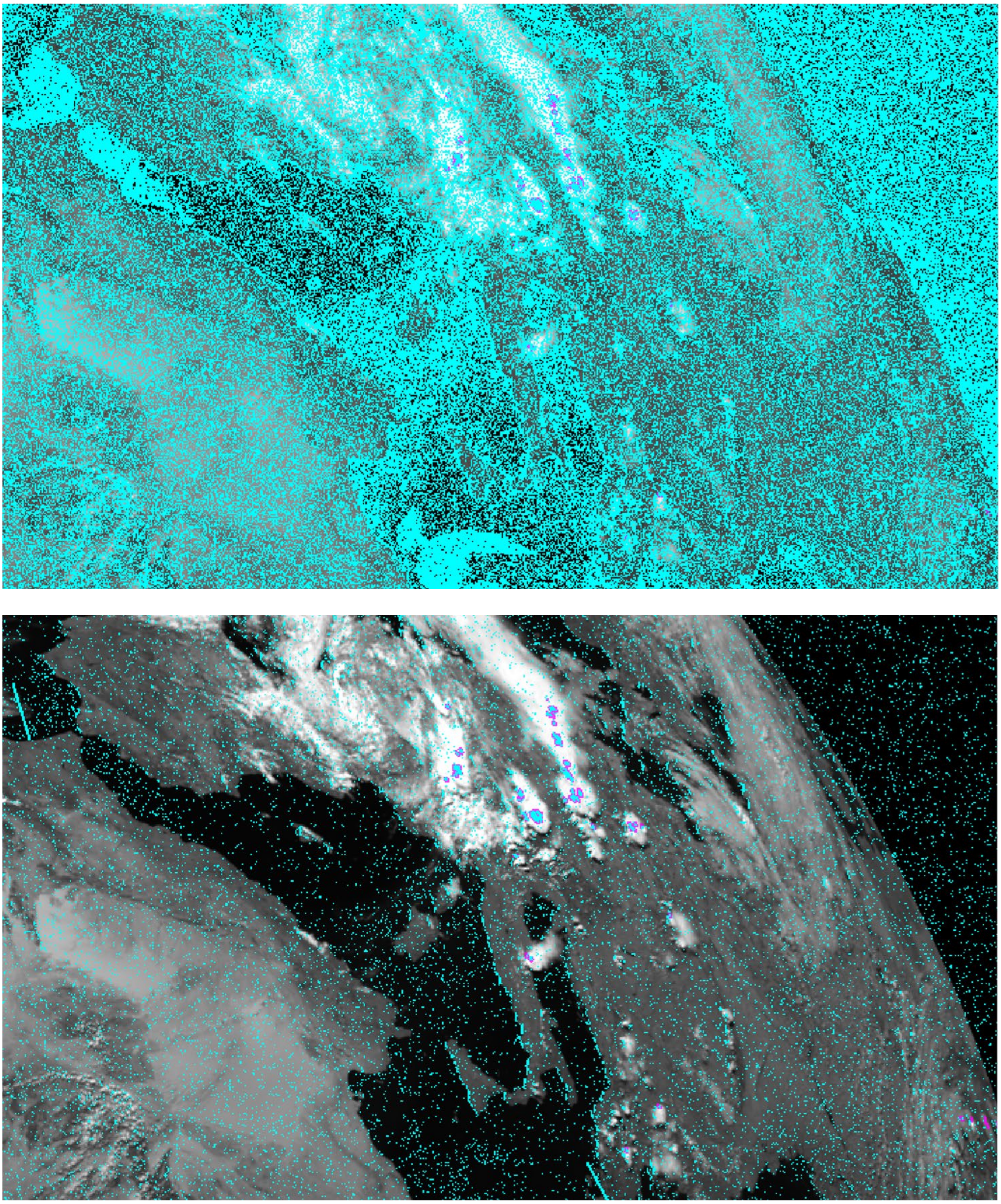

Figure 4: Impact of the Level 0 filtering on 10 sec of accumulated acquisitions from simulations in a portion of OC2. Pixels in cyan are marking the DTs generated by the simulation that passed were detected at RTPP and that survived the on-board filtering. Top panel: the DTs at RTPP (detection). Bottom panel: the Level 0 DTs. In the images the purple patches are indicating the location of the lightning optical pulses used as input for the simulation; finally, the highly elongated features are simulated high energy particles impacts.

3.3 Level 1b DT filtering

In this section we provide a brief presentation of the LI Level 1b DT filtering steps following the ones described in Section 3.2.2. It is worth stressing that at Level 1b two additional key processing steps are performed: *i)* radiometric calibration, and *ii)* navigation of both DTs and background, respectively. The Level 1b filtering will make use of the quantities provided by *i)* and *ii)*, however a description of their processing is beyond the scope of this document. The Level 1b DT filtering has a key difference with respect to the LI Level 0 filtering (see Section 3.2.2): in this process one can use data collected over a certain time window/buffer and use the properties of a large sample of DTs to perform filtering. The LI Level 1b filters are the following:

3.3.1 Pre-Processor

In this analysis step the DTs that fall outside the Earth disk within each one of the OCs are flagged as false. Such DTs can be generated by the different noise sources listed in Section 3.2.1: for example in Figure 4 the reader can see how off-Earth-disk DTs are generated by simulations. When FTs are individuated by this analysis step these are qualified FT with 100% confidence. The LI Level 1b pre-processor is a binary filter[4].

3.3.2 Random Telegraphic Signal (RTS) Filter

In this analysis step one aims at detecting and flagging as false the DTs generated by the RTS noise, i.e., a purely electronic noise that one expects to have for any semiconductor. This noise, characterized by sudden signal variation between a low signal and a high signal (similar to a square function), can trigger DTs at RTPP (see Section 3.2.1) that are stable in time and space (within the same pixel): RTS-generated DTs look very much like DTs produced by lightning pulses. For this reason a sequence of DTs is flagged as a sequence of (RTS) FTs if:

- the sequence of DTs lasts at least a certain amount of time (configurable parameter/threshold);
- AND the DT radiances within this sequence vary between two well identified levels; this is checked by means of the ratio between the standard deviation of the radiance and the average radiance in the DT sequence. If the ratio is above a configurable threshold the sequence of DTs is considered to be composed by TT; in the other case the DTs are flagged as FTs.

FTs individuated by this analysis step are qualified FT with a confidence level in the interval [0, 1]. Such confidence is computed as one minus the ratio between the configurable threshold on the duration of the RTS signal and the measured duration for the identified FT RTS sequence.

3.3.3 Particle Filter

High-energy particles impacting the detectors on the LI focal plane can trigger the production of a high number of electrons within the impacted detectors that can be interpreted by the RTPP as DTs (see Figure 4 bottom panel for two simulated particle features). Moreover, depending on the direction and angle of impact the particle-DTs can be found in more or less elongated features that are acquired over a single acquisition frame. The analysis looking for particle signatures

[4] A DT is either in or off the disk.

checks if in the detected frames there are DTs that are grouped in highly elongated trapezoidal features. The processing takes place in two main steps:
1. identification of the elongated features;
2. identification of all the DTs belongings to such features.

Three configurable parameters are used in the analysis: these are used to check key properties of the candidate particle features such as the elongation and the thickness. When FTs are individuated by this analysis step these are qualified FT with 100% confidence. The LI Level 1b particle analysis is a binary filter. The algorithm performing the particle analysis proposed by industry is highly refined and time consuming. For this reason in the Level 2 analysis of the properties of groups another particle filter is proposed (see Section 4.6.1).

3.3.4 Ghost Filter

The ghost image is due to reflections/refractions that appear on the focal plane of LI. The properties of the LI optical system imply that the LI ghost is symmetric with respect to the centre of the OC. As a consequence the analysis of the ghost filter is focused on finding correlated pairs of DTs (or groups of DTs) within the frames acquired by a single OC. For the individuated pairs the following processing steps are performed:
- correction of the DT lightning net effective radiance by removal of the ghost effect component which is quantified by means of a configurable ghost radiance fraction;
- comparison of the corrected radiance against the RTPP threshold to conclude on the origin of the DTs, in detail, if after the ghost radiance correction the residual radiance of the DT is above/below the RTPP threshold one can state that the DT is a TT/FT.

The DTs analysed by this analysis step are qualified with a confidence level in the interval [0, 1]. Such confidence is computed as one minus the ratio of the ghost corrected radiance and the RTPP threshold for the FT.

3.3.5 Jitter (reconstruction) Filter

The jitter (reconstruction) filter complements the analysis performed at Level 0 by the MVF (see Section 3.2.2.2). Differently from the Level 0 analysis, at Level 1b this is done by exploiting the information over 1000 frames (i.e., 1 sec buffer) in the following processing sequence:
1. reconstructing the jitter (micro-vibration) spectrum;
2. correcting the DT net signal for the jitter-induced signal;
3. flagging as FTs those DTs that after the correction do not pass anymore the Level 0 RTPP detection threshold.

The approach adopted for the jitter reconstruction (point 1) is the following:
- selection of DT beacons: the jitter is reconstructed by exploiting DTs with a very specific property, i.e., a ratio between the net signal and the background radiance gradient (evaluated by adding up along-x and along-y gradients) above a configurable threshold;
- estimation of the jitter movement for a limited number of frames by solving a system of equations which describes, for all the beacons, the net DT signal as the sum of the maximum along-x gradient times the x component of the jitter plus the same quantity along y, i.e., exploiting the underlying assumptions that for the beacons the net signal is completely defined by the jitter movement;

- finally, reconstruct the jitter signal for all the frames in the analysed buffer by performing a fit, with a configurable number of harmonics, of the jitter movement estimated from the previous point.

The DTs analysed by this analysis step are qualified with a confidence level in the interval [0, 1]. Such confidence is computed as one minus the ratio of the jitter corrected radiance and the RTPP threshold for the FTs.

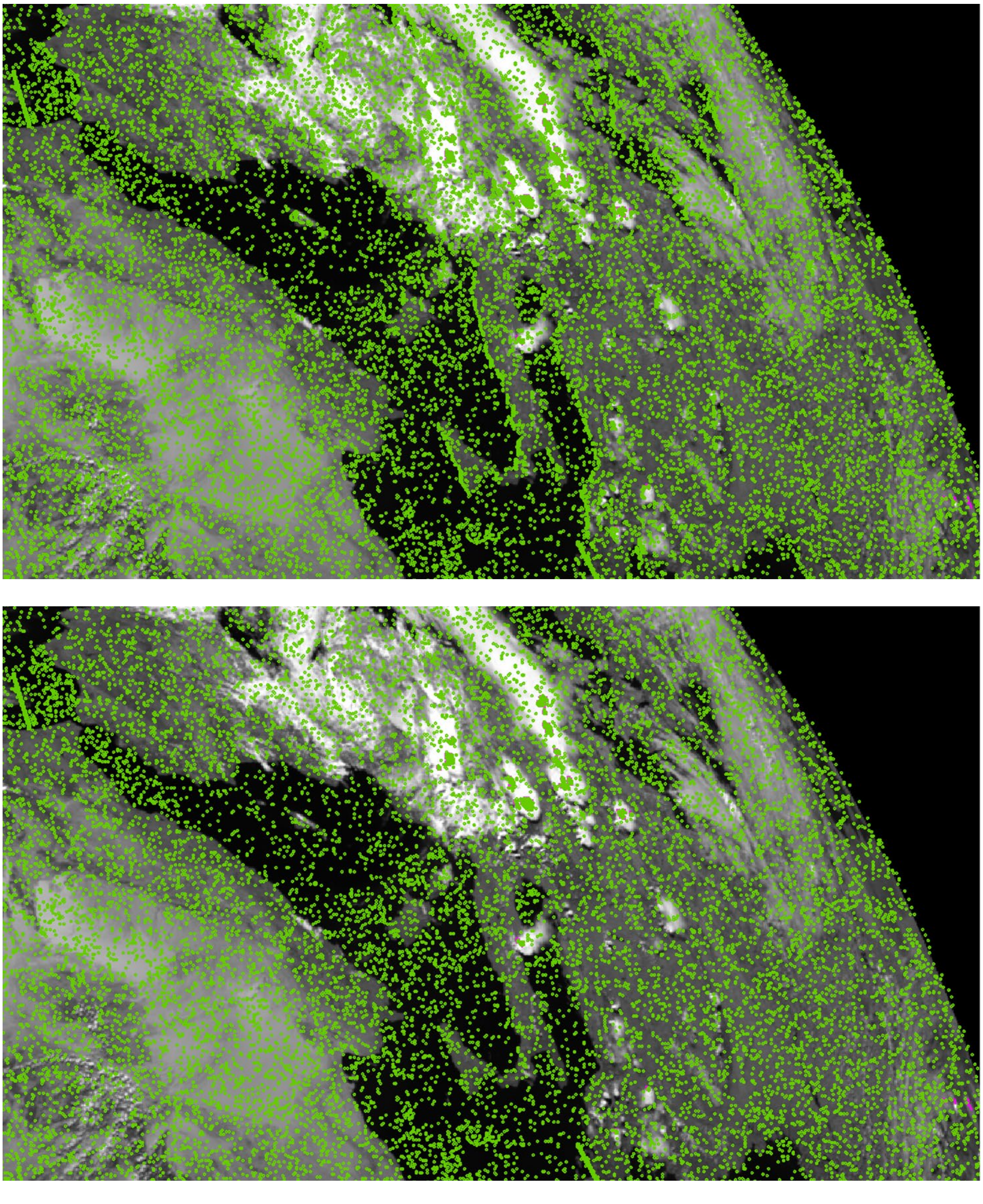

Figure 5: Impact of the Level 1b Jitter Filter on the outcome of the pre-processor. Pixels with green circles are marking the DTs that passed the filtering steps. Top panel: the data that

passed the pre-processor filtering, i.e., the data in the bottom panel of Figure 4 without off-disk DTs. Bottom panel: the data that passed the jitter filter, e.g., notice how the chains of DTs found in the upper panel along Italy's west coast lines are rejected.

3.3.6 Spatio Temporal Coherency (STC) Filter

The STC filter complements the analysis performed at Level 0 by the SDTF (see Section 3.2.2). Differently from the Level 0 analysis, at Level 1b this is done by exploiting the information over 1000 frames (i.e., 1 sec frame buffer) in the following processing sequence. In detail, for each DT available at Level 1b to be considered a TT according to the SDTF analysis one must be able to find at least one more DT which is close in space AND close in time. The check on the spatial and temporal proximity is performed by means on two configurable thresholds. When FTs are individuated by this analysis step these are qualified FT with 100% confidence. The LI Level 1b STC filter is a binary filter.

3.3.7 Hybrid Filter

The hybrid filter is aimed at spotting DTs that have been generated by radiometric noise. In detail it consists in applying, with a more stringent approach, both the RTPP and the SDT filter (see Sections 3.2.1 and 3.2.2). The filter checks the margin with which each DT has passed the RTPP and SDT filter detection/filtering. DTs analysed by this analysis step are qualified with a confidence level in the interval [0, 1]. Such confidence is computed as the product between one minus the ratio of the RTPP detection margin over the new RTPP threshold used in the Hybrid filter and the same quantity computed for the SDT filter values.

3.3.8 On the use of the frame buffers

Table 3 lists the amount of data (expressed in length of the time buffer) over which each Level 1b filter works.

Table 3: Level 1b filter time buffer

Filter	**Frame buffer (1 frame / ms)**
Pre-processor	500 frames
RTS	500 frames
Particle	500 frames
Ghost	500 frames
Jitter	1000 frames
STC	1000 frames
Hybrid	500 frame

Five out of seven of the Level 1b filters work on time buffers of 500 frames, i.e., 0.5 sec, which corresponds to the standard time slot of Level 1b processing. For these no further clarification is needed. Two of the filters work on a time buffer of 1 sec:

- Jitter (reconstruction) filter (see Section 3.3.5)
  The filter is applied to non-overlapping 1 sec time buffers, meaning that if one considers a sequence of 0.5 sec buffers numbered as **n**, **n+1**, **n+2**, and **n+3** the filter analyses the pairs **n**, **n+1** and **n+2**, **n+3**; a rolling window approach is not applied since conflictual flagging of

DTs from two different analyses applied to the same time slot may be obtained. At the same time the assumption that the jitter reconstruction can be performed correctly on 1 sec time buffers is done.

- STC filter (see Section 3.3.6)
  The filter is applied to 1 sec time buffers which overlap over 0.5 sec, meaning that if one considers a sequence 0.5 sec buffers numbered as **n**, **n+1**, **n+2**, and **n+3** the filter analyses the pairs **n**, **n+1** at first **n+1**, **n+2** in the second step, and so on. The rolling window approach is applied since the coherency must be checked over time.

4 LEVEL 2 PROCESSING

4.1 On the Level 2 filtering thresholds

In this document each computation step will use configurable parameters. Here the standard values for the parameters are provided, together with a description of the typical range of variability for each parameter. However, each parameter will be provided as a Look-Up-Table (LUT) that will describe the variation of the parameter itself with the illumination conditions (i.e., with the Sun Zenith Angle, SZA). This will allow one an illumination-dependent Level 2 processing. In the following we provide an example to describe how to pick the value of the parameter for a specific filtering step here named **`L2Filt`**.

Let's consider the filtering of a Flash whose average position is described by **`F_LatAvg/LonAvg`** and whose temporal occurrence is described by the average of the occurring times of its groups. By means of these three quantities one can derive the SZA for the flash. At this point, the threshold for the filter **`L2Filt_Thld`** can be derived from the **`L2Filt_LUT(SZA)`** by employing a configurable interpolation method that can be set by means of **`L2_LUT_InterpMethod`**. Finally, an important remark is due: the LUT for each filter will be provided per OC.

Table 4: tuneable parameter of the procedure to derive the threshold for the Level 2 filtering steps

Parameter	**Standard Value**	**Range**
`L2_LUT_InterpMethod`	`To be defined`	`1 for linear` `2 for nearest - neighbour`

4.2 Level 1b DT Acceptance for Level 2 Processing

The DTs to be processed at Level 2 can be selected from Level 1b DTs as follows. For each DT one gets out of the Level 1b processing the quantity: **`DT_L1bFilt`**$_k$, which is the outcome of the single **`k`**-th filter (**`k = 1, 2, 3, …, 7`**, see Section 3.3) providing the probability of the DT of being FT[5]: in detail, 1 means 100% probability of FT while 0 means TT. By using the outcome of these filters a "binary" (true/false, 0/1) approach is defined to accept Level 1b DT for Level 2 processing; this is a combination of conditions to be satisfied that can be defined by means of a set of flags: **`L1b_Filt_Flag`**$_k$. As complementary information the quantity **`DT_L2QA`** is derived with the purpose of quantifying the margin with which the DT selected for Level 2 processing has passed the acceptance step.

If	**Then**
`L1b_Filt_Flag`$_k$ `* DT_L1bFilt`$_k$ `< L1b_Filt_ThldRej`$_k$	`DT goes to Level 2 processing`

[5] According to a specific filter.

`for all k = 1, 2, 3, …, 7 the L1b filtering steps`	`with DT_L2QA as a descriptor`
`else`	`DT does not go to Level 2 processing`

`DT_L2QA` is computed as follows: **`max(DT_L1bFilt`**$_k$**`)`** for those **`k`** with **`L1b_Filt_Flag`**$_k$ **`= 1`**. This is indicating that the DT is as close to be false as the worst outcome of the Level 1b filter considered in the acceptance procedure[6].

Table 5: tuneable parameter of the procedure to accept Level 1b data at Level 2

Parameter	**Standard Value**	**Range**
`L1b_Filt_Flag`$_k$	`1 for all the Level 1b filters`	`either 0 or 1`
`L1b_Filt_ThldRej`$_k$	`To be defined depending on the Level 1b filtering method`	`[0, 1] in LUT(SZA, OC)`

4.3 Total Number of DTs

In order to support the analysis of groups presented in Section 4.6.3 the variation, as a function of the frame, of the total number of Level 1b DTs is needed (**`L1b_Trans`**). Such number is derived by using all the DTs available at Level 1b independently from the Level 1b filtering outcome.

4.4 Level 2 Groups and Flashes Computation and Filtering

In Figure 7 and Figure 8 the diagrams describing the whole Level 2 processing are presented. In the following sections (from Section 4.5 to Section 4.9) the details of each one of the processing steps are provided; for clarification the "Level 1b DT Acceptance for Level 2 Processing" described in Section 4.2 is represented by the block named "L1b data selection" while **`L1b_Trans`** is computed from the input named "L1b data".

For the sake of shortness it is worth introducing at this point a simple formulation that is employed all along the groups and flashes analyses steps. In order to classify a group or a flash as composed by FTs a value ranging in [0, 1] is provided. The template for such classification is a standard function **`P(x, MinThld, MaxThld)`** (see Figure 6). **`P(x, MinThld, MaxThld)`** is the probability of a group/flash of being composed by FTs derived from a measurable property **`x`** and two thresholds on the measure itself (**`MinThld`**, and **`MaxThld`**). Below **`MinThld`** the group/flash is considered to be composed by TTs while above **`MaxThld`** it is considered to be composed by FTs. This approach allows the user to have a flexible way of classifying groups/flashes with a linear variation of the likelihood from 0 to 1 when going from the

[6] Of course **`DT_L2QA < L1b_Filt_ThldRej`**$_k$ for those **`k`** with **`L1b_Filt_Flag`**$_k$ **`= 1`**.

minimum threshold to the maximum threshold. By employing the formula **`1 - P`** one can invert such variation. Finally, by setting the two thresholds to the same value one is capable of getting a binary classification 0/1. In a compact fashion:

Table 6: template of the probability computation for the different analyses of groups and flashes.

If	**Then**
`x <= MinThld`	`P = 0`
`MinThld < x < MaxThld`	`P = (x - MinThld) / (MaxThld - MinThld)`
`x >= MaxThld`	`P = 1`

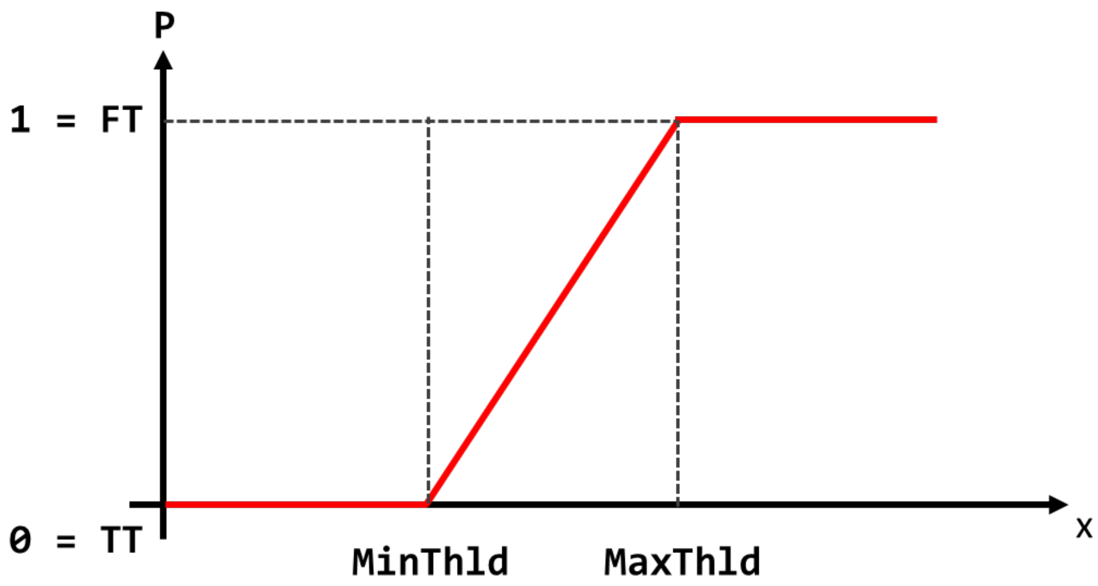

Figure 6: standard function for the classification of both groups and flashes.

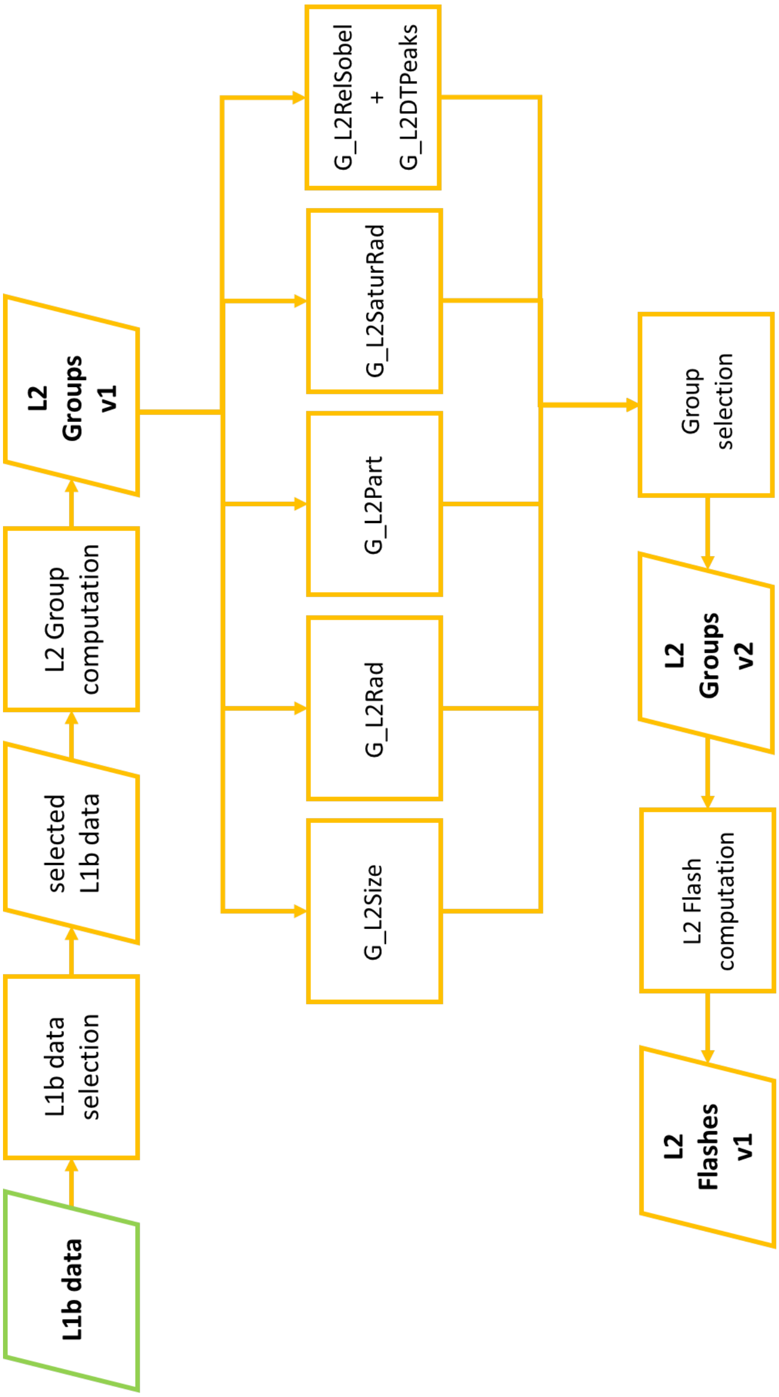

Figure 7: Level 2 groups and flash computation and filtering (A).

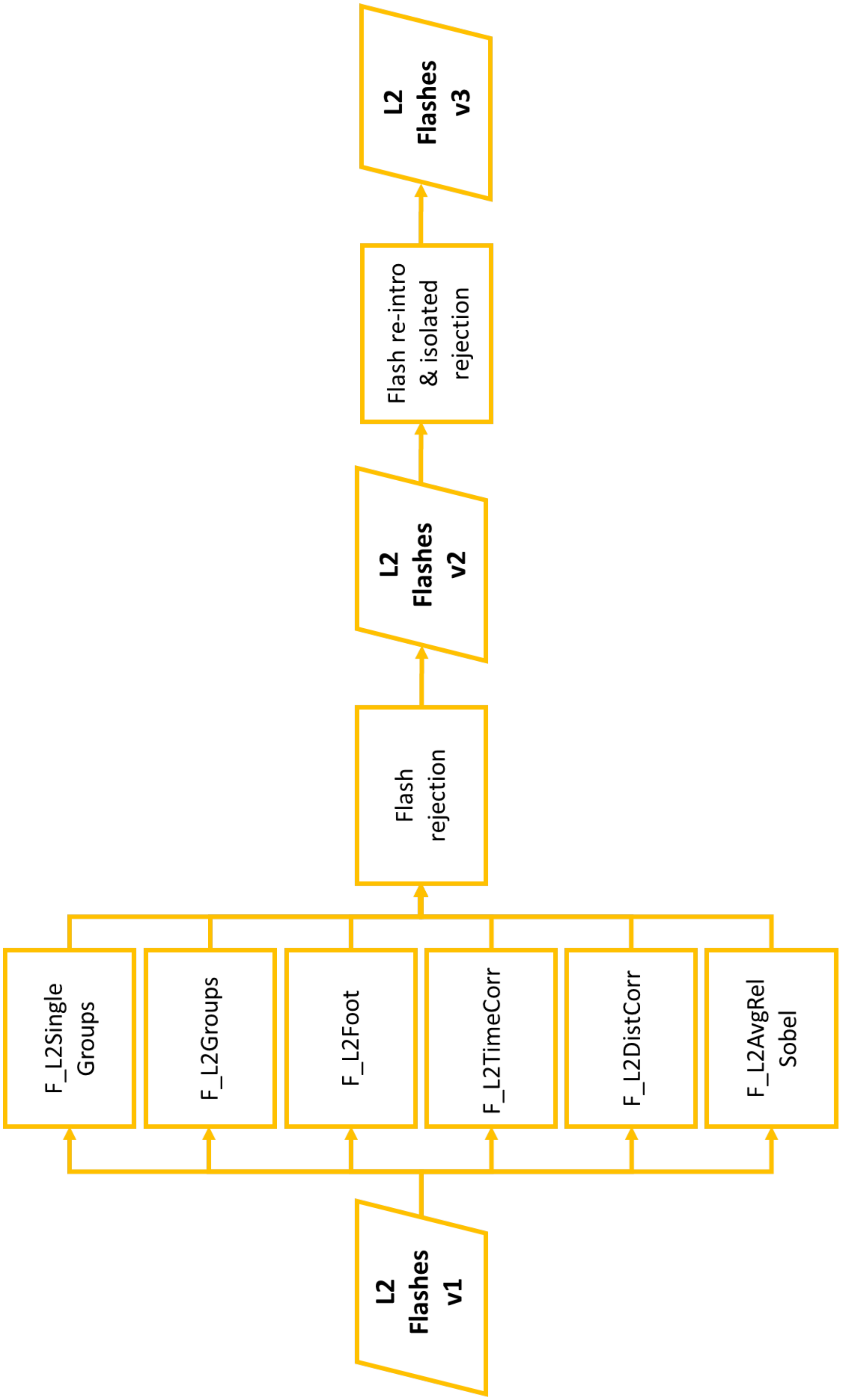

Figure 8: Level 2 groups and flash computation and filtering (B). The processing starts at "Level 2 Flashes v1" box (see Figure 7).

4.5 Computation of groups

The computation of groups is performed with the following steps repeated for each acquired frame and for each LI OC, i.e., from 1 to 4; it is very important to stress that the outcome of the computation for each OC must be kept separated from the others, i.e., at the end of the processing the groups will be available per OC. In the following the processing within a single frame is described:

1. A binary (black and white) image with size [1000, 1170] (rows and columns of one LI OC) is populated with 1 at the locations of the DTs that are accepted for Level 2 processing (see Section 4.2).
2. On the binary image defined in the previous step a Connected Component Labelling (CCL) is applied with connectivity checked over the **`G_ConnNeighbour`** neighbour pixels of each pixel at 1. The connected components from this analysis are the Level 2 groups in which DTs are grouped (for reference on the function used in the Matlab prototype refer to **`bwconncomp`**).
3. For each transient composing the groups the following quantities will be used in the Level 2 processing steps:
   - **`DT_ID`**: the ID of the DT;
   - **`DT_Frame`**: index of the frame in which the DT has been acquired;
   - **`DT_Time`**: the acquisition time of the DT (directly related to **`DT_Frame`**);
   - **`DT_Row`**: the row in the LI OC of the DT;
   - **`DT_Col`**: the column in the LI OC of the DT;
   - **`DT_Rad`**: the radiance for the central pixel of the DT window;
   - **`DT_Lat`**: the latitude of the central pixel of the DT window;
   - **`DT_Lon`**: the longitude of the central pixel of the DT window;
   - **`DT_BkgMin`**: the minimum background radiance in the DT window;
   - **`DT_Sobel`**: the Sobel gradient for each DT computed within the DT window.
   - **`DT_L2QA`**: the confidence of the DT of being TT (see Section 4.2).
4. For each group the following quantities are computed and stored for the following Level 2 processing steps:
   - **`G_ID`**: unique identifier of the group;
   - **`G_Size`**: total number of transients composing the group;
   - **`G_Frame`**: index of the frame in which the group has been defined;
   - **`G_LatAvg`**: the average latitude of the group computed by using as weights the radiance of the events composing the group;
   - **`G_LonAvg`**: the average longitude of the group computed by using as weights the radiance of the events composing the group;
   - **`G_Rad`**: the average radiance of the group computed by using only the DT central pixel;
   - **`G_Time`**: the acquisition time of the group (directly related **`G_Frame`**);
   - **`G_Elong`**: the elongation of the group signature in the binary image, i.e., the ratio between the major and minor axis of the ellipse with the same second momentum of the connected region (for reference on the function used in the Matlab prototype refer to source code of the **`regionprops`**);
   - **`G_L2QA`**: the confidence of the group of being composed by TT (see Section 4.6.7);

- **`G_FlashID`**: link to the flash ID to which the group is part of (to be populated during the definition of the flashes; see Section 4.7).

Table 7: tuneable parameters for the computation of the groups

Parameter	**Standard value**	**Range**

`G_ConnNeighbour`	`8`	`8 check over all the surrounding pixels (also the diagonal ones)`
		
		`4 check along X and Y.`

Considering connected DTs over single frames may appear to be too restrictive, however this ease the use of the analyses checking, for example, the shape/size of groups, and also the format of the Level 2 data that will be archived/disseminated. Moreover, one must consider that a much less strict approach in relating/collecting DTs is then applied at flash level, this means that DTs that have not been included in the same group only because the group definition is done on one frame will be collected in the same flash, but as part of different groups (see Section 4.7).

4.6 Analyses of Groups' Properties

4.6.1 Check on the particle signature (`G_L2Part`)

Particle signature on the focal plane are known to be highly elongated features; the settings to classify groups according to the elongation as particle signatures are presented in the following. The key quantities to be employed in the template of Table 6 are:

- **`G_Elong = x`**;
- **`G_L2Part = P`**.

Table 8: tuneable parameter of the Level 2 **`G_L2Part`** *analysis.*

Template parameter	**Parameter**	**Standard Value**	**Range**
`MinThld`	`L2Part_MinElongThld`	`10`	`> 1; in LUT(SZA, OC)`
`MaxThld`	`L2Part_MaxElongThld`	`10`	`> 1; in LUT(SZA, OC)`

4.6.2 Check on the saturation of the radiance of the group (`G_L2SaturRad`)

In case of either solar intrusion, Sun glint, or stray-light, DTs with very high radiances are expected to be detected; these are classified as FTs in the Level 2 processing. By referring to the DT radiances (**`DT_Rad`**) available for every DT within the group one can assign to groups a likelihood of being related to the type of source mentioned above. The key quantities to be employed in the template of Table 6 are:

- **G_SaturFract = x** which is the number of DTs in the with **DT_Rad > L2SaturRad_SatRad** normalized by the total number of DTs in the group (**G_Size**);
- with moreover **G_L2SaturRad = P**.

The analysis here presented can be complemented by the information available in the Level 2 product **LI-L1B-LE-BODY** in the fields:

- **pixel_detector_quality** which has flags for *i)* **saturation_warning** and *ii)* **stray_light_warning**.
- **pixel_scene_quality** which has a flag for the **possible_sun_glint**.

By setting the flag **L2SaturRad_UseL1bQA** to 1 the analysis will employ the quality indicators in the following way:

If	**then**
pixel_detector_quality == saturation_warning for a fraction of transients in the group >= L2SaturRad_MinFractThld	G_L2SaturRad = 1
pixel_scene_quality == possible_sunglint for a fraction of transients in the group >= L2SaturRad_MinFractThld	G_L2SaturRad = 1
pixel_detector_quality == stray_light_warning for a fraction of transients in the group >= L2SaturRad_MinFractThld	G_L2SaturRad = 1
else	G_L2SaturRad is derived from the template

Table 9: tuneable parameter of the Level 2 **G_L2SaturRad** *analysis.*

Template parameter	**Parameter**	**Standard Value**	**Range**
MinThld	L2SaturRad_MinFractThld	0.3	[0, 1]; in LUT(SZA, OC)

`MaxThld`	`L2SaturRad_MaxFractThld`	`0.3`	`[0, 1]; in LUT(SZA, OC)`
`na`	`L2SaturRad_UseL1bQA`	`0`	`either 0 or 1`
`na`	`L2SaturRad_SatRad`	`600 mW/(m² sr)`	`> 0; in LUT(SZA, OC)`

4.6.3 Check on the Sobel gradient of the background (`G_L2RelSobel`)

By referring to the group properties **`DT_BkgMin`** and **`DT_Sobel`** available for every DT within the group one can compute the likelihood of having defined a group composed by FTs generated by the instrument micro-vibrations at the location of a steep background gradient. The ratio between **`DT_Sobel`** and **`DT_BkgMin`** allows one to compute the likelihood of having such group. The key quantities to be employed in the template of Table 6 are:

- **`RelativeSobel = avg(DT_Sobel/DT_BkgMin) = x`** (computed within the group);
- **`G_L2RelSobel = P`**.

Table 10: tuneable parameter of the Level 2 **`G_L2RelSobel`** *analysis.*

Template parameter	Parameter	Standard Value	Range
`MinThld`	`L2RelSobel_MinThld`	`10`	`> 0; in LUT(SZA, OC)`
`MaxThld`	`L2RelSobel_MaxThld`	`10`	`> 0; in LUT(SZA, OC)`

4.6.4 Using the number of Level 1b DTs in the `L2RelSobel` context (`G_L2DTPeaks`)

The analysis described in Section 4.6.3 can be complemented by using as extra information the temporal variation of the total number of Level 1b DTs (without any filter applied, see Section 4.3). In detail, if a group with a high value of **`G_L2RelSobel`** is found in correspondence of a peak in the temporal variation of the total number of Level 1b DTs (**`L1b_Trans`**), then one has extra information to conclude on the micro – vibration origin of the group itself. In the following the computation of **`G_L2DTPeaks`** is presented.

1. employ a 1D median filter (see for example the **`medfilt1`** Matlab function) to remove the large spikes from **`L1b_Trans`** that are originated by the jitter and derive a description of the DT fluctuations due to radiometric noise by computing the average and standard deviation of the filtered data (**`L1b_TransFilt_Avg`** and **`L1b_TransFilt_Stddev`**);
2. compute the following normalized difference for the frame of the group (i.e., **`G_Frame`**):

`L1b_Trans_Dev = (L1b_Trans(G_Frame) - L1b_TransFilt_Avg) / L1b_TransFilt_Stddev`;

which is the deviation of the Level 1b DT time sequence with respect to the average radiometric noise behaviour and normalized to the standard deviation describing the radiometric noise fluctuations.

The key quantities to be employed in the template of Table 6 are:

- **`L1b_Trans_Dev = x`**;
- **`G_L2DTPeaks = P`**.

Table 11: tuneable parameter of the identification of the peaks in the Level 1b DT variation (`G_L2DTPeaks`).

Template parameter	**Parameter**	**Standard Value**	**Range**
`MinThld`	`L2DTPeaks_MinDevThld`	`3`	`> 0; in LUT(SZA, OC)`
`MaxThld`	`L2DTPeaks_MaxDevThld`	`4`	`> 0; in LUT(SZA, OC)`

4.6.5 Check on the radiance of the group (`G_L2Rad`)

By referring to the radiance of the central pixel of a DT (**`DT_Rad`**) available for every DT within the group one can assign to a group a probability of being composed by FTs. By employing the threshold on the radiance **`L2Rad_Thld`** one can compute the fraction of the group with a high radiance value (**`G_HighRadFrac`**). The key quantities to be employed in the template of Table 6 are:

- **`G_HighRadFract = x`** which is the number of DTs in the with **`DT_Rad > L2Rad_Thld`** normalized by the total number of DTs in the group (**`G_Size`**);
- **`G_L2Rad = 1 - P`**;

Table 12: tuneable parameter of the Level 2 `G_L2Rad` analysis.

Template Parameter	**Parameter**	**Standard Value**	**Range**
`MinThld`	`L2Rad_MinFracThld`	`0.2`	`[0, 1]; in LUT(SZA, OC)`
`MaxThld`	`L2Rad_MaxFracThld`	`0.5`	`[0, 1]; in LUT(SZA, OC)`

`na`	`L2Rad_Thld`	`10 mW/(m² sr)`	`> 0; in LUT(Bkg, SZA, OC)`

Please note that In Table 12 a dependence on the DT background of one of the LUT has been specified.

4.6.6 Check on the size of the group (`G_L2Size`)

By referring to the number of transients in a group (**`G_Size`**) or to the physical size of a group in km^2 (**`G_Area`**) one can compute the probability of the group itself of being composed by FTs. This stems from the fact that the noise should hardly create sequences of transients that are coherent in space and time. In order to switch from number of DTs to physical area the flag **`L2Size_UseArea`** must be set to 1. If set to 0 the number of DTs will be used. The key quantities to be employed in the template of Table 6 are:

- **`G_Size (G_Area) = x`**;
- **`G_L2Size = 1 – P`**.

Table 13: tuneable parameter of the Level 2 **`G_L2Size`** *analysis.*

Template parameter	Parameter	Standard Value	Range
`MinThld`	`L2Trans_MinThld`	`4`	`> 0; in LUT(SZA, OC)`
`MaxThld`	`L2Trans_MaxThld`	`5`	`> 0; in LUT(SZA, OC)`
`MinThld`	`L2Area_MinThld`	`10 km²`	`> 0; in LUT(SZA, OC)`
`MaxThld`	`L2Area_MaxThld`	`30 km²`	`> 0; in LUT(SZA, OC)`
`na`	`L2Size_UseArea`	`0`	`either 0 or 1`

4.6.7 Rejection of Groups prior to the Computation of Flashes

For each group analysed at Level 2 one gets the quantity: **`G_L2Filt`**$_{k}$, which is the outcome of the single **`k`**-th filter providing the probability of the group of being a composed by FTs. For the groups **`k = 1, 2, …, 6`**. Two possible approaches can be employed to filter the groups prior to the computation of flashes; both exploit the outcome of the five analyses steps:

1. A "binary" approach implemented as a combination of conditions to be satisfied (against thresholds), and complemented by the computation of the **G_L2QA** that has the purpose of quantifying the margin with which the each selected group has passed the selection.
2. A "continuous" method in which **G_L2QA** is employed for the selection of the group by means of a comparison against a threshold (**G_L2QA_ThldRej**).

The two approaches can be selected by setting **L2_GRej_Approach** to 1 or 2, respectively.

If	**then**
`L2_GRej_Approach == 1`	

`L2Part_Flag * G_L2Part <= L2Part_ThldRej AND`
`L2SaturRad_Flag * G_L2SaturRad <= L2SaturRad_ThldRej AND`
 	
`((L2RelSobel_Flag * G_L2RelSobel <= L2RelSobel_ThldRej AND L2RelSobel_Flag * L2DTPeaks_Flag * G_L2DTPeaks <= L2DTPeaks_ThldRej) OR`
 	
`L2Rad_Flag * G_L2Rad <= L2Rad_ThldRej OR`
`L2Size_Flag * G_L2Size <= L2Size_ThldRej)`
	`Group goes to flash processing with a descriptor G_L2QA`

`else`	`Group is rejected`
`L2_GRej_Approach == 2`	

`L2Part_Flag * G_L2Part <= L2Part_ThldRej AND`
`L2SaturRad_Flag * G_L2SaturRad <= L2SaturRad_ThldRej AND`
 	
`G_L2QA < G_L2QA_ThldRej`
	`Group goes to flash processing with a descriptor G_L2QA`

`else`	`Group is rejected`

G_L2QA is computed as follows for the groups:

G_L2QA = (L2RelSobel_w * G_L2RelSobel + L2DTPeaks_w * G_L2DTPeaks + L2Rad_w * G_L2Rad + L2Size_w * G_L2Size + L2_DTQA_w * <DT_L2QA>$_G$) / (L2RelSobel_w + L2DTPeaks_w + L2Rad_w + L2Size_w + L2_DTQA_w).

It is important to stress that in this computation step the analyses **G_L2Part** and **G_L2SaturRad** are considered as necessary conditions to be satisfied (there is the option though of turning off these selection criteria through the flags). These two filters are the "strong" ones that a group must pass; as a consequence the quality description is only a function of the remaining analyses. Finally, **<DT_L2QA>$_G$** is the average of the DT quality indicator of the DTs in the group (see Section 4.2).

Table 14: tuneable parameter of the Level 2 group rejection.

Parameter	**Standard Value**	**Range**
`L2_GRej_Approach`	`1`	`either 1 or 2`
`L2Part_Flag`	`1`	`either 0 or 1`
`L2SaturRad_Flag`	`1`	`either 0 or 1`
`L2RelSobel_Flag`	`1`	`either 0 or 1`
`L2DTPeaks_Flag (usable only with L2RelSobel_Flag = 1)`	`1`	`either 0 or 1`
`L2Rad_Flag`	`1`	`either 0 or 1`
`L2Size_Flag`	`1`	`either 0 or 1`
`L2Part_ThldRej`	`1`	`[0, 1]; in LUT(SZA, OC)`
`L2SaturRad_ThldRej`	`1`	`[0, 1]; in LUT(SZA, OC)`
`L2RelSobel_ThldRej`	`1`	`[0, 1]; in LUT(SZA, OC)`
`L2DTPeaks_ThldRej`	`1`	`[0, 1]; in LUT(SZA, OC)`
`L2Rad_ThldRej`	`1`	`[0, 1]; in LUT(SZA, OC)`
`L2Size_ThldRej`	`1`	`[0, 1]; in LUT(SZA, OC)`
`G_L2QA_ThldRej`	`0.5`	`[0, 1]; in LUT(SZA, OC)`

4.7 Computation of Flashes

The Level 2 flash computation consists in the aggregation of groups in space and time using typical spatial and temporal distances to define the limits within which such aggregation can take place. This processing step can be performed in two ways for LI.

1. Flash clustering based on the WED algorithm: according to the WED flash clustering algorithm, a group has to be spatially and temporally near one other group in a flash to be part of a multi-group flash, such that the following relationship is fulfilled [MACH07]:

   $$WED = \sqrt{\left(\frac{D}{D_{diff}}\right)^2 + \left(\frac{T}{T_{diff}}\right)^2} \leq 1.0$$

   Where:

   T = Difference between the two groups times/frames (in ms).

   D = The distance between the two groups.

   D_{diff} = Configurable threshold on group distance (**`L2F_DistThld`**).

   T_{diff} = Configurable threshold on group time difference (**`L2F_TimeThld`**).

   For MTG-LI it shall be configurable parameter supplied in the static application data. It is also necessary for the clustering distance values used to vary over the FOV, since the footprint on ground increases towards the edges of the FOV. The actual values used in the WED equation are to be taken from interpolating into a static LUT, based on location.
2. Flash clustering based on separate time/distance checks: in this approach the distance and time checks are considered separated so that there are no trade off effects, e.g., with spatially close groups that are separated by a longer time. In this method two groups are considered as part of the same flash only when both of the following conditions are met:

   $D <= D_{diff}$ and $T <= T_{diff}$ with the same meaning of the quantities in the previous formula.

The temporal distance (T) between groups is trivial since each group is defined on a single frame (identified by **`G_Frame`**). The distance value (D) is calculated using either a group-centroid or a group-footprint method. Both methods calculate the closest distance over the Earth's surface between two points by calculation of great circle distances. For the accuracy required by this process one can assume a spherical Earth. In addition as the groups will be relatively close together the Haversine formula [SINN0T84] can be used:

$$\Delta\sigma = 2\arcsin\left(\sqrt{\sin^2\left(\frac{\Delta\varphi}{2}\right) + \cos\varphi_1 \cos\varphi_2 \sin^2\left(\frac{\Delta\lambda}{2}\right)}\right)$$

$D = R \cdot \Delta\sigma$

Where:

$\varphi 1$ = geographical latitude of group #1 (of the compared pair);

$\varphi 2$ = geographical latitude of group #2 (of the compared pair);

$\Delta\varphi$ = absolute difference of latitude of groups #1 and #2 (of the compared pair);

$\Delta\lambda$ = absolute difference of longitude of groups #1 and #2 (of the compared pair);

$\Delta\varphi$ = Central angle between the two points (calculated in 3.3a);

R = Earth's radius (provided as a configuration parameter, but a mean value of 6371.009 km can be assumed).

As part of the flash computation the processing takes care of keeping track of duplicated groups within a flash in those regions of overlap between OCs. Duplicate groups are individuated by means of a distance threshold (**L2F_DuplGroupDistThld**) and of course by the occurrence in the same frame (**G_Frame**).

For each flash the following quantities are computed and stored for the following Level 2 processing steps:

- **F_ID**: the ID identifying the flash (this populates the field **G_FlashID** in Section 4.5);
- **F_NumEvents**: total number of transients composing the flash;
- **F_NumGroups**: total number of groups composing the flash;
- **F_NumOC**: the number of OCs covered by the flash.
- **F_FirstFrame**: the first frame of the flash derived from the DTs of the flash;
- **F_LastFrame**: the last frame of the flash derived from the DTs of the flash;
- **F_Duration**: the temporal length of the flash;
- **F_NumPixFoot**: the number of pixels composing the flash footprint;
- **F_AreaFoot**: area of the flash footprint in square kilometres;
- **F_NumSubFoot**: the total number of disconnected sub-components defining the flash footprint;
- **F_NumPixSubFoot**: the number of pixels of each sub-component of the flash;
- **F_AreaSubFoot**: area in square kilometres of each sub-component of the flash;
- **F_LatAvg**: the average latitude of the flash computed from the **G_LatMap** values by using as weights the **G_EventMap** values;
- **F_LonAvg**: the average longitude of the group computed from the **G_LonMap** values by using as weights the **G_EventMap** values;
- **F_L2QA**: the confidence of the flash of being composed by TT (see Section 4.8.7).

Table 15: tuneable parameters for the computation of the flashes.

Parameter	**Standard value**	**Range**
L2F_DistThld	16.5 km	>= 0
L2F_TimeThld	330 ms	>= 0
L2F_DuplGroupDistThld	5 km	>= 0

4.8 Analyses of Flashes' properties

In the following Sections the analyses steps composing the flash filtering are described. These must be applied only to the flashes been closed, and not to those that may still be complemented by information in the next data chunk. For this reason there will be the need of keeping track of the "open/close" status of flashes.

4.8.1 Check on the single-group flashes (`F_L2SingleGroup`)

Single-group flashes are a specific case of flashes that are mostly related to FTs. However, in order to avoid any a-priori decision that may cause the rejection of TTs one can exploit the outcome of the analyses described in 4.6.7 to classify this kind of flash. After flash definition, single-group flashes can be described as very specific groups: these have passed the group filtering as groups composed by TTs, but after the last processing step they could be considered to be composed by FTs. For this reason, in order to keep single – group flashes a second threshold – based filtering is performed on **`G_L2QA`** by employing, for example, a threshold that is lower than **`G_L2QA_ThldRej`** (it is important to stress that this threshold is employed in the group filtering only if **`L2_GRej_Approach == 2`**). This second threshold is named **`F_L2SGFQA_Thld`**.

If	**then**
`F_NumGroups == 1`	
`G_L2QA < F_L2SGFQA_Thld`	`Flash is kept to define Level 2 product with the descriptor F_L2QA = G_L2QA (see Section 4.6.7). No extra filtering step is applied to this flash.`
`else`	`Reject flash`
`F_NumGroups > 1`	`The analysis is not applied`

In order to avoid to have selected single-group flashes with **`F_L2QA`** larger than flashes with multiple groups (which are most likely composed by TTs) a clamping of the quality indicator for single-group flashes is used with a configurable value.

`if F_L2QA < F_L2SGQA_Clamp then F_L2QA = F_L2SGQA_Clamp`.

Table 16: tuneable parameter of the **`F_L2SingleGroup`** *analysis.*

Parameter	**Standard Value**	**Range**

`F_L2SGFQA_Thld`	`0.05`	`[0, 1]; in LUT(SZA, OC)`
`F_L2SGQA_Clamp`	`0.05`	`[0, 1]`

4.8.2 Check on the number of groups within the flash (`F_L2Groups`)

By referring to the number of groups in a flash (**`F_NumGroups`**) one can compute the probability of the flash itself of being composed by FTs. This stems from the fact that the noise should hardly create sequences of groups that are coherent in space and time to form flashes with high number of groups. The key quantities to be employed in the template of Table 6 are:

- **`F_NumGroups = x`**;
- **`F_L2Groups = 1 – P`**.

Table 17: tuneable parameter of the Level 2 `F_L2Groups` *analysis.*

Template parameter	**Parameter**	**Standard Value**	**Range**
`MinThld`	`L2Groups_MinThld`	`2`	`[0, 1]; in LUT(SZA, OC)`
`MaxThld`	`L2Groups_MaxThld`	`2`	`[0, 1]; in LUT(SZA, OC)`

4.8.3 Check on the "footprint" of a flash (`F_L2Foot`)

The analysis allows the user to handle two different cases: *i)* flash footprint composed by a single feature, and *ii)* flash footprint composed by multiple features. In both cases two thresholds are used to assign to the flash a likelihood of being false (with values in [0, 1]). In order to switch from "Pixels" to "Area" thresholding the flag **`L2Foot_UseArea`** must be set to 1 (by default the method works on the flash footprint pixels; flag at 0). The key quantities to be employed in the template of Table 6 are:

a) In the case in which **`F_NumSubFoot = 1`**:
   - **`F_NumPixFoot = x`**;
   - **`F_L2Foot = 1 – P`**.

b) In the case in which **`F_NumSubFoot > 1`**:
   - **`max(F_NumPixSubFoot) = x`**;
   - **`F_L2Foot = 1 – P`**.

The same applies by replacing "**NumPix**" with "**Area**".

Table 18: tuneable parameter of the F_L2Foot *analysis.*

Template parameter	Parameter	Standard Value	Range
na	L2Foot_UseArea	0	Either 0 or 1
MinThld	L2Pix_MinThld	3	>= 0; in LUT(SZA, OC)
MaxThld	L2Pix_MaxThld	3	>= 0; in LUT(SZA, OC)
MinThld	L2Pix_SubFootMinThld	3	>= 0; in LUT(SZA, OC)
MaxThld	L2Pix_SubFootMaxThld	3	>= 0; in LUT(SZA, OC)
MinThld	L2Area_MinThld	50 km^2	> 0; in LUT(SZA, OC)
MaxThld	L2Area_MaxThld	50 km^2	> 0; in LUT(SZA, OC)
MinThld	L2Area_SubFootMinThld	50 km^2	> 0; in LUT(SZA, OC)
MaxThld	L2Area_SubFootMaxThld	50 km^2	> 0; in LUT(SZA, OC)

4.8.4 Check on the time correlation between groups within a flash (F_L2TimeCorr)

This analysis approach has the aim of highlighting either flashes that are too scattered in time for being composed by groups of TTs or the groups within a flash that are too far in time from the flash core of groups to be associated to the flash itself. The analysis approach is the following:

1. the temporal barycentre of the flash is set at the average of the occurrence of the groups in the flash;
2. the temporal distance (in msec) of each group in the flash from the temporal barycentre can be calculated by means of **G_Frame**, this is **L2TimeCorr_GroupDist**;

3. the average time distance (complemented by the standard deviation) of the groups within the flash can be calculated as the average of all the distances computed in point 2, these are `L2Flash_GroupAvgTimeDist` and `L2Flash_GroupStdTimeDist`, respectively.

The key quantities to be employed in the template of Table 6 are:

- `L2Flash_GroupAvgTimeDist = x`;
- `F_L2TimeCorr = P`.

Optionally the analysis can be used to remove form the flash (and from the final Level 2 product) the groups that are too far from the flash temporal barycentre and that cannot be classified as single-group flashes. By setting to 1 the flag `L2TimeCorr_RejGroups`:

If	**then**
`L2TimeCorr_GroupDist > L2TimeCorr_RejGroupsThld * L2Flash_GroupStdTimeDist AND G_L2QA > F_L2SGFQA_Thld`	`Remove group from Level 2`
`L2TimeCorr_GroupDist > L2TimeCorr_RejGroupsThld * L2Flash_GroupStdTimeDist AND G_L2QA < F_L2SGFQA_Thld`	`Group is kept to define Level 2 product.`

Table 19: tuneable parameter of the* `F_L2DistCorr` *analysis.

Template parameter	**Parameter**	**Standard Value**	**Range**
`MinThld`	`L2TimeCorr_MinThld`	`70 msec`	`>= 0; in LUT(SZA, OC)`
`MaxThld`	`L2TimeCorr_MaxThld`	`70 msec`	`>= 0; in LUT(SZA, OC)`
`na`	`L2TimeCorr_RejGroups`	`0`	`either 0 or 1`
`na`	`L2TimeCorr_RejGroupsThld`	`3`	`>= 0; in LUT(SZA, OC)`

4.8.5 Check on the spatial correlation between groups in a flash (`F_L2DistCorr`)

This analysis approach has the aim of highlighting either flashes that are too scattered in space for being composed by groups of TTs or the groups within a flash that are too far from the flash barycentre to be associated to the flash itself. The analysis approach is the following:

1. the barycentre of the flash is at the position `F_LatAvg/Lon`;
2. the distance (in km) of each group in the flash from the barycentre can be calculated by means of `G_AvgLat/Lon`, this is `L2DistCorr_GroupDist`;
3. the average distance (complemented by the standard deviation) of the groups within the flash can be calculated as the average of all the distances computed in point 2, these are `L2Flash_GroupAvgDist L2Flash_GroupStdDist`.

The key quantities to be employed in the template of Table 6 are:
- `L2Flash_GroupAvgDist = x`;
- `F_L2DistCorr = P`.

Optionally the analysis can be used to remove form the flash (and from the Level 2 product) the groups that are too far from the flash barycentre compared to the average of the groups. By activating the flag `L2DistCorr_RejGroups`:

If	**then**
`L2DistCorr_GroupDist > L2DistCorr_RejGroupsThld * L2Flash_GroupStdTimeDist AND G_L2QA > F_L2SGFQA_Thld`	`Remove group from Level 2`
`L2DistCorr_GroupDist > L2DistCorr_RejGroupsThld * L2Flash_GroupStdTimeDist AND G_L2QA < F_L2SGFQA_Thld`	`Group is kept to define Level 2 product.`

Table 20: tuneable parameter of the* `F_L2DistCorr` *analysis.

Template parameter	**Parameter**	**Standard Value**	**Range**
`MinThld`	`L2DistCorr_MinThld`	`5 km`	`>= 0; in LUT(SZA, OC)`
`MaxThld`	`L2DistCorr_MaxThld`	`5 km`	`>= 0; in LUT(SZA, OC)`
`na`	`L2DistCorr_RejGroups`	`0`	`either 0 or 1`
`na`	`L2DistCorr_RejGroupsThld`	`3`	`>= 0; in LUT(SZA, OC)`

4.8.6 Check on the Sobel gradient of the background (`F_L2AvgRelSobel`)

This analysis has the aim of applying to flashes a similar analysis of Section 4.6.3 (applied to groups). In detail, the computation of the relative Sobel gradient is performed over the whole flash by averaging the ratio **`DT_Sobel/DT_BkgMin`** over all the DTs composing the flash and by rounding the average to the closest integer. The key quantities to be employed in the template of Table 6 are:

- **`avg(DT_Sobel/DT_BkgMin) = x`**;
- **`F_L2AvgRelSobel = 1 – P`**.

Table 21: tuneable parameter of the `F_L2AvgRelSobel` *analysis.*

Template parameter	**Parameter**	**Standard Value**	**Range**
`MinThld`	`L2AvgRelSobel_MinThld`	`20`	`>= 0; in LUT(SZA, OC)`
`MaxThld`	`L2AvgRelSobel_MaxThld`	`20`	`>= 0; in LUT(SZA, OC)`

4.8.7 Rejection of flashes

For each flash analysed at Level 2 one gets the quantity: **`F_L2Filt`**$_{k}$, which is the outcome of the single **`k`** – th filter providing the probability of the flash of being a composed by FTs. For the groups **`k = 1, 2, …, 6`**. Within the Level 2 processing flashes are divided into two categories:

1. single – group flashes: analysed/classified by means of one method (see Section 4.8.1), and described by **`F_L2QA = G_L2QA`** when classified as flashes composed by TT to be included in the Level 2 product;
2. flashes composed by more than one group: these are analysed by five filters (**`k = 2, 3, …, 6)`**. For these flashes the rejection is performed by adopting an approach similar to the one in Section 4.6.7 for the groups:
   a. a “binary” approach implemented as a combination of conditions to be satisfied, and complemented by the computation of the **`F_L2QA`** that has the purpose of quantifying the margin with which the each selected flash has passed the selection.
   b. A “continuous” method in which **`F_L2QA`** is employed for the selection of the flash after comparison against a threshold (**`F_L2QA_ThldRej`**).

The two approaches can be selected by setting **`L2_FRej_Approach`** to 1 and 2, respectively.

If	**then**
`L2_FRej_Approach == 1`	

L2Groups_Flag * F_L2Groups < L2Groups_ThldRej AND L2Foot_Flag * F_L2Foot < L2Foot_ThldRej AND L2TimeCorr_Flag * F_L2TimeCorr < L2TimeCorr_ThldRej AND L2DistCorr_Flag * F_L2DistCorr < L2DistCorr_Thldrej AND L2AvgRelSobel_Flag * F_L2AvgRelSobel < L2AvgRelSobel_ThldRej	Flash is kept to define Level 2 product with the descriptor F_L2QA
else	Flash is rejected
L2_FRej_Approach == 2	
L2Groups_Flag * F_L2Groups < L2Groups_ThldRej AND L2Foot_Flag * F_L2Foot < L2Foot_ThldRej AND L2TimeCorr_Flag * F_L2TimeCorr < L2TimeCorr_ThldRej AND L2DistCorr_Flag * F_L2DistCorr < L2DistCorr_Thldrej AND L2AvgRelSobel_Flag * F_L2AvgRelSobel < L2AvgRelSobel_ThldRej AND F_L2QA < F_L2QA_ThldRej	Flash is kept to define Level 2 product with the descriptor F_L2QA
else	Flash is rejected

The descriptor **F_L2QA** is defined as follows:
F_L2QA = (L2Groups_w * F_L2Groups + L2Foot_w * F_L2Foot + L2TimeCorr_w * F_L2TimeCorr + L2DistCorr_w * F_L2DistCorr + L2AvgRelSobel * F_L2AvgRelSobel + G_L2QA_w * <G_L2QA>$_F$) / (L2Groups_w + L2Foot_w + L2TimeCorr_w + L2DistCorr_w + L2AvgRelSobel_w + G_L2QA_w).

In this formula **<G_L2QA>$_F$** is the average of the quality descriptors of the groups within the flash.

Table 22: tuneable parameters of the Level 2 flash rejection

Parameter	Standard Value	Range
L2_FRej_Approach	1	either 1 or 2
L2Groups_Flag	1	either 0 or 1
L2Foot_Flag	1	either 0 or 1
L2TimeCorr_Flag	1	either 1 or 0

L2DistCorr_Flag	1	either 1 or 0
L2AvgRelSobel_Flag	1	either 1 or 0
L2Groups_ThldRej	To be defined	[0, 1]; in LUT(SZA, OC)
L2Foot_ThldRej	To be defined	[0, 1]; in LUT(SZA, OC)
L2TimeCorr_ThldRej	To be defined	[0, 1]; in LUT(SZA, OC)
L2DistCorr_ThldRej	To be defined	[0, 1]; in LUT(SZA, OC)
L2AvgRelSobel_ThldRej	To be defined	[0, 1]; in LUT(SZA, OC)
L2Groups_w	1	[0, 1]; in LUT(SZA, OC)
L2Foot_w	1	[0, 1]; in LUT(SZA, OC)
L2TimeCorr_w	1	[0, 1]; in LUT(SZA, OC)
L2DistCorr_w	1	[0, 1]; in LUT(SZA, OC)
L2AvgRelSobel_w	1	[0, 1]; in LUT(SZA, OC)
G_L2QA_w	1	[0, 1]; in LUT(SZA, OC)

4.9 A posteriori re-introduction of flashes by exploiting the flash footprint

This analysis step has the aim of using the outcome of the Level 2 processing to re – introduce flashes that have been rejected by the Level 2 filtering. The analysis performs a check of the spatio – temporal distance between the rejected flashes and the flashes that passed Level 2 filtering. When a rejected flash is found to be close enough (in space and time) to a flash considered true by the Level 2 processing: the rejected flash will be reintroduced in the Level 2 product. It is important to stress that the distance between the flashes should not be computed by means of the barycentre or average properties; the spatio – temporal distance should be evaluated using the events composing the flashes: as the minimum spatial distance between events (**L2_FF_MinDistSpace**, in km) combined to the minimum temporal distance between events (**L2_FF_MinDistTime**, in msec). The final decision on the re – introduction of the flash among the true flashes is performed by computing the following quantity:

L2_FF_Dist = sqrt(DistTime_w * (L2_FF_MinDistTime/DistTime_Thld)^2 + DistSpace_w * (L2_FF_MinDistSpace/DistSpace_Thld)^2)

The analysis can be activated by setting to 1 the flag **L2PostReInject_Flag**.

Table 23: tuneable parameter for the a-posteriori analysis of flashes.

Parameter	Standard Value	Range
DistTime_w	1	[0, 1]; in LUT(SZA, OC)
DistTime_w	1	[0, 1]; in LUT(SZA, OC)
DistTime_Thld	To be defined	>= 0; in LUT(SZA, OC)
DistSpace_Thld	To be defined	>= 0; in LUT(SZA, OC)

The flash that have been re – introduced through this process will be flagged at 1 in **F_L2ReIntro**. Otherwise this parameter is kept at 0.

4.10 Accumulation

The last Level 2 processing step is the definition of the Level 2 accumulated products. These are three different products, namely:
1. Accumulated Flash (**F_AF**),
2. Accumulated Flash Area (**F_AFA**),
3. Accumulated Flash Radiance (**F_AFR**).

The three are defined staring from the final flash version (i.e., flash v3 in Figure 8), and are computed as follows: for each flash that passed the Level 2 filtering the associated events are considered; from each one of these events:
1. **F_AF(DT_Row, DT_Col) = (F_AF(DT_Row, DT_Col) + 1) / F_NumEvents**;
2. **F_AFA(DT_Row, DT_Col) = F_AF(DT_Row, DT_Col) + 1**;
3. **F_AFR(DT_Row, DT_Col) = F_AF(DT_Row, DT_Col) + DT_Rad**.

The products are defined over time windows of size **F_AF_Time**; the criteria with which flashes that are found with DTs in two adjacent time windows are handled remains to be defined.
The final step of the definition of the accumulated products is the re-gridding on a reference 2 km FCI grid. The user will be able to configure the method with which the re-gridding is performed between: nearest-neighbour, bi-linear, bi-cubic, and spline.

Table 24: tuneable parameters for the computation of the accumulated products

Parameter	Standard value	Range
`F_AF_Time`	`30 sec`	`>= 0`
`F_AF_ReGrid_Method`	`Nearest – neighbours`	`Bi-linear, bi-cubic, spline.`

5 LEVEL 2 PRODUCTS

The detailed description of the content and format of the LI Level 2 products is provided in [L2_FS].

APPENDIX A LEVEL 2 SETTINGS FROM PRE-FLIGHT PERFORMANCE ASSESSMENT

In the context of the preparation of the LI Mission Advisory Group (MAG) meeting #10, EUMETSAT undertook an assessment of the expected Level 2 performance. The details of the analysis and the resulting Level 2 performances are presented in [L2_PERF]. Here we focus on the settings that were employed for deriving such performances.

A.1 Acceptance step

The settings here reported have been used for all the scenarios analysed in [L2_PERF] (see A.2, A.3, and 0). It is worth stressing that such settings do not allow one to employ the QA value in the Level 2 filtering since all the accepted DTs have QA at 0 (i.e., 100% True for all the selected Level 1b filters).

Table 25: Level 2 acceptance settings

Parameter	Value	Range
$L1b\_Filt\_Flag_k$	1 for the Pre-processor, Hybrid filter, Jitter reconstruction filter, and Spatio-Temporal Correlation filter	either 0 or 1
$L1b\_Filt\_ThldRej_k$	0	[0, 1] in LUT(SZA, OC)

A.2 day scenario

A.2.1 Group filtering

Table 26: Level 2 filtering settings for Groups for the* day *scenario. The filters that are activated are highlighted in green.

Parameter	Value	Range
L2_GRej_Approach	1	either 1 or 2
L2Part_Flag	1	either 0 or 1
L2SaturRad_Flag	0	either 0 or 1

L2RelSobel_Flag	0	either 0 or 1
L2DTPeaks_Flag (usable only with L2RelSobel_Flag = 1)	0	either 0 or 1
L2Rad_Flag	1	either 0 or 1
L2Size_Flag	0	either 0 or 1
L2Part_ThldRej	1	[0, 1]; in LUT(SZA, OC)
L2SaturRad_ThldRej	1	[0, 1]; in LUT(SZA, OC)
L2RelSobel_ThldRej	0	[0, 1]; in LUT(SZA, OC)
L2DTPeaks_ThldRej	0	[0, 1]; in LUT(SZA, OC)
L2Rad_ThldRej	1	[0, 1]; in LUT(SZA, OC)
L2Size_ThldRej	0	[0, 1]; in LUT(SZA, OC)
G_L2QA_ThldRej	0.5	[0, 1]; in LUT(SZA, OC)

Table 27: G_L2Part *filter settings for Groups for the* day *scenario*

Template parameter	**Parameter**	**Value**	**Range**
MinThld	L2Part_MinElongThld	10	> 1; in LUT(SZA, OC)
MaxThld	L2Part_MaxElongThld	10	> 1; in LUT(SZA, OC)

Table 28: G_L2Rad *filter settings for the* day *scenario*

Template Parameter	Parameter	Value	Range
MinThld	L2Rad_MinFracThld	0.5	[0, 1]; in LUT(SZA, OC)
MaxThld	L2Rad_MaxFracThld	0.5	[0, 1]; in LUT(SZA, OC)
na	L2Rad_Thld	6 mW/(m^2 sr)	> 0; in LUT(Bkg, SZA, OC)

A.2.2 Flash filtering

Table 29: Level 2 filtering settings for Flashes for the day *scenario. The filters that are activated are highlighted in green.*

Parameter	Value	Range
L2_FRej_Approach	1	either 1 or 2
L2Groups_Flag	0	either 0 or 1
L2Foot_Flag	1	either 0 or 1
L2TimeCorr_Flag	0	either 1 or 0
L2DistCorr_Flag	1	either 1 or 0
L2AvgRelSobel_Flag	1	either 1 or 0
L2Groups_ThldRej	1	[0, 1]; in LUT(SZA, OC)
L2Foot_ThldRej	1	[0, 1]; in LUT(SZA, OC)
L2TimeCorr_ThldRej	1	[0, 1]; in LUT(SZA, OC)

L2DistCorr_ThldRej	1	[0, 1]; in LUT(SZA, OC)
L2AvgRelSobel_ThldRej	1	[0, 1]; in LUT(SZA, OC)
L2Groups_w	1	[0, 1]; in LUT(SZA, OC)
L2Foot_w	1	[0, 1]; in LUT(SZA, OC)
L2TimeCorr_w	1	[0, 1]; in LUT(SZA, OC)
L2DistCorr_w	1	[0, 1]; in LUT(SZA, OC)
L2AvgRelSobel_w	1	[0, 1]; in LUT(SZA, OC)
G_L2QA_w	1	[0, 1]; in LUT(SZA, OC)

Table 30: F_L2SingleGroup *filter settings for the* day *scenario*

Parameter	Value	Range
F_L2SGFQA_Thld	0.0	[0, 1]; in LUT(SZA, OC)
F_L2SGQA_Clamp	0.0	[0, 1]

Table 31: F_L2Foot *filter settings for the* day *scenario*

Template parameter	Parameter	Standard Value	Range
na	L2Foot_UseArea	0	Either 0 or 1
MinThld	L2Pix_MinThld	3	>= 0; in LUT(SZA, OC)
MaxThld	L2Pix_MaxThld	3	>= 0; in LUT(SZA, OC)

MinThld	L2Pix_SubFootMinThld	3	>= 0; in LUT(SZA, OC)
MaxThld	L2Pix_SubFootMaxThld	3	>= 0; in LUT(SZA, OC)
MinThld	L2Area_MinThld	50 km^2	> 0; in LUT(SZA, OC)
MaxThld	L2Area_MaxThld	50 km^2	> 0; in LUT(SZA, OC)
MinThld	L2Area_SubFootMinThld	50 km^2	> 0; in LUT(SZA, OC)
MaxThld	L2Area_SubFootMaxThld	50 km^2	> 0; in LUT(SZA, OC)

Table 32: `F_L2DistCorr` *filter settings for the* `day` *scenario*

Template parameter	Parameter	Standard Value	Range
MinThld	L2DistCorr_MinThld	10 km	>= 0; in LUT(SZA, OC)
MaxThld	L2DistCorr_MaxThld	10 km	>= 0; in LUT(SZA, OC)
na	L2DistCorr_RejGroups	0	either 0 or 1
na	L2DistCorr_RejGroupsThld	3	>= 0; in LUT(SZA, OC)

Table 33: `F_L2AvgRelSobel` *filter settings for the* `day` *scenario*

Template parameter	Parameter	Standard Value	Range
MinThld	L2AvgRelSobel_MinTh	10	>= 0; in LUT(SZA,

	`ld`		`OC)`
`MaxThld`	`L2AvgRelSobel_MaxThld`	`10`	`>= 0; in LUT(SZA, OC)`

A.2.3 Filtering rationale

The `day` scenario is characterized by pulses that are located on very bright clouds (see Figure 8 of [L2_PERF]). Two Group filters are employed:

1. The Particle filter (**`G_L2Part`**) which is always activated with standard settings.
2. The Radiance filter (**`G_L2Rad`**) that requires to have at least half of the group pixels with a radiance of 6 mW/(m^2 sr) (equivalent to 6 µJ/(m^2 sr) within the 1 msec LI integration time). Such a value is below the minimum required detectable energy for the day (see [SRD]). This approach is particularly effective in removing false Groups, and it is employed for all the scenarios by varying the threshold to account for the illumination conditions of the background.

At Flash level four filters are employed:

1. Single-Group Flash filter (**`F_L2SingleGroup`**) with settings that stem from Acceptance (see A.1).
2. The Flash Footprint filter (**`F_L2Foot`**) is meant to retain only those Flashes that are characterized by at least three connected DTs. This choice is done to remove small false Flashes that are very common for very bright scenes.
3. The Spatial Correlation filter (**`F_L2DistCorr`**) is meant to filter those flashes that are created by scattered collections of false DTs. Such false Flashes are very common for very bright scenes.
4. The Average Sobel Gradient Filter (**`F_L2AvgRelSobel`**) is activated to take into account the false flashes generated at the edges of high-contrast regions. These are very common for very bright scenes.

A.3 `night` scenario

A.3.1 Group Filtering

Same settings as in Table 26 and Table 27 and the following settings for Group Radiance filter.

Table 34: `G_L2Rad` filter settings for the `night` scenario

Template Parameter	**Parameter**	**Value**	**Range**
`MinThld`	`L2Rad_MinFracThld`	`0.5`	`[0, 1]; in LUT(SZA, OC)`

MaxThld	L2Rad_MaxFracThld	0.5	[0, 1]; in LUT(SZA, OC)
na	L2Rad_Thld	2 mW/(m² sr)	> 0; in LUT(Bkg, SZA, OC)

A.3.2 Flash Filtering

Parameter	Value	Range
L2_FRej_Approach	1	either 1 or 2
L2Groups_Flag	1	either 0 or 1
L2Foot_Flag	1	either 0 or 1
L2TimeCorr_Flag	0	either 1 or 0
L2DistCorr_Flag	0	either 1 or 0
L2AvgRelSobel_Flag	0	either 1 or 0
L2Groups_ThldRej	1	[0, 1]; in LUT(SZA, OC)
L2Foot_ThldRej	1	[0, 1]; in LUT(SZA, OC)
L2TimeCorr_ThldRej	1	[0, 1]; in LUT(SZA, OC)
L2DistCorr_ThldRej	1	[0, 1]; in LUT(SZA, OC)
L2AvgRelSobel_ThldRej	1	[0, 1]; in LUT(SZA, OC)
L2Groups_w	1	[0, 1]; in LUT(SZA, OC)
L2Foot_w	1	[0, 1]; in LUT(SZA, OC)

`L2TimeCorr_w`	`1`	`[0, 1]; in LUT(SZA, OC)`
`L2DistCorr_w`	`1`	`[0, 1]; in LUT(SZA, OC)`
`L2AvgRelSobel_w`	`1`	`[0, 1]; in LUT(SZA, OC)`
`G_L2QA_w`	`1`	`[0, 1]; in LUT(SZA, OC)`

Same settings as Table 30, Table 31, and the following settings for the (number of) Groups filter

Table 35: `F_L2Groups` *settings for the* `night` *scenario*

Template parameter	**Parameter**	**Standard Value**	**Range**
`MinThld`	`L2Groups_MinThld`	`3`	`[0, 1]; in LUT(SZA, OC)`
`MaxThld`	`L2Groups_MaxThld`	`3`	`[0, 1]; in LUT(SZA, OC)`

A.3.3 Filtering rationale

The `night` scenario is characterized by pulses that are located on totally dark scenes (see Figure 12 of [L2_PERF]). Two Group filters are employed:
1. The Particle filter (**`G_L2Part`**) which is always activated with standard settings.
2. The Radiance filter (**`G_L2Rad`**) that requires to have at least half of the group pixels with a radiance of 2 mW/(m^2 sr) (equivalent to 2 µJ/(m^2 sr) within the 1 msec LI integration time). Such a value is below the minimum required detectable energy for the night (see [SRD]).

At Flash level three filters are employed:
1. Single-Group Flash filter (**`F_L2SingleGroup`**) with settings that stem from Acceptance (see A.1).
2. The Flash Groups filter (**`F_L2Group`**) is meant to retain only those Flashes that have at least three Groups. This condition is used only over totally dark scenes, and stems from the fact that the number of groups per flash detected at night-time is much higher than at day-time.

A.4 `half` scenario

A.4.1 Group Filtering

Same settings as in Table 26 and Table 27 and the following settings for Group Radiance filter.

Template Parameter	Parameter	Value	Range
MinThld	L2Rad_MinFracThld	0.5	[0, 1]; in LUT(SZA, OC)
MaxThld	L2Rad_MaxFracThld	0.5	[0, 1]; in LUT(SZA, OC)
na	L2Rad_Thld	4 mW/(m^2 sr) for OC1, 2, and 4 2 mW/(m^2 sr) for OC3	> 0; in LUT(Bkg, SZA, OC)

A.4.2 Flash Filtering

Parameter	Value	Range
L2_FRej_Approach	1	either 1 or 2
L2Groups_Flag	1 for OC3	either 0 or 1
L2Foot_Flag	1	either 0 or 1
L2TimeCorr_Flag	0	either 1 or 0
L2DistCorr_Flag	1 for OC1, 2, and 4	either 1 or 0
L2AvgRelSobel_Flag	1 for OC1, 2, and 4	either 1 or 0
L2Groups_ThldRej	1	[0, 1]; in LUT(SZA, OC)
L2Foot_ThldRej	1	[0, 1]; in LUT(SZA, OC)
L2TimeCorr_ThldRej	1	[0, 1]; in LUT(SZA, OC)
L2DistCorr_ThldRej	1	[0, 1]; in LUT(SZA, OC)

`L2AvgRelSobel_ThldRej`	`1`	`[0, 1]; in LUT(SZA, OC)`
`L2Groups_w`	`1`	`[0, 1]; in LUT(SZA, OC)`
`L2Foot_w`	`1`	`[0, 1]; in LUT(SZA, OC)`
`L2TimeCorr_w`	`1`	`[0, 1]; in LUT(SZA, OC)`
`L2DistCorr_w`	`1`	`[0, 1]; in LUT(SZA, OC)`
`L2AvgRelSobel_w`	`1`	`[0, 1]; in LUT(SZA, OC)`
`G_L2QA_w`	`1`	`[0, 1]; in LUT(SZA, OC)`

Same settings as Table 30, Table 31, Table 32 and Table 33.

A.4.3 Filtering rationale

The `half` scenario is characterized by pulses that are located on a scene that varies from night-time conditions to day-time conditions. For this reason, the settings for both Group and Flash filtering vary for the different OC. The settings are organized in three groups: for OC1 (day), for OC2 and OC4 (characterized by the terminator), and for OC3 (night). The rationale stems from the ones described in A.2.3 and A.3.3, combined.