

# Flash Detection Software - FDS

## User Manual

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## 1 INTRODUCTION

Near-Earth-Objects (NEO) are leftovers from the solar system formation process and are an essential part of the space environment. Smaller NEOs are frequent but typically burn up in the Earth's atmosphere and therefore pose little threat on the ground. However, orbiting spacecraft are not protected by the atmosphere and thus are at risk from collisions with small NEOs. The frequency and distribution of small NEOs are poorly understood, but the information is critical to quantify the risk posed to space assets. A fast-frame observation of NEO impact events on a non-illuminated part of the Moon is a promising methodology for better estimating these parameters.

Flash Detection Software (FDS) is a tool for detecting lunar impact flashes. This software can be used by any amateur or professional astronomer performing lunar monitoring observations with video cameras or CCDs to process their data and flag all potential flash events. The ultimate goal is to encourage and increase the observations of impact flashes from both professional and amateur astronomers and to enable verification of impact flashes from multiple sites.

### 1.1 Requirements

For proper functioning of the software, the following requirements are assumed to be fulfilled:

- The user has a telescope and a camera.
- The telescope's field of view shall allow observing the non-sunlit part of the Moon, including the limb.
- The telescope shall be able to track the Moon.
- The camera frame shall be able to image a significant fraction of the non-illuminated part of the Moon's disk.
- The camera shall be one of the following: Altair, Basler, FLIR/PGR, IDS, NexImage, QHY, Skyris, TIS, ZWO ASI.
- The camera drivers have been installed in the user's computer

Moreover, regarding the software use, the following requirements are assumed to be fulfilled:

- The user has downloaded and installed [Java Version 8](#) or later.
- The user has downloaded and installed [FireCapture](#).
- The user has downloaded and installed the FDS plugin.
- The user has downloaded and installed the FDS stand-alone application.
- The user has enough storage in the computer, around 2GB per observation night.
- The user has a USB3.0 or later port in the computer, able to run in fast mode.
- The user has a USB3.0 or later to connect the camera to the computer.

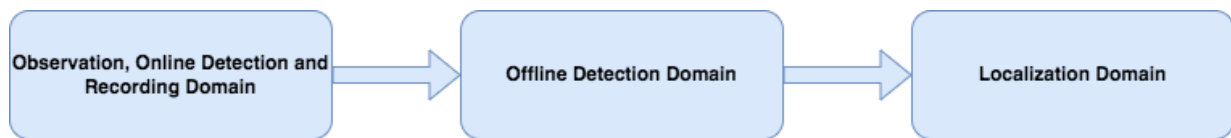
### 1.2 Software Architecture

The Flash Detection Software (FDS) system is split into three separate functional domains regarding the operations and the use cases' applicability (Fig. 1):

- **Observation, Online Detection and Recording Domain** [Observation] - Carries out three processes simultaneously: observations with a telescope (TEL) of the Moon and specific sources, images acquisition with a camera system (CAM) during the observations. Afterward, it applies a real-time event-detecting algorithm and records the event image frames and specific metadata on a storage device. All these processes are developed as a plugin for FireCapture.
- **Offline Detection Domain** [Offline Detection] -

Processes the recorded images to classify them as true-positive or false-positive and extract helpful information regarding the event, such as the Full width at half maximum value.

- **Localization Domain** [Localization] -  
Performs the task of Localization of these Lunar Impact Flashes to the Selenographic Coordinates.



**Fig. 1 FDS system functional domains**

In the Observation Domain, the user should set up the telescope and the camera and open the FireCapture application afterward. In the "pre-processing" section of FireCapture, the user will find our provided plugin, named FDS. The user should initialize the plugin parameters, such as the number of frames recorded before and after the event and the threshold parameter. The online detection feature allows the user to store less data on storage during an observation session. The final result of this domain is a hierarchical directory with the captured frames and meta-data files regarding each captured event.

After the Observation phase, the user must load all this data (frames and meta-data files) to the stand-alone Detector GUI program provided. As a result, the Offline Detection Algorithm will classify all the recorded events as true-positive or false-positive. After this classification, the user will have a CSV file report informing him about which of the recorded directories are impact flashes and which are not. Afterward, the user has the option to use the Localization tool we provide to find the Selenographic coordinates of the given impact flashes.

This concept is illustrated in the figure below:

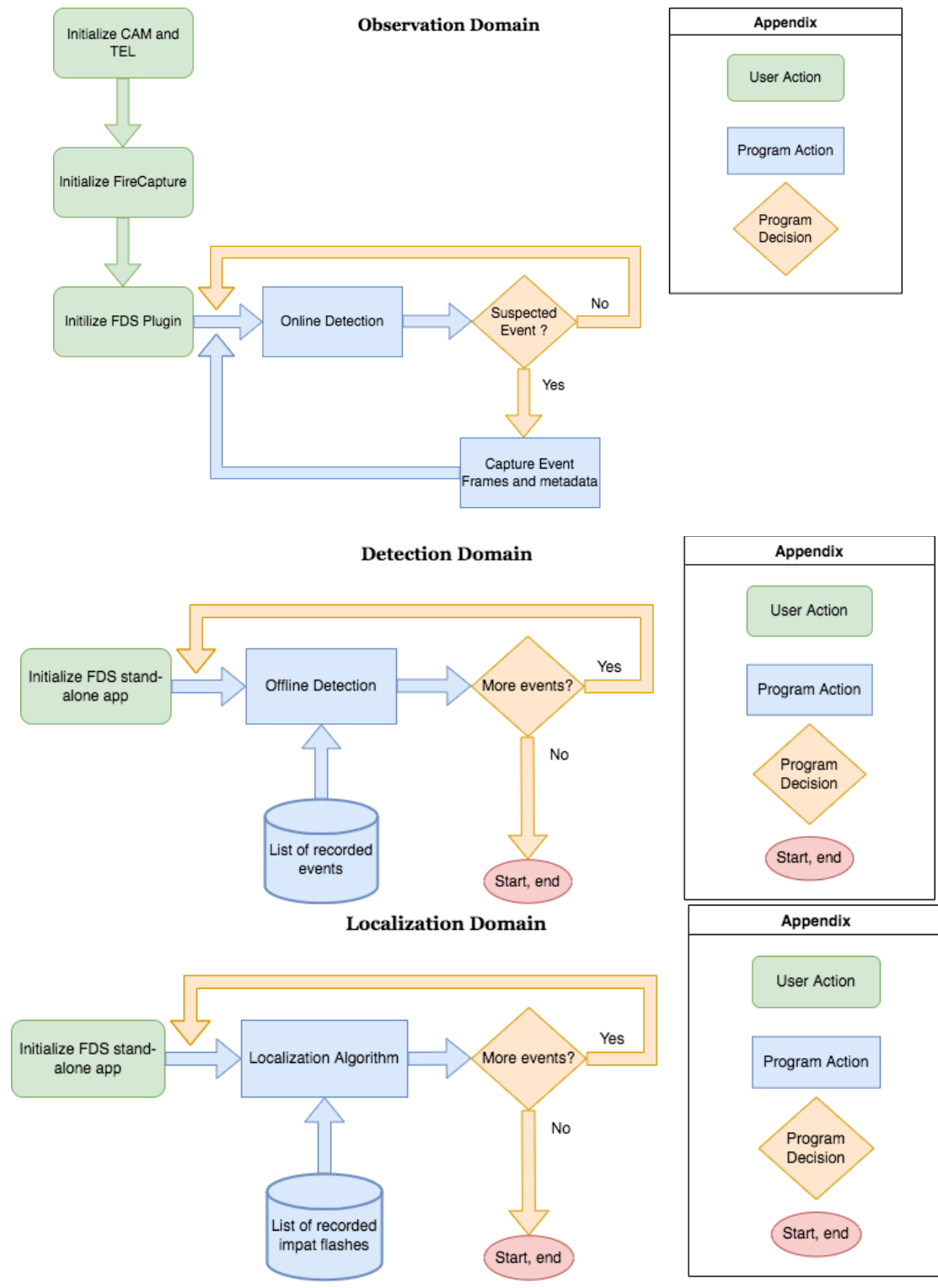


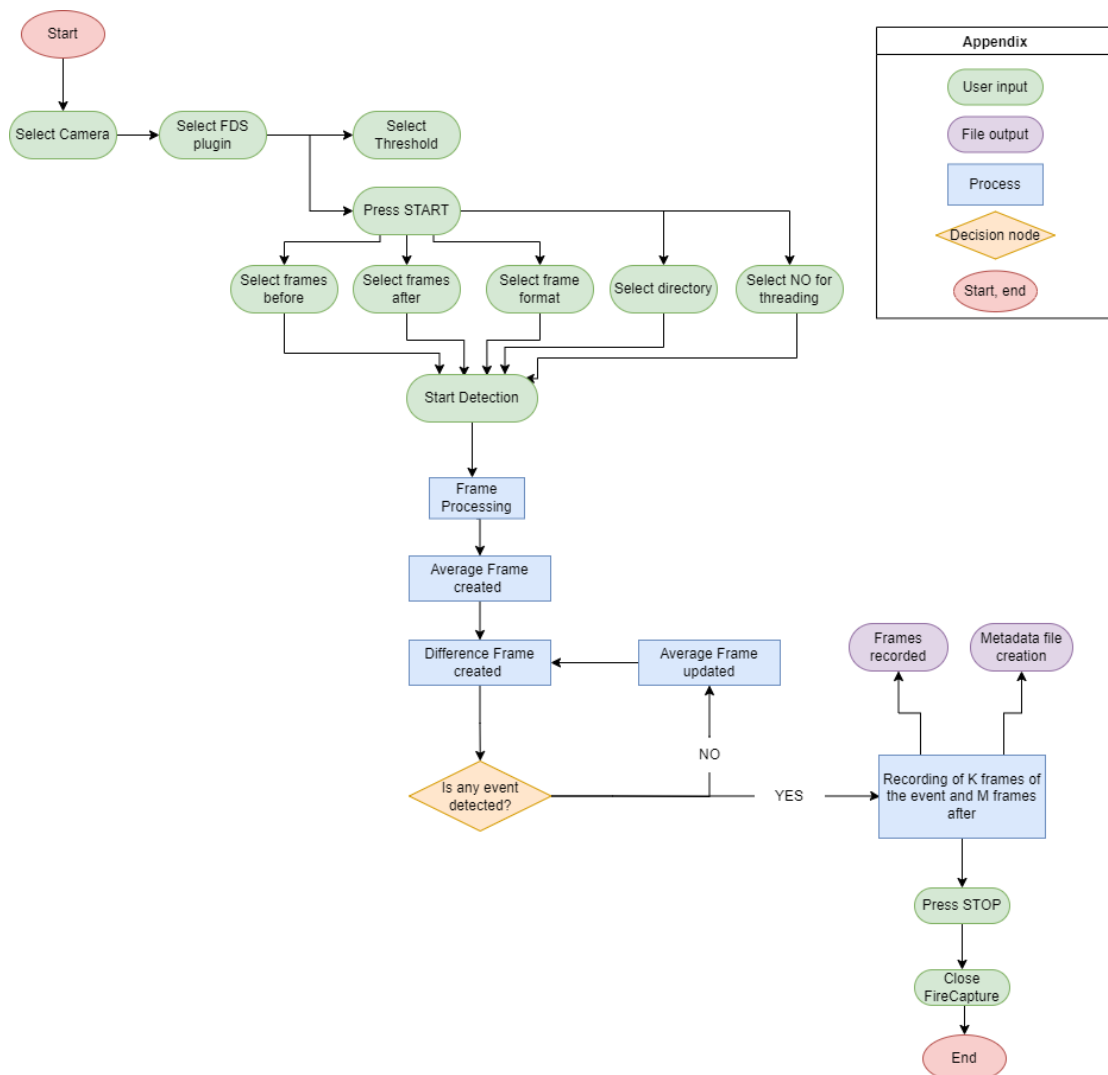
Fig. 2 Domains Control Flow

## 2 OBSERVATION DOMAIN

### 2.1 Overview

The overview of the Observation Domain is the following:

- Start FireCapture, select the camera that is connected and select the FDS plugin from the plugin list.
- Set the threshold to an appropriate value, given the observation conditions and press the START button on the plugin interface.
- Select the number of frames before and after the event that will be recorded, the format of the frames, the recording folder and “yes” for the threading option. Allow the detection to start, pressing the OK button.
- When the first event occurs, wait for the plugin to finish the saving of the frames and the creation of the metadata file.
- After the end of the observation process, stop the FDS plugin, using the STOP button and finish the session in FireCapture, using the close button.



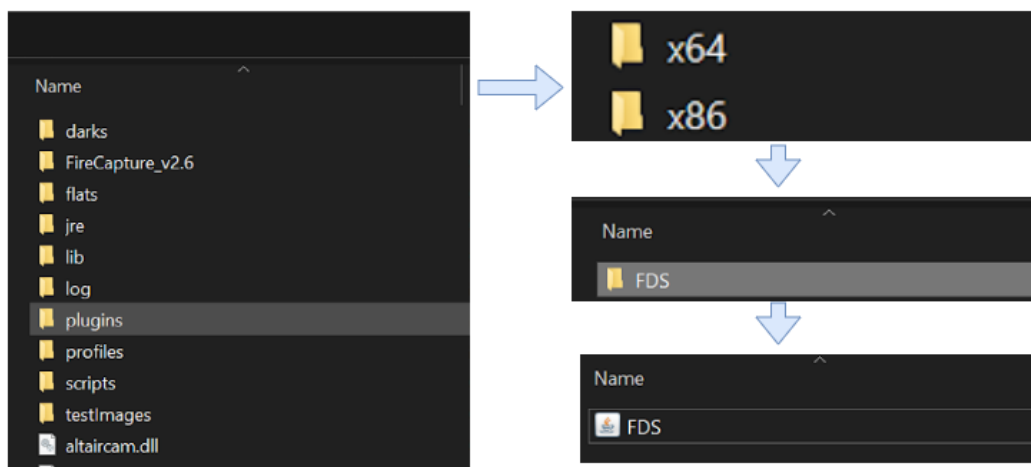
## 2.2 Download and Installation

Firstly, the user should download the FDS plugin provided here.

Then depending on the Operating System that he/she has, the instructions for installing the FDS plugin in FireCapture are different.

The procedure for installing the FDS plugin for Windows is:

- Open the FireCapture folder.
- Then, open the Plugins folder.
- Then, open the x64 or x86 folder, depending on your installation.
- There create a folder and name it FDS.
- Inside this folder, place the provided plugin "FDS.jar".



The procedure for installing the FDS plugin for Linux is:

- Open the Plugins folder, which is located at the following address:
  - /opt/FireCapture\_v2.7/plugins/
- Then, open the x64 or x86 folder, depending on your installation.
- There create a folder and name it FDS.
- Inside this folder, place the provided plugin "FDS.jar".

Sometimes, the Linux user may need to change the permission of the directory where they want to write their detected impact flashes. For example, if the user would like to write their detected flashes in the directory:

- /home/user

He/she should type in the terminal the following command:

- `sudo chmod -R 777 /home/user`

The procedure for installing the FDS plugin for MacOS is:

- Open the Plugins folder, which is located at the following address:
  - /Applications/FireCapture v2.7.app/Contents/Resources/plugins
- Then, open the x64 or x86 folder, depending on your installation.
- There create a folder and name it FDS.
- Inside this folder, place the provided plugin "FDS.jar".

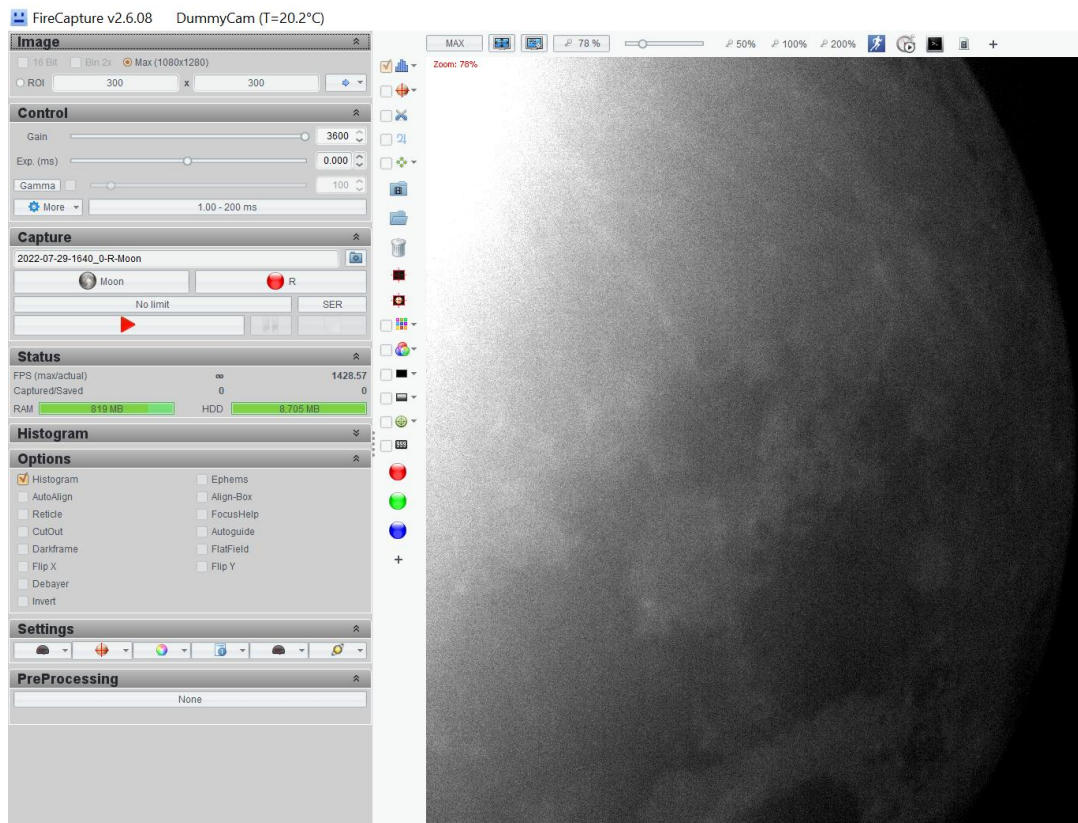


## 2.3 Prepare Observation

Firstly, the user should open the FireCapture app and select the camera that will be used during observation.



The FireCapture Interface is the following (it may differ depending the Operating System):



Then the user shall press the 'None' button in the PreProcessing Section of FireCapture and select to use the FDS.

PreProcessing & Plugins

Reset all Filter / Plugins

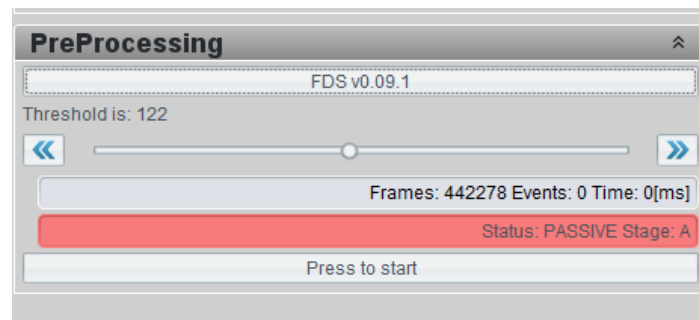
ON / OFF	Visible	Filter / Plugin
✗		Contrast
✗		Live-Stacking
✗		Average
✗		Mosaic-Helper
		Color-Saturation
✗		Bright Object
✗		Moving Object (daytime)
✗		Moving Object (night)
✗		Planetary mask
✗		FDS v0.09.1
✓	✓	FDS v0.09.1
✗		Planetary mask

Before starting the observation, the user should choose the threshold that he/she will use, while the threshold can be changed anytime during the observation night.

A proper threshold value is essential because the FDS searches each pixel of the difference incoming frame, and the detection will be triggered if at least one pixel of this image is greater than the threshold.

Setting an enormous threshold will lead to missing some events. On the other hand, setting a small threshold value will cause false positives.

The optimal value is to set a threshold a little bigger than the value that triggers constant detections. While choosing the threshold, the user should consider the weather conditions and the system.



## 2.4 Tools

When the user clicks on "Press to start", the observation and online detection process will start. During the observation process, the user is presented with several tools:

### FDS parameters GUI

Only the suspected impact flash frames will be recorded during observation. This is a feature that applies memory economy throughout the whole process. The user will choose the number of frames before and after the suspected frames to be recorded. Thus each recording of a suspected event will

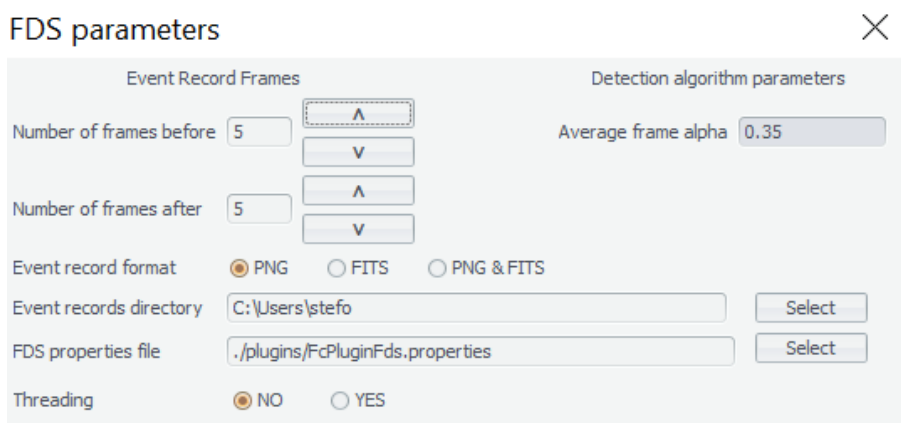
contain #N frames before, and #M frames after the suspected frames. These parameters can be selected when starting the plugin through the GUI.

Moreover, the user can choose the file format of the recorded frames, where he/she can choose between png or FITS or both and the location of the event record directory.

Finally, the user should choose if he would like to use threading or not. Suppose the user chooses not to use threading while using the FDS; when an event is detected and recorded, the program will stop searching for more events until the writing process has ended. On the other hand, if the user chooses to use threading, the program will continue searching for more events while writing the previously detected events.

The other important point for the detection is the 'alpha' parameter, the constant in the running weighted average. The running weighted average is calculated and updated as follows: A combination of two frames is used to calculate the first average. The first frame contributes to the average frame with a percentage of  $1-\alpha$ , while the second frame contributes with a percentage of  $\alpha$ . Similarly, two frames are used for the second average frame. The first average frame contributes to the second average frame with a percentage of  $1-\alpha$  and the third with a percentage of  $\alpha$ . This way, all the average frames are computed until the 10th frame, when the algorithm stops. The user can select the desired 'alpha,' but the pre-defined alpha is set to 0.35, similar to NELIOTA paper.

All the above can be easily configured by the FDS parameters GUI before starting the observation:



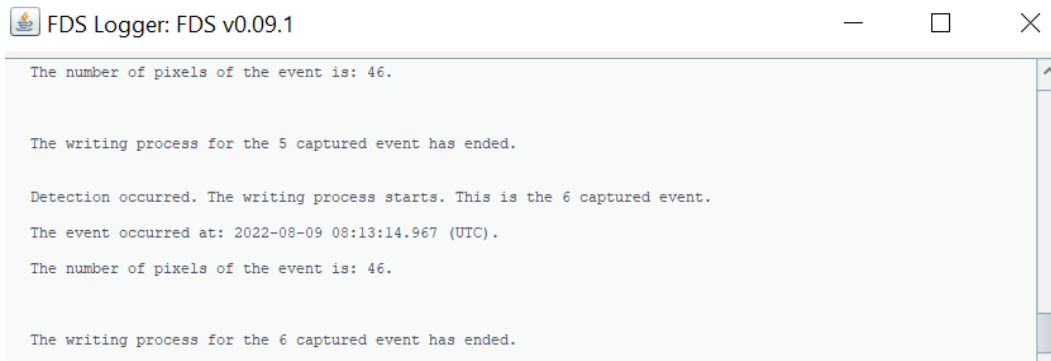
## FDS Properties File

FDS Properties File is an alternative way of making changes than entering them in the GUI. The user can change the FDS parameters by modifying the FDS properties file located in the "Plugins" directory. There the user can change the same parameters with any text editor.

## FDS Logger GUI

During the whole process, the user should look at the "Logger", which exchanges useful messages from the program to the user, such as:

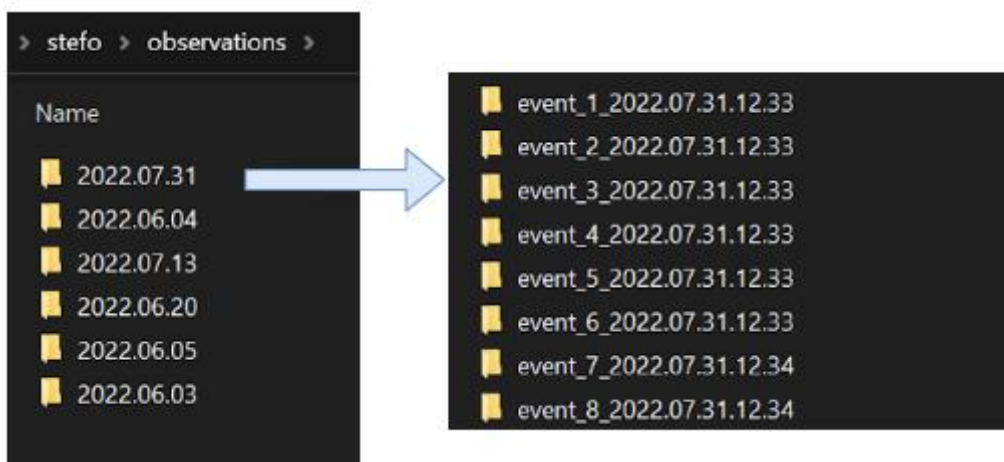
- The detection of an event
- Some statistics of the event
- The program state



## 2.5 Results

### Location of output files

The user configures the location of the output files in the FDS parameters GUI. When the user detects the first event, a folder named "observations" will be automatically created in the selected location. Inside this folder, a sub-folder of the observation day will be created. Inside this directory, all the detected events will be recorded. Thus, by the end of the observation, the user can select the day's folder, and there he/she will find all the detected events enumerated.



### Output Folder

In an event's folder, the user can find:

- A metadata file with helpful information regarding the observation
- Several frames, recording in png or FITS format.

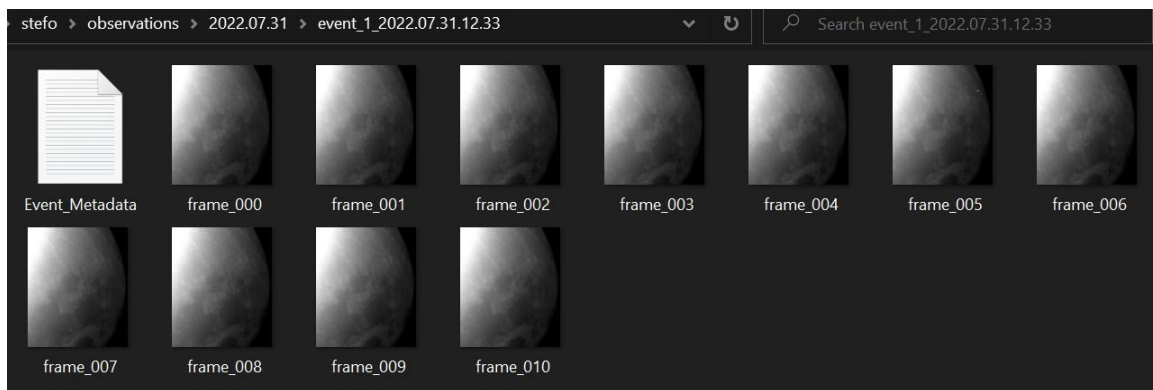
The metadata file includes information such as:

- The timestamp of each frame
- The number of pixels that have a greater value than the given threshold (in the difference image)
- The Location (x and y axis values) of these pixels
- The average Frame Per Second (FPS) during the capturing of the event

- Event information
- Camera information
- Capturing information

Regarding the Location of the pixels that have a greater value than the given threshold, the user should consider that the start of the x and y axes is the lower left corner of the image.

Inside this folder, the user can also find #N frames before and #M frames after the event. These #N and #M parameters are configurable either by the FDS parameters GUI or the FDS Properties File. The event starts in the N-th frame; the user can also find this information inside the metadata file. Moreover, the type of the frames, whether they are recorded as png or FITS files, can be configured by the FDS parameters GUI.



## 2.6 Useful Tips

### Tips for optimal observations

The following are tips for optimal observations:

- Include only the non-sunlit side
- Observe when the lunar Phase is between  $\sim 0.1$ -  $0.5$  to avoid stray light
- Obtain observations under clear weather conditions, without clouds and pollution
- Observe when the moon is higher than  $\sim 20$  deg from the horizon
- Avoid fast movements with the telescope
- Correct for Moon drifting

These are the optimal observation conditions, although the FDS can perform in non-optimal conditions, for example, when the sunlit part is included in the field of view.

### Region Of Interest

The user can select to perform the task of online detection only in a particular region of interest (ROI). ROI could be helpful when the weather conditions are non-optimal, or the user wants to exclude the sunlit part of the Moon (if the field of view of the camera is quite extensive and includes both the sunlit and the non-sunlit part of the Moon).

## **Threading**

FDS allows threading during the program to write a suspected event in the output directory. Threading allows the program to write this event and continue the detection process for another potential event. Threading is recommended to be used by everyone if the weather conditions are optimal. Threading can be selected or not by the FDS Parametres GUI.

## **Monochrome Camera vs Multi-Colour Camera**

When the user has both a monochrome camera and a multi-color camera, it is advised to use the monochrome camera. With the monochrome camera, they will achieve the fastest interaction with FireCapture and the FDS program.

If they only have a multi-color camera, they should use the R filter or the IR filter provided by FireCapture in the section Capture.

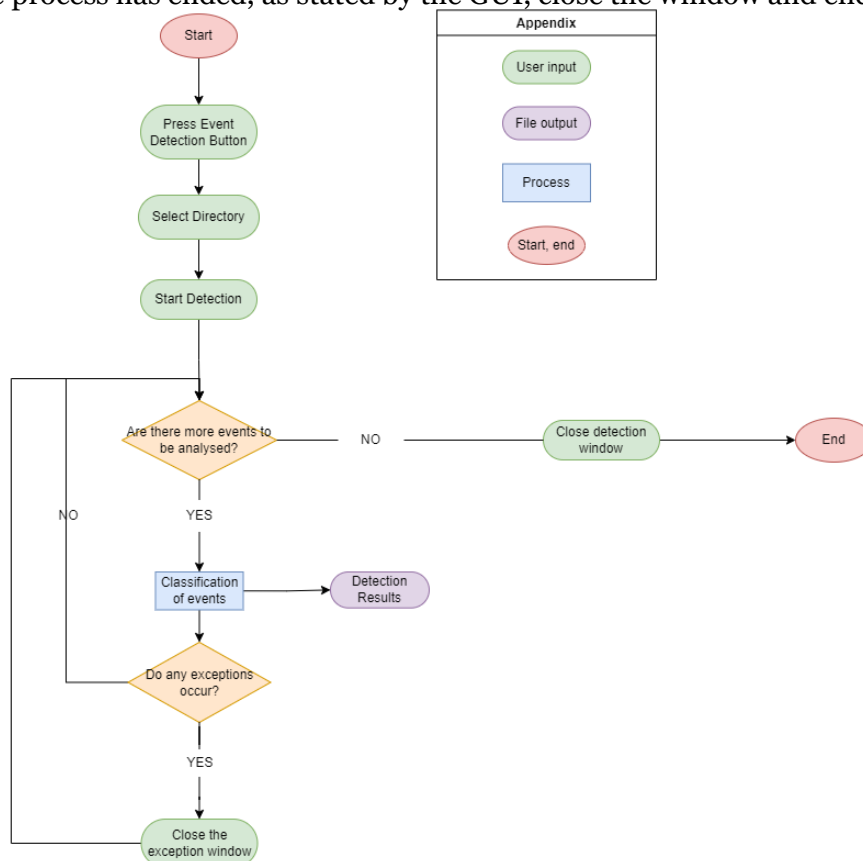
### 3 OFFLINE DETECTION DOMAIN

#### 3.1 Overview

The Offline Detection Process takes place after the end of the Observation Phase. After the Observation phase the user should have a directory named “observations” and a sub-directory with the name of the day that the observation occurred. Internet connection is needed during this phase. Afterwards, the user initiates a session of offline detection in a directory that contains the events produced by the observations of an entire day. The offline detection is part of the standalone tool.

#### Normal flow

1. Start the Standalone Tool, press the Event Detection Button.
2. Using the Select Directory Button, select the directory that will be analysed and press the Start Detection button to initiate the process.
3. Once the process has ended, as stated by the GUI, close the window and end the program.



#### 3.2 Download and Installation

Firstly, the user should download the FDS stand-alone provided here. Then depending on the Operating System that he/she has, the instructions for installing the FDS plugin in FireCapture are different.

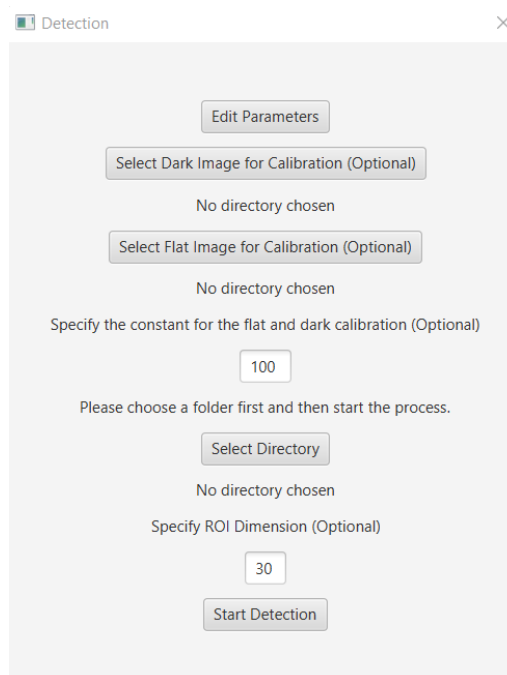
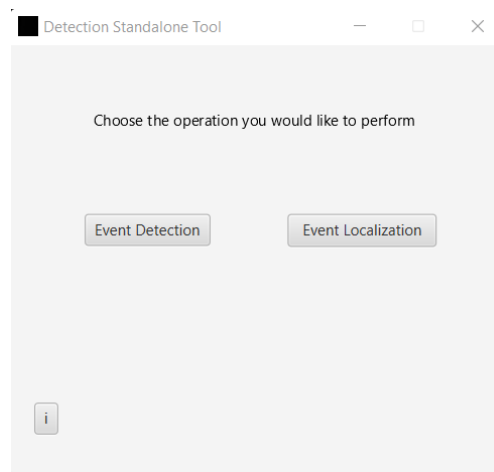
The installation of the FDS stand-alone for the **Windows** user is following:

- tbd
- tbd

### 3.3 Prepare Offline Detection

#### 3.3.1 Starting screen

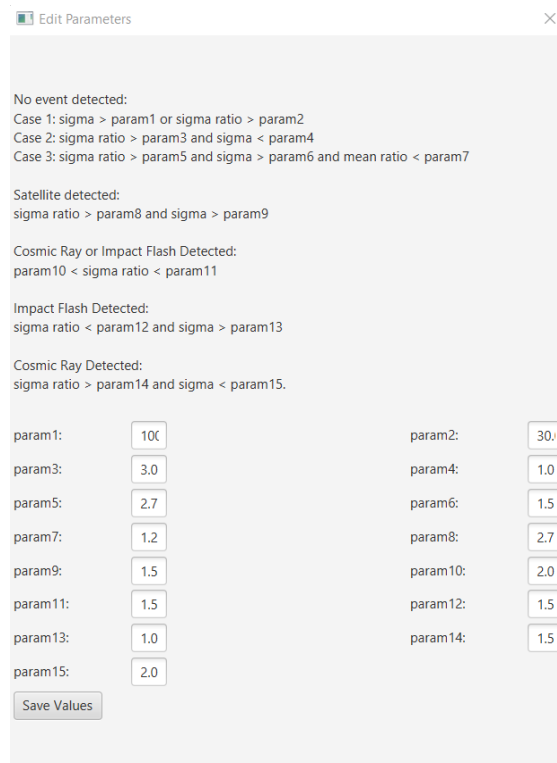
Start the DetectionStandalone application and click [Event Detection] to access the starting screen.





### 3.3.2 Input parameters

Input the parameters param1 - param14 of the classification process (optional) by clicking on the [Edit Parameters] button.



**Edit Parameters**

No event detected:  
 Case 1:  $\sigma > \text{param1}$  or  $\sigma \text{ ratio} > \text{param2}$   
 Case 2:  $\sigma \text{ ratio} > \text{param3}$  and  $\sigma < \text{param4}$   
 Case 3:  $\sigma \text{ ratio} > \text{param5}$  and  $\sigma > \text{param6}$  and  $\text{mean ratio} < \text{param7}$

Satellite detected:  
 $\sigma \text{ ratio} > \text{param8}$  and  $\sigma > \text{param9}$

Cosmic Ray or Impact Flash Detected:  
 $\text{param10} < \sigma \text{ ratio} < \text{param11}$

Impact Flash Detected:  
 $\sigma \text{ ratio} < \text{param12}$  and  $\sigma > \text{param13}$

Cosmic Ray Detected:  
 $\sigma \text{ ratio} > \text{param14}$  and  $\sigma < \text{param15}$ .

param1:	<input type="text" value="100"/>	param2:	<input type="text" value="30.0"/>
param3:	<input type="text" value="3.0"/>	param4:	<input type="text" value="1.0"/>
param5:	<input type="text" value="2.7"/>	param6:	<input type="text" value="1.5"/>
param7:	<input type="text" value="1.2"/>	param8:	<input type="text" value="2.7"/>
param9:	<input type="text" value="1.5"/>	param10:	<input type="text" value="2.0"/>
param11:	<input type="text" value="1.5"/>	param12:	<input type="text" value="1.5"/>
param13:	<input type="text" value="1.0"/>	param14:	<input type="text" value="1.5"/>
param15:	<input type="text" value="2.0"/>		

Input constant for the flat and dark calibration (optional) by editing the first text field on the starting screen.

Input the ROI size (optional).

If no changes are made, then all the parameters maintain their default values, which are also shown on the graphical user interface.

### 3.3.3 Directory selection

Click [Select Dark Image for Calibration (Optional)] and then choose an image for calibration from a local directory. After a directory is selected, its path will be displayed under the corresponding button.

Click [Select Flat Image for Calibration (Optional)] and then choose an image for calibration from a local directory. After a directory is selected, its path will be displayed under the corresponding button.

Click [Select Directory] and then choose a directory for detection (obligatory). After a directory is selected, its path will be displayed under the [Select Directory] button.

The directory chosen may be either:

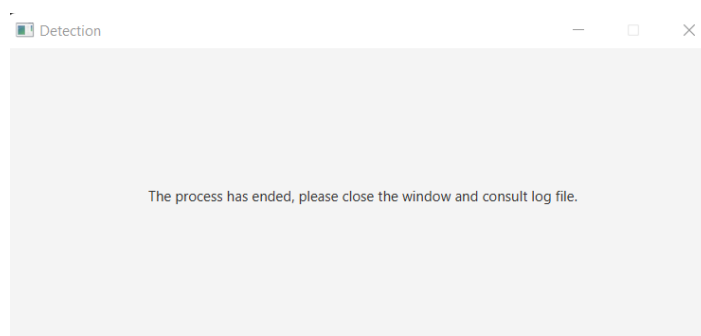
- A single event directory containing frames and an Event\_Metadata.txt file.
- A directory containing multiple event directories. Detection will be performed sequentially on all subdirectories containing an Event\_Metadata.txt file.

Frames can be either in png, jpeg or FITS format and must be named frame\_000, frame\_001, etc. When you are ready click [Start Detection].

### **3.3.4 Detection and classification**

#### **Displayed information**

After clicking the [Start Detection] button, the user can see which event directory is classified and check the progress of the procedure. When the detection ends, the user is notified via a pop-up window.



#### **Exceptions**

If an exception occurs for any of the directories, the user is notified through a pop-up window. Exceptions occur for any invalid usage of the tool, such as directories that do not contain events, events without a metadata file, or events with frames missing. In any case, an informing message appears and when the user closes it, the procedure continues, for the rest of the directories, if any.

## **3.4 Results**

### **Directories**

The output is a folder named Detection\_Results in each event folder containing the event, the stacked, the difference and the ROI image in the same format as the event frames, a .txt file and a .csv file with the results of the specific folder and in the root directory another folder named

Detection\_Results containing a .csv file with all the subfolder results and the ROI images for each event. If the frames of the event are PNG or FITS, the result frames are of the same format. If in the event folder exist frames of both types, then the result frames will be written in PNG format.

## Text files

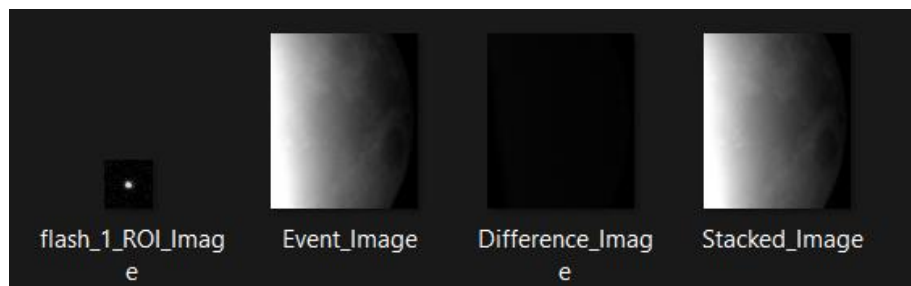
The csv file of the root folder contains the list of events analyzed and for each one of them, the FWHM values for x and y of the Gaussian fit, the results of the classification and the coordinates of the event in the image.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Event Directory	FWHM x	FWHM y	Impact Flash	Satellite	Hot Pixel	Cosmic Ray	Event outside of the limb	Result:				
2	flash_1	3,571	3,198	TRUE	TRUE	FALSE	FALSE	FALSE	Impact flash detected. (Coordinates: 1006, 721).				
3	flash 6	2,255	2,453	TRUE	TRUE	FALSE	FALSE	FALSE	Impact flash detected. (Coordinates: 410, 235).				
4	event_5_2022.0	2,399	22,761	TRUE	TRUE	FALSE	FALSE	FALSE	Satellite detected. (Coordinates: 747, 302).				
5													

The txt file can be found in the directory inside each event and contains the results of the classification.

## Images

The images created are the event image, the difference image, the stacked image inside of each event and all the ROI images in the Detection\_Results of the root folder.



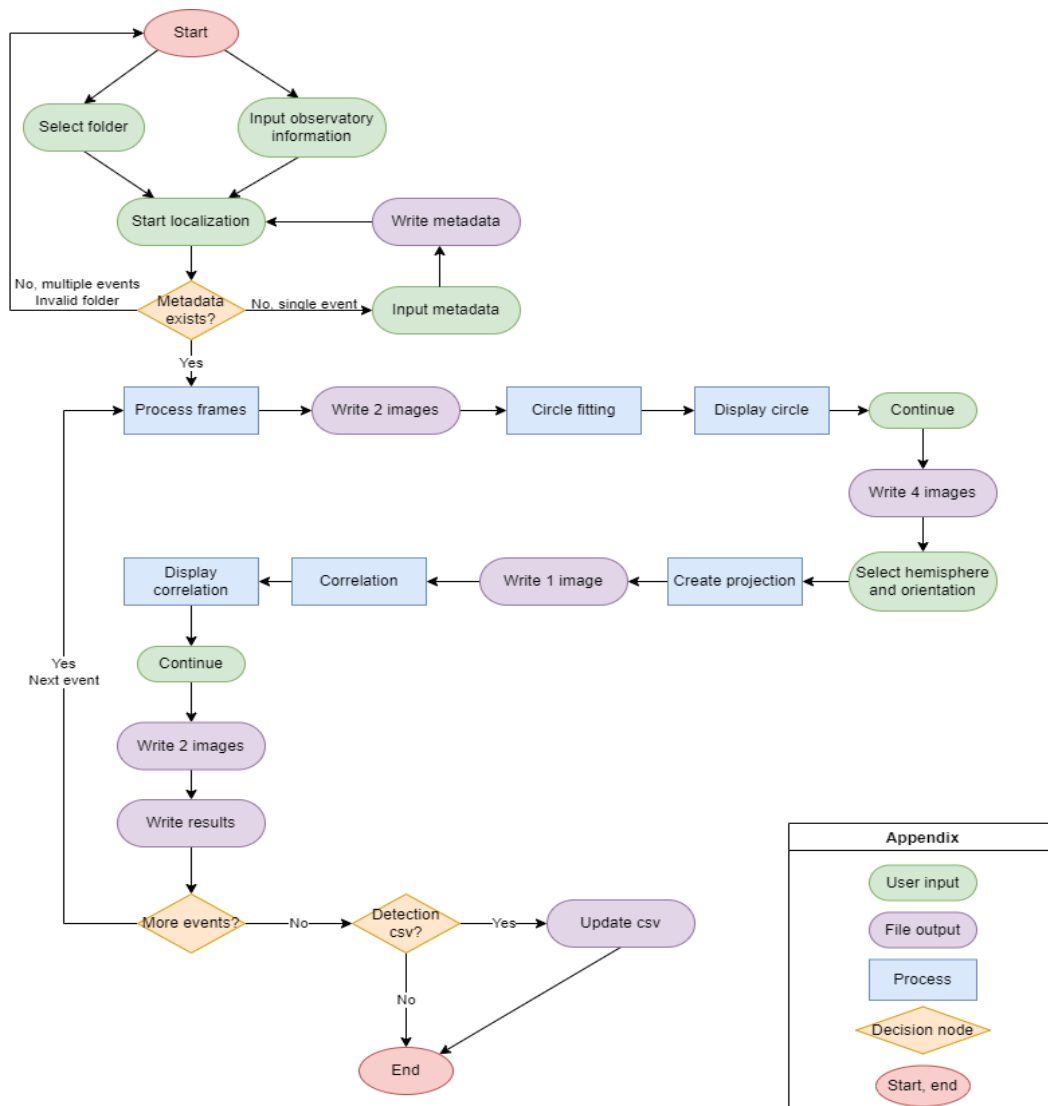
## 4 LOCALIZATION DOMAIN

### 4.1 Overview

The Localization Process takes place after the end of the Offline Detection Domain. Internet connection is needed during this phase. The offline detection is part of the offline standalone tool.

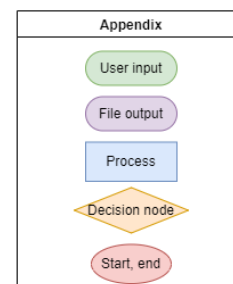
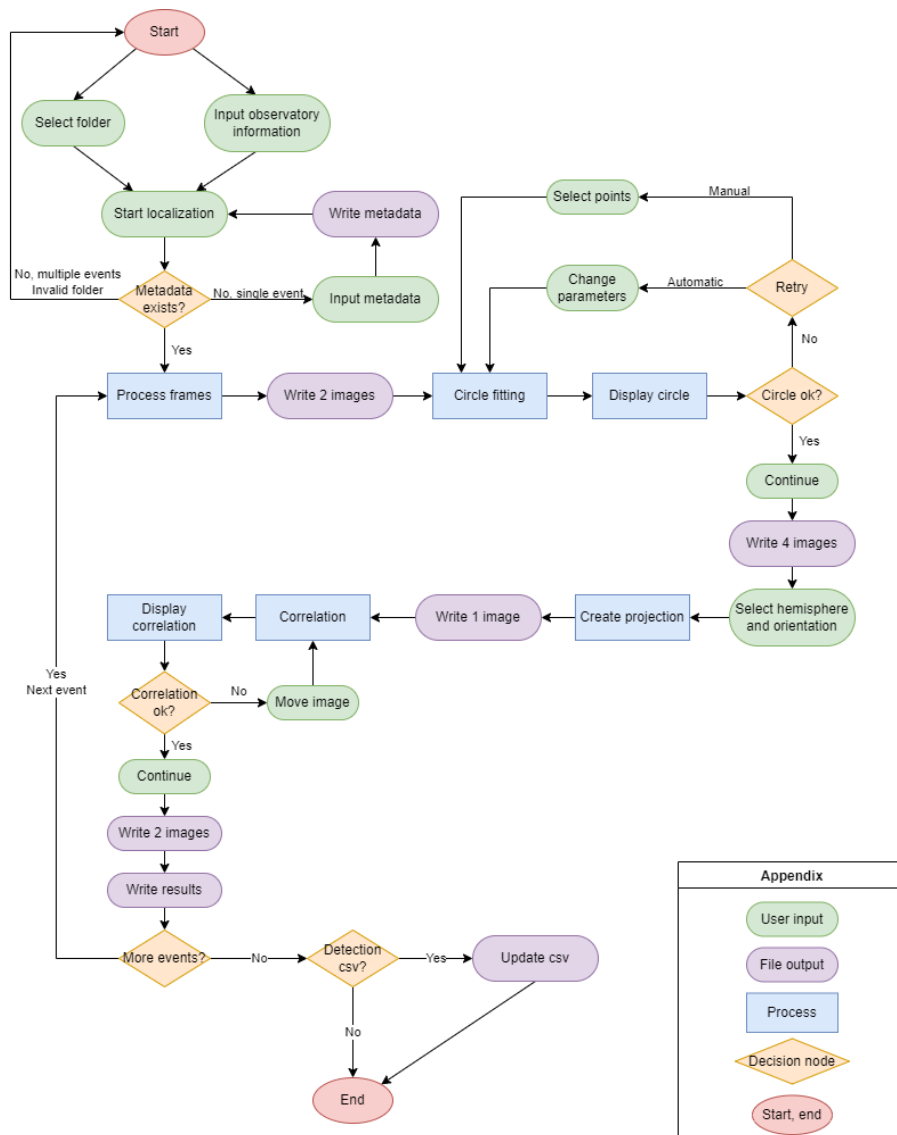
#### 4.1.1 Localization without manual adjustments

1. Input the event folder(s), observatory information and (optionally) telescope focal length and start the process.
2. If a single event without a detection metadata file was selected, input the necessary metadata when prompted and allow the process to continue.
3. For each valid event:
  - 3.1. Wait for the program to finish circle fitting and allow the process to continue.
  - 3.2. Input the correct hemisphere and orientation and allow the process to continue.
  - 3.3. Wait for the program to finish correlation and allow the results to be written.



### 4.1.2 Localization with manual adjustments

1. Input the event folder(s), observatory information and (optionally) telescope focal length and start the process.
2. If a single event without a detection metadata file was selected, input the necessary metadata when prompted and allow the process to continue.
3. For each valid event:
  - 3.1. Wait for the program to finish circle fitting.
  - 3.2. Reattempt manual or automatic circle fitting as many times necessary, then allow the process to continue.
  - 3.3. Input the correct hemisphere and orientation and allow the process to continue.
  - 3.4. Wait for the program to finish correlation.
  - 3.5. Move the image manually as many times as necessary then allow results to be written.



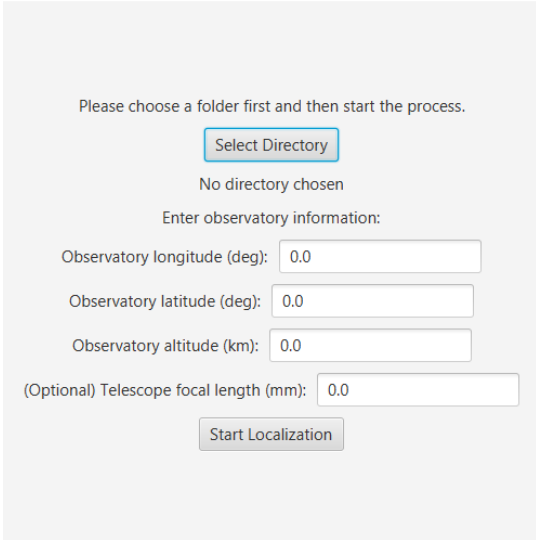
## 4.2 Download and Installation

The Localization tool is part of the standalone tool. Instructions for downloading the Localization tool have been provided in the previous section. If the standalone tool has successfully been downloaded and installed in the last paragraph, no more steps are needed for the Localization.

## 4.3 Prepare Localization

### 4.3.1 Starting screen

Start the DetectionStandalone application and click [Event Localization] to access the starting screen.



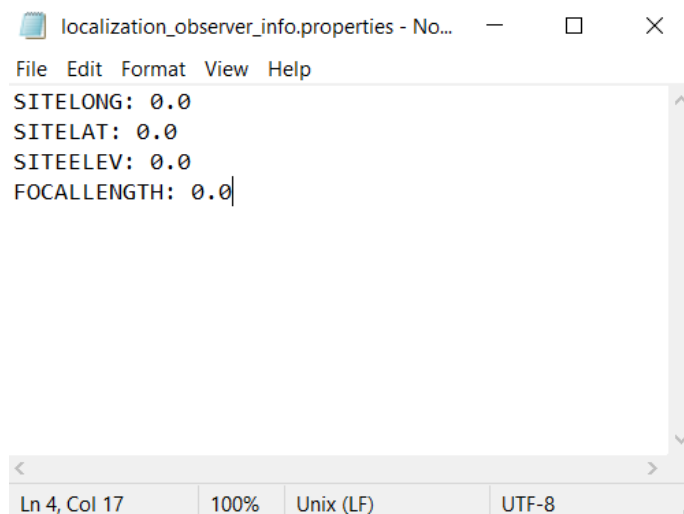
The screenshot shows a software interface for localization. At the top, it says "Please choose a folder first and then start the process." Below this is a blue button labeled "Select Directory". Underneath, it says "No directory chosen". Then, it prompts "Enter observatory information:" followed by four text input fields: "Observatory longitude (deg): 0.0", "Observatory latitude (deg): 0.0", "Observatory altitude (km): 0.0", and "(Optional) Telescope focal length (mm): 0.0". At the bottom, there is a grey button labeled "Start Localization".

### 4.3.2 Input observatory information

Input observatory information into the text fields:

- Longitude of observatory site (degrees). Must be between -360 and +360.
- Latitude of observatory site (degrees). Must be between -180 and +180.
- Elevation of observatory site (km). Must be between 0 and 8.
- (OPTIONAL) Focal length of telescope (mm). This may be left blank. Any non-positive number is considered blank.

The observatory information is stored into the `localization_observer_info.properties` file after each use. Next time the application is opened, the input will initially be read from the properties file. The file can also be directly edited.



### 4.3.3 Directory selection

Click [Select Directory] and then choose a directory for localization. After a directory is selected, its path will be displayed under the [Select Directory] button.

The directory chosen may be either:

- A single event directory containing frames and an Event\_Metadata.txt file.
- A single event directory only containing frames, without an Event\_Metadata.txt file.
- A directory containing multiple event directories. Localization will be performed sequentially on all child directories containing an Event\_Metadata.txt file.
- A directory containing multiple event directories and an OfflineDetectionResults.csv file. Localization will be performed sequentially only on possible NEO event directories.

Frames can be either in png, jpeg or FITS format and must be named frame\_000, frame\_001, etc. When you are ready click [Start Localization].

#### Event without metadata

If a directory containing frames but not an Event\_Metadata.txt file is chosen, a pop-up window will appear allowing you to create a dummy Event\_Metadata.txt file with all data required for localization. The following window will be displayed:

Fill in the following information necessary for localization.

Date of event:

Time of event:

---

Number of frames:

Impact frame number:

Impact x coordinate (pixels):

Impact y coordinate (pixels):

---

Camera pixel size (microns):

Is the bit depth more than 8 bit?

Yes

No

Is bin2 enabled?

Yes

No

Fill in the fields:

- Date of event (any format, the calendar may also be used)
- Time of event in format hh:mm:ss
- Number of frames in the directory
- Impact frame number (from the name of the frame, eg 0 for frame\_000)
- Pixel coordinates of impact flash in the impact frame (bottom left pixel corresponds to 0,0 and top right to width-1, height-1)
- Pixel size of camera in microns ( $\mu\text{m}$ )

Also pick whether the bit depth is more than 8bit and whether binning was enabled.

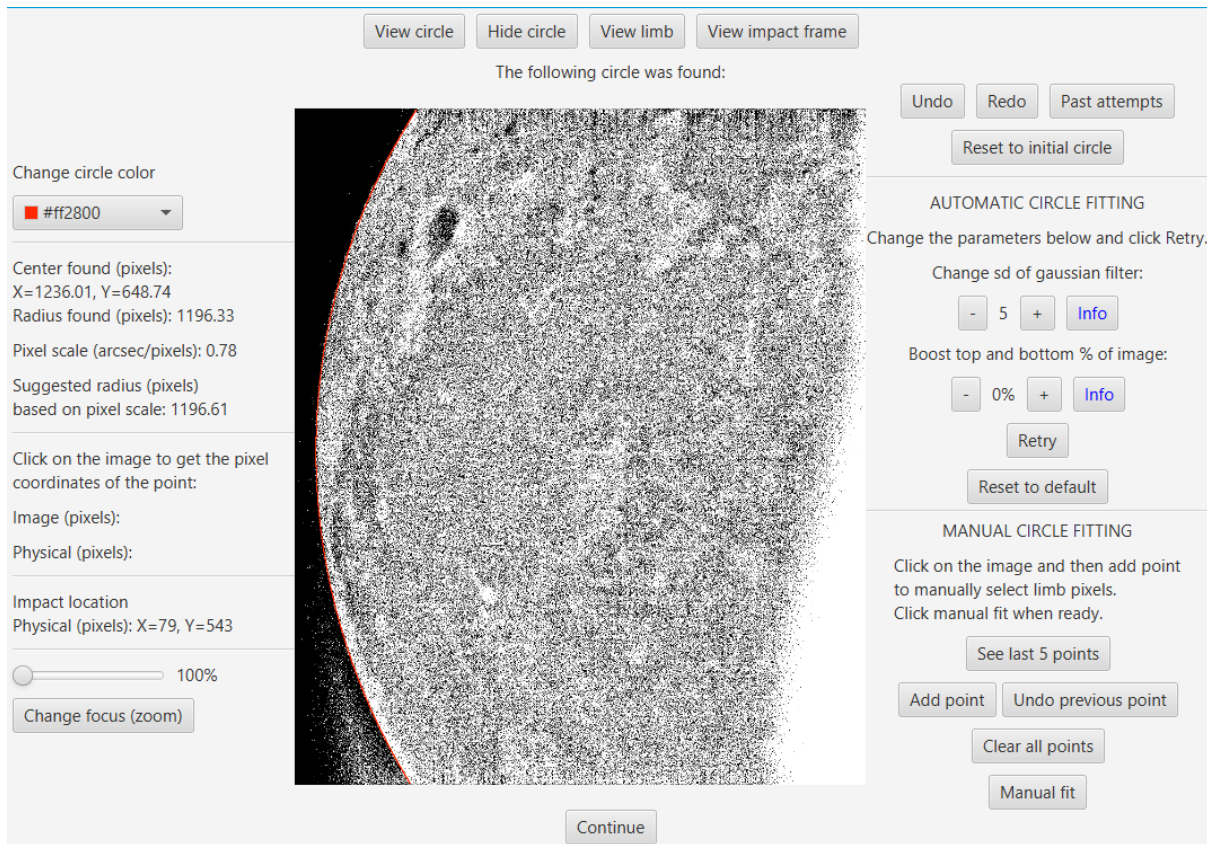
Click [Create metadata file] to attempt to write the file. If the input was not given correctly an error pop-up window is displayed. If the input was given correctly the program will return to the starting screen and you may click [Start Localization] to begin.

### 4.3.4 Circle fitting

#### 4.3.4.1 Displayed information

The program pauses on this screen, showing the circle it found:





Localization circle fit screen

In the middle of the screen, a filtered version of the event frames is displayed, with a red line indicating the circle found that FITS the limb. The color of the line can be changed using the color picker on the top left part of the window.

On top of the image there are four buttons:

- [View circle] displays the image with the red circle.
- [Hide circle] removes the red circle.
- [View limb] displays a binary image, where the detected limb pixels are white.
- [View impact frame] displays the impact frame.

On the left side of the image is displayed information about the circle found:

- Pixel coordinates of the center of the circle (pixels)
- Length of the circle's radius in pixels (pixels)
- Pixel scale of the image (arcsec/pixels), if the telescope focal length was given.
- Suggested radius in pixels, if the telescope focal length was given. Calculated using the pixel scale.

Clicking on any point on the middle images shows the image and physical pixel coordinates of the point on the left side of the screen. Image coordinates correspond to the pixel location on the displayed image, while physical coordinates correspond to the pixel location on the actual image, before it was resized to fit the screen. The bottom left pixel of the image corresponds to (0,0). The physical pixel coordinates of the impact flash are also displayed.

On the bottom left part of the screen there is a slider to change the focus (zoom) of the image. Adjust the slider (from 100% to 10%) then click [Change focus (zoom)] to zoom in or out of the last pixel clicked inside the image. If no pixel has been clicked, it zooms in/out centered at the impact flash location.

If the circle found is satisfactory, click [Continue] on the bottom of the screen.

Note that the radius must not be smaller than 3 pixels or larger than 4000 pixels. In these cases an error pop-up will be displayed.

#### 4.3.4.2 How to judge circle

There are a few ways to judge the circle that was found:

- Toggle the circle on and off to see if it FITS the limb well.
- If a correct telescope focal length was given, the radius of the circle found should be as close to the suggested radius as possible.
- Observe the detected limb pixels. If the detected pixels are not on the limb it is likely that the circle is wrong.

If the circle found is not satisfactory, there are some options to fix it on the right side of the screen.

One way is to tweak some parameters and retry the algorithm (see Automatic circle fitting), while another way is to manually pick limb pixels (see manual circle fitting).

On the top right of the screen are some helpful buttons:

[Undo] and [Redo] to undo and redo one single circle fit attempt.

[Reset to initial circle] resets to the first circle found by the algorithm.

[Past attempts] displays information about the past 5 circle fitting attempts. For each attempt, the radius is shown, and for automatic attempts the parameters are also shown.

#### 4.3.4.3 Automatic circle fitting

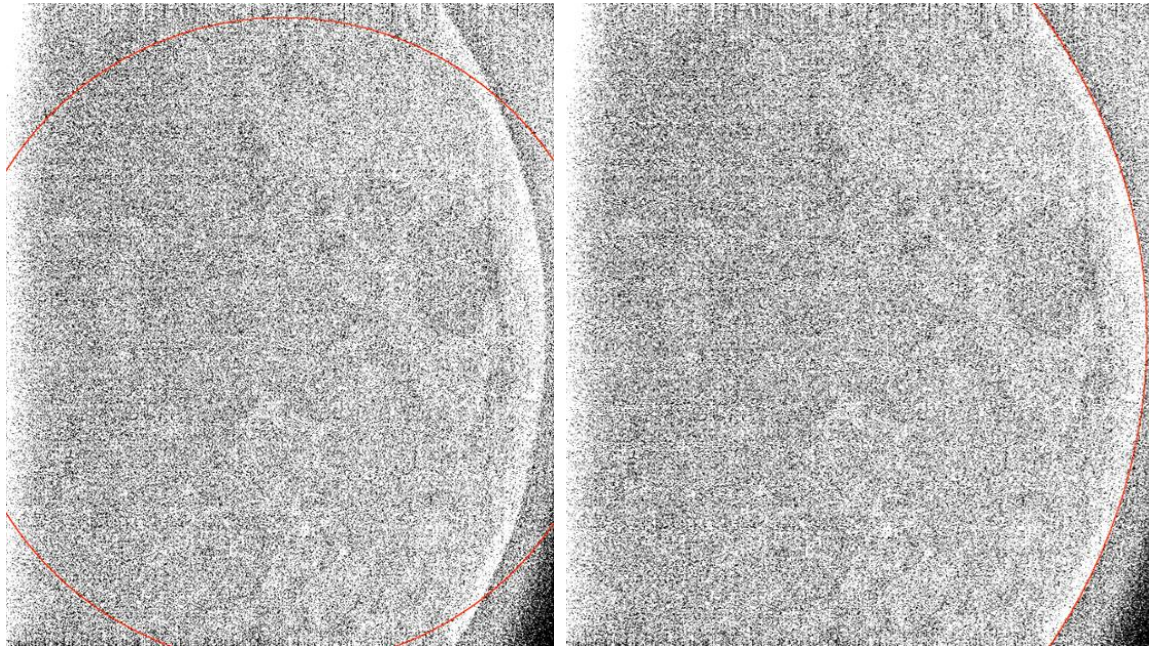
On the right part of the screen there is a section labeled Automatic circle fitting. In this section some parameters can be tweaked, then the [Retry] button can be pressed to attempt the circle fitting algorithm with the new parameters.

Two parameters can be changed by clicking the [-] and [+] buttons. Clicking [Info] next to a parameter displays some information about it.

The sd parameter can be changed from 3 to 9, with a default value of 5. The boost parameter can be changed from 0 to 25, with a default value of 0. Clicking [Reset to default] will set the parameters to their default values.

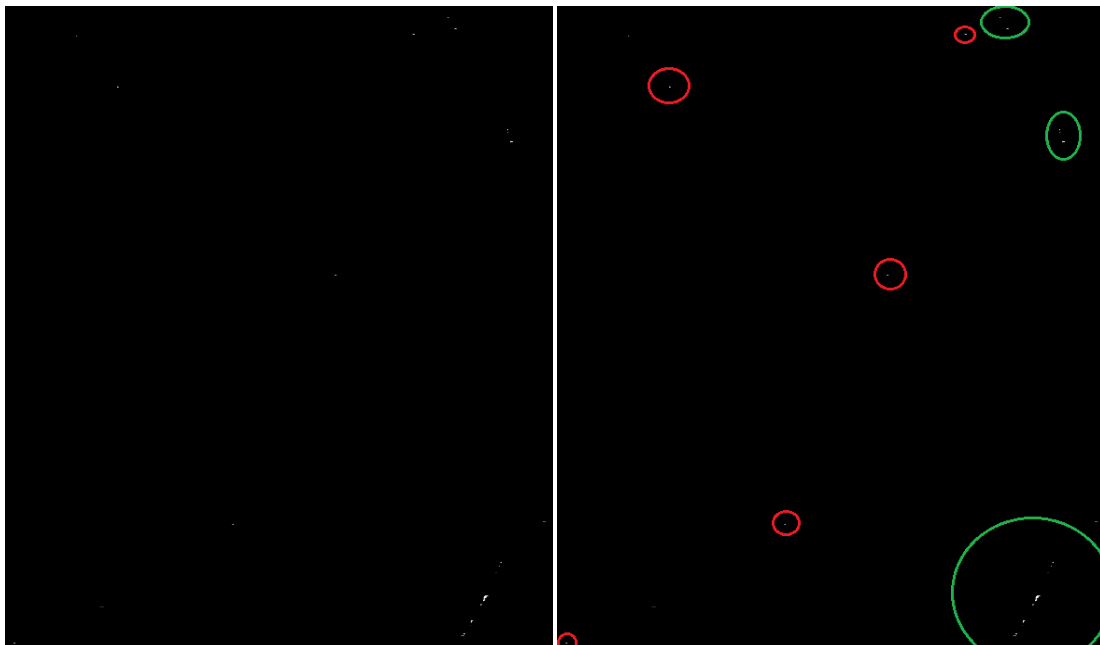
- *sd parameter*

The first parameter that can be changed is the standard deviation (sd) of a gaussian filter. This filter is responsible for cleaning the image from noise, and increasing the sd makes the filter stronger. This parameter should be increased if the circle found is much smaller than the Moon, which is usually a consequence of too much noise.



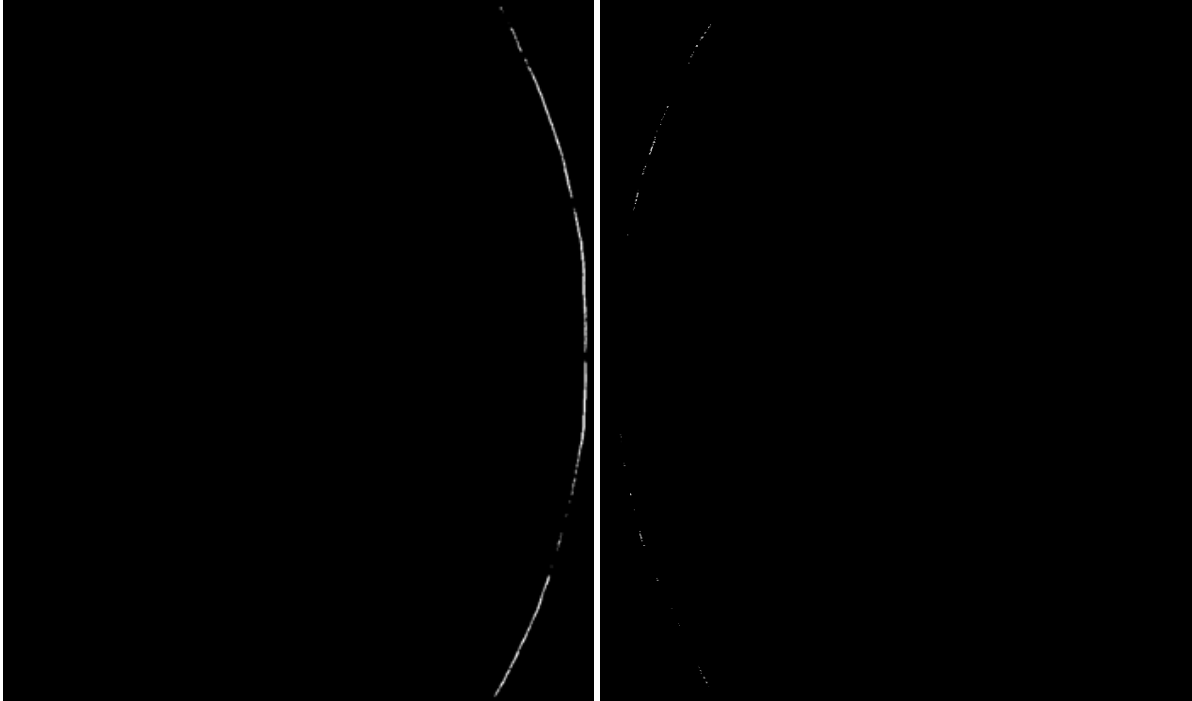
Example: the left picture shows a typical case of a smaller circle found due to noise. The right picture shows the result after increasing the standard deviation from 5 to 8.

Another indicator that the *sd* parameter should be increased is if the limb image contains stray white pixels inside the Moon. Clicking [View limb] on the top part of the screen will display a black image where the detected limb pixels appear in white. Any white pixels inside the Moon are a result of noise and cause a smaller circle to be found.



Example: Limb image of the above bad circle. The green circles indicate correct limb pixels, while the red circles indicate noise pixels inside the Moon. Increasing the *sd* removes the noise pixels.

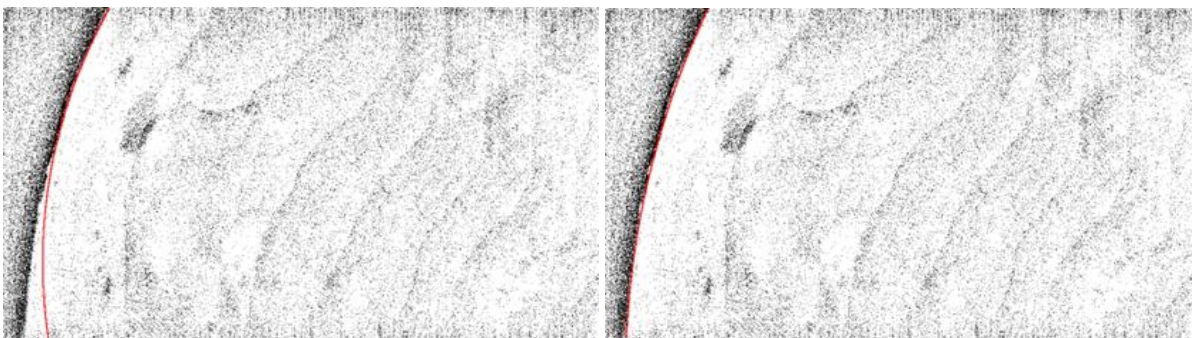
Note that the noisier the original image is, the stricter the limb detection will be, resulting in sparser limbs. However a sparse limb by itself is not an indication of failure. The problem is if there are white pixels far from the limb regardless of limb density.



Two examples of good limbs: one very visible, one sparser.

- **Boost parameter**

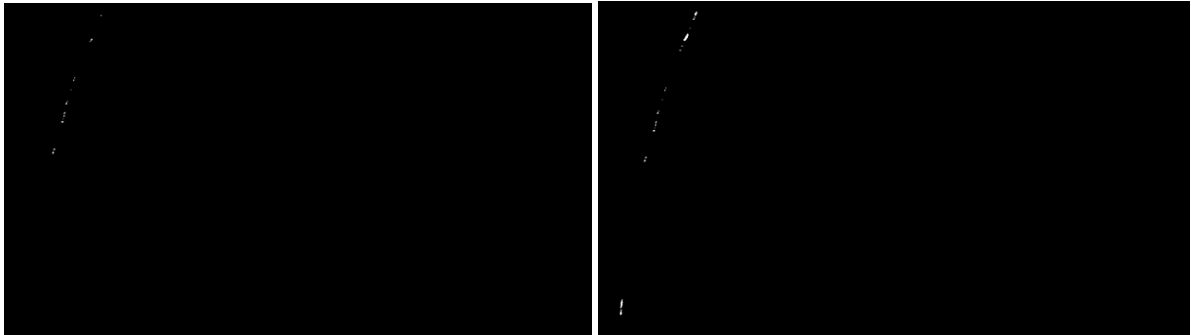
The second parameter that can be changed is the boost parameter. This parameter should be increased if the circle found is wrong near the top or bottom part of the image.



Example: the left image shows a typical case where the circle found fails to follow the limb near the edge of the image. The right image shows the result after increasing the boost parameter from 0% to 10%.

This failure can also be detected by clicking [View limb]. In these cases no pixels are detected near the edge of the image. Increasing the boost parameter makes limb detection 15% less strict on the

top and bottom part of the image (a % of the total image size, equal to boost parameter), resulting in more pixels detected there.



Example: limbs detected on the above pictures. On the left, no pixels were detected on the bottom part, causing the circle to fail. On the right, boosting the top and bottom 10% caused multiple pixels to be detected there, resulting in a better circle.

#### **4.3.4.4 Manual circle fitting**

On the bottom right part of the screen there is a section labeled Manual circle fitting. In this section you can attempt to fit a circle by manually selecting limb pixels.

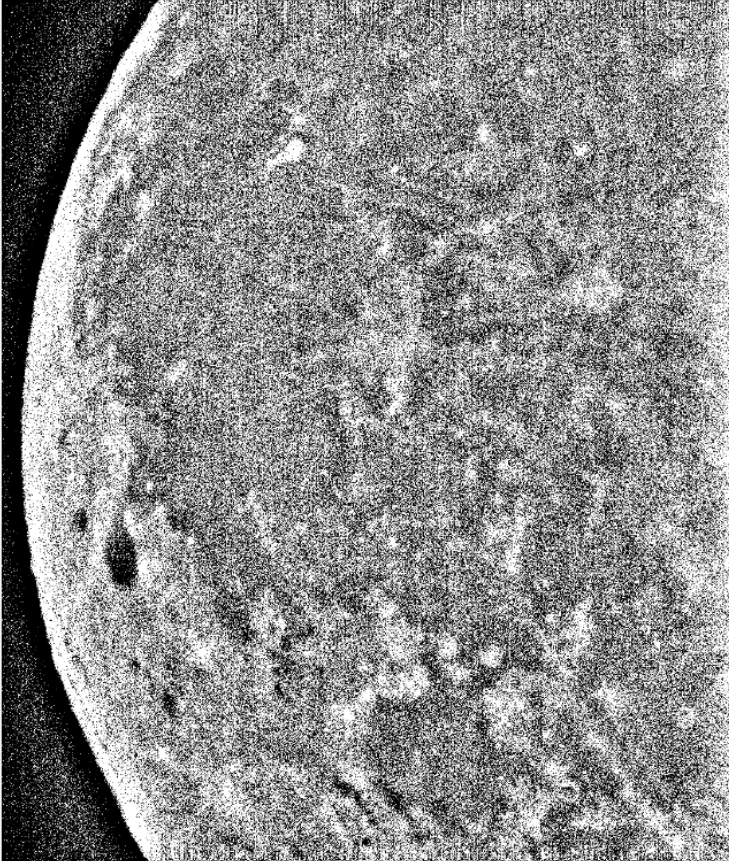
- Click on any point on the image and then click [Add point] to select the pixel. Repeat as many times as you want.
- Clicking [Undo previous point] will remove the last added point.
- Clicking [Clear all points] will remove all selected points.
- Clicking [See last 5 points] will display the physical pixel coordinates of the last 5 selected points.
- Click [Manual fit] when you are ready to run the circle fitting algorithm on the points selected.

#### **4.3.5 Select hemisphere and orientation**

After circle fitting, the following screen will be shown:

View filtered image
View reference
View impact frame

Filtered observation image



Use the reference moon picture (click View reference) to pick hemisphere and identify if the observation image is flipped

Pick non-sunlit lunar hemisphere:

East

West

Is the image flipped on the Y-axis? (upside down)

Yes

No

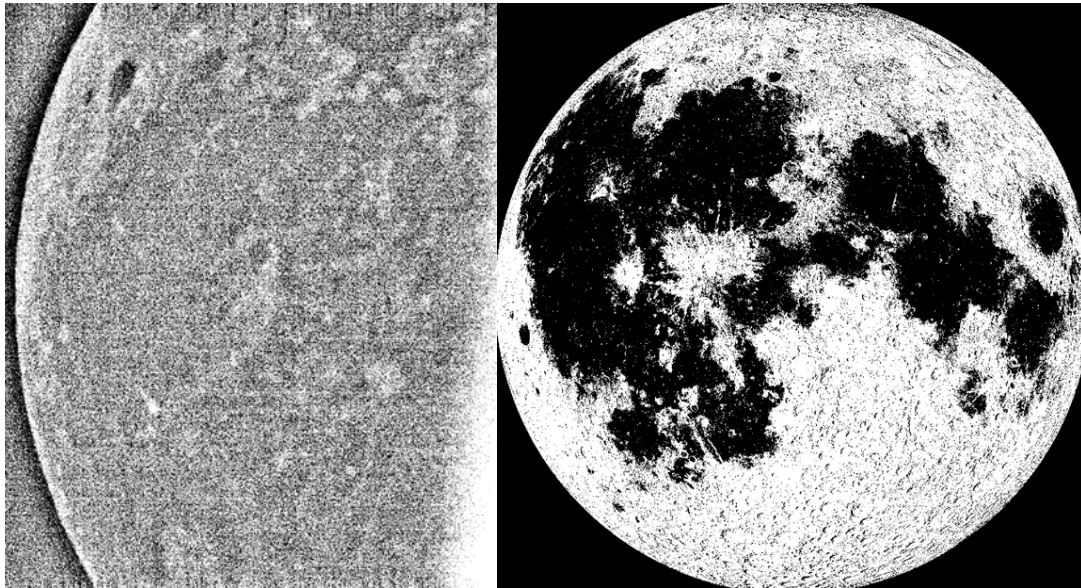
Continue

Continue without automatic rotation

Here you must select whether the observation image depicts the eastern or western lunar hemisphere. If a larger part of the Moon is visible, select the non-sunlit hemisphere. You must also select whether the image has been flipped vertically.

On the top part of the screen are three buttons to help you pick:

- [View filtered image] displays the filtered observation image
- [View impact frame] displays the impact frame
- [View reference] displays a reference image of the moon to use for comparison with the observation image.



Example: on the left, a filtered observation image. On the right, the reference Moon picture. In this case the observation image is of the western hemisphere, due to the Grimaldi crater being visible. The image is also flipped vertically, because the Riccioli crater appears to the south of the Grimaldi crater in the observation image, instead of to the north.

Selecting a wrong orientation or hemisphere will cause the automatic algorithm to more likely fail the next part, requiring more manual adjustments.

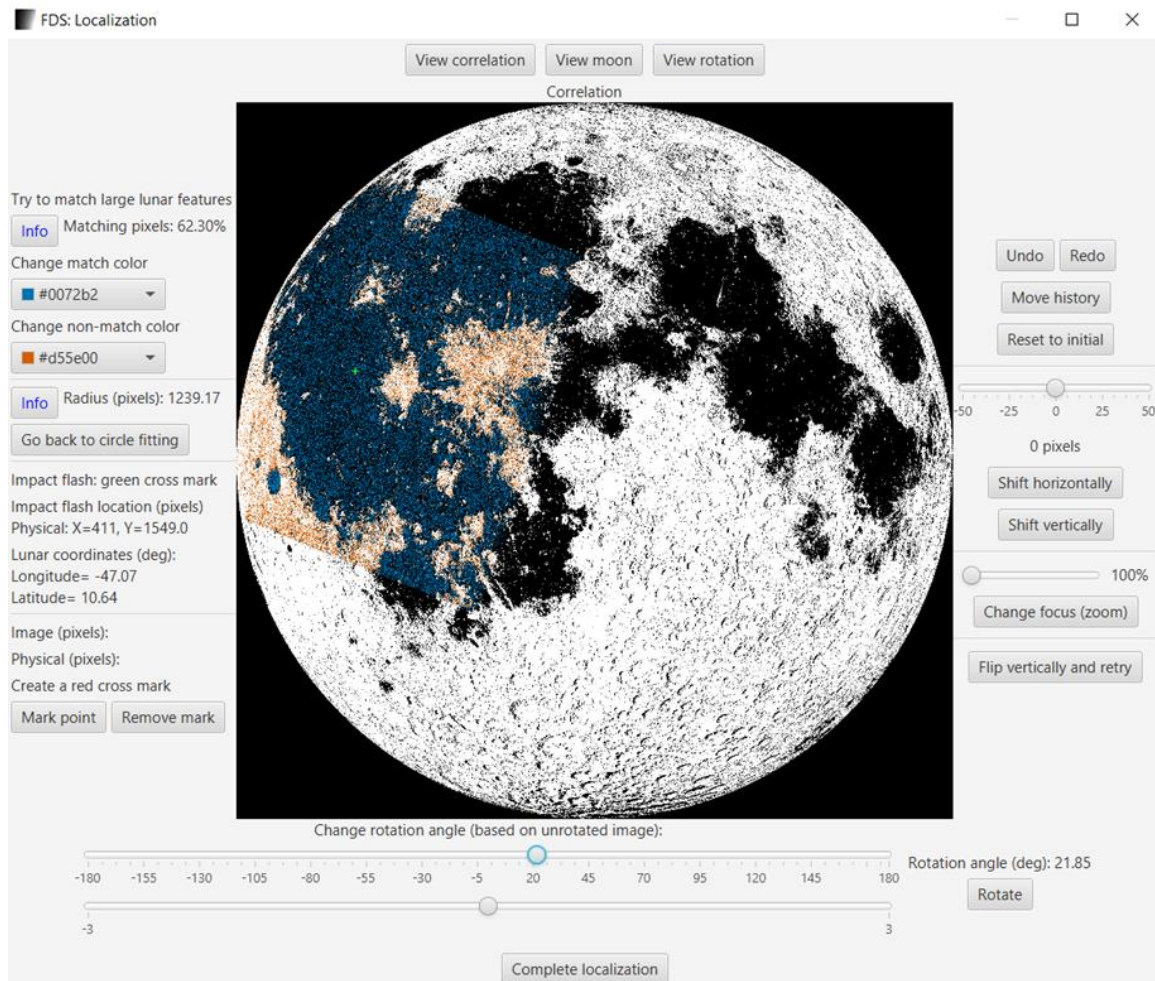
When you are ready, click [Continue]. The next part takes a few minutes to complete, depending on how large the observation images are, so be patient while a transition screen is displayed.

You may also click [Continue without automatic rotation] to continue to the next screen faster, but automatic rotation will not run and you will have to manually rotate the image (see next section). The rotation angle will be set to 0.

## **4.3.6 Correlation**

### **4.3.6.1 Displayed information**

The program pauses on this screen.



Correlation screen

In the middle of the screen, the result of correlation is displayed. If you are satisfied, click [Complete localization] to write the results to a file (see output section).

On top of the image there are three buttons:

- [View correlation] displays the correlation image.
- [View moon] displays only the black and white moon background.
- [View rotation] displays only the rotated observation image.





(a) Correlation image

(b) Moon image

(c) Rotation image

The correlation image is created by coloring the rotation image and imposing it onto the Moon image. By default, matching black pixels between the rotation and the Moon are colored blue, while pixels that are black on the rotation image and white on the Moon are colored orange. These colors can be changed using the color pixels on the left part of the screen.

On the left side of the screen there is some information about the image:

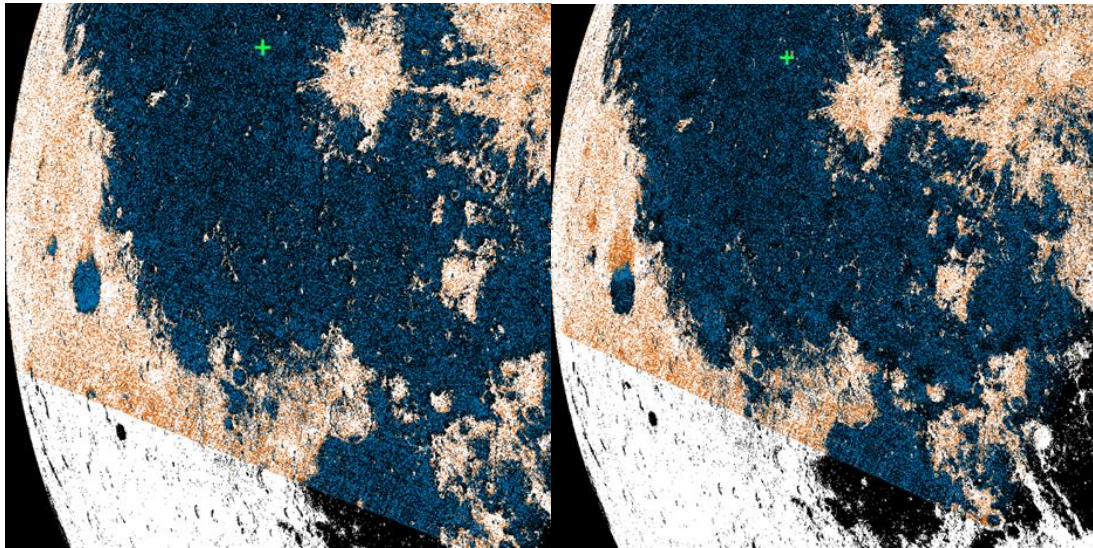
- The percentage of matching pixels, as well as an information pop-up button (see next section).
- The radius of the circle in pixels, as well as an information pop-up button (see next section)
- The physical pixel coordinates and lunar coordinates of the impact flash are displayed. It is also marked by a green cross on the correlation image.
- The physical and image pixel coordinates of any point clicked on the images are displayed.

On the right part of the screen there is a slider to change the focus (zoom) of the image. Adjust the slider (from 100% to 10%) then click [Change focus (zoom)] to zoom in or out of the last pixel clicked inside the image. If no pixel has been clicked, it zooms in/out centered at the impact flash location.

#### 4.3.6.2 Manual adjustments

The goal of correlation is to match the rotated observation image onto the lunar background. The algorithm rotates the image to find the best rotation angle, and displays its suggestion as the initial correlation. The rotation angle is shown on the bottom right part of the screen. If you clicked [Continue without automatic rotation] in the hemisphere selection screen, the rotation angle will be 0. Otherwise, the algorithm checks for angles between -30 and +30.

To judge a correlation, the important part is that the large, identifiable lunar features should be matching (blue color). If possible, prioritize features near the impact flash. A different way to see this is by toggling between the Moon and rotation images: the large features should be at the same spot.



Example: On the left, a good correlation is shown. Grimaldi crater has been matched correctly (blue). On the right, a worse correlation is shown. Grimaldi crater has not been matched correctly, as it is a bit higher than its correct spot (in orange).

If the automatic suggestion is unsatisfactory, or if you did not run automatic rotation, there are several manual adjustments you may do:

- Rotate manually: on the bottom part of the screen is the option to rotate the image manually around its center. Two sliders are provided to choose the rotation angle. The top slider has a range of (-180,180) degrees, while the second slider has a range of (-3,3) degrees, for finer adjustments. On the right of the sliders the selected rotation angle is displayed. Whenever you are ready, click [Rotate] to rotate the image manually. Note that the rotation angle is always based on the unrotated image, and rotating will remove any previous shifts.
- Shift vertically or horizontally: on the right part of the screen is the option to shift the image. Adjust the slider to set the amount of pixels to shift (from -50 to +50) and click [Shift horizontally] or [Shift vertically] to shift the rotated image in the chosen direction. This shifts the whole rotation image including the circle. Note that rotating the image after shifting removes all the shifts.
- Flip vertically: if you selected wrong in the orientation selected screen, there is an option on the right side of the screen to flip the image vertically and retry the automatic rotation algorithm. Afterwards the image will be flipped.

After each move, the location of the impact flash will be updated.

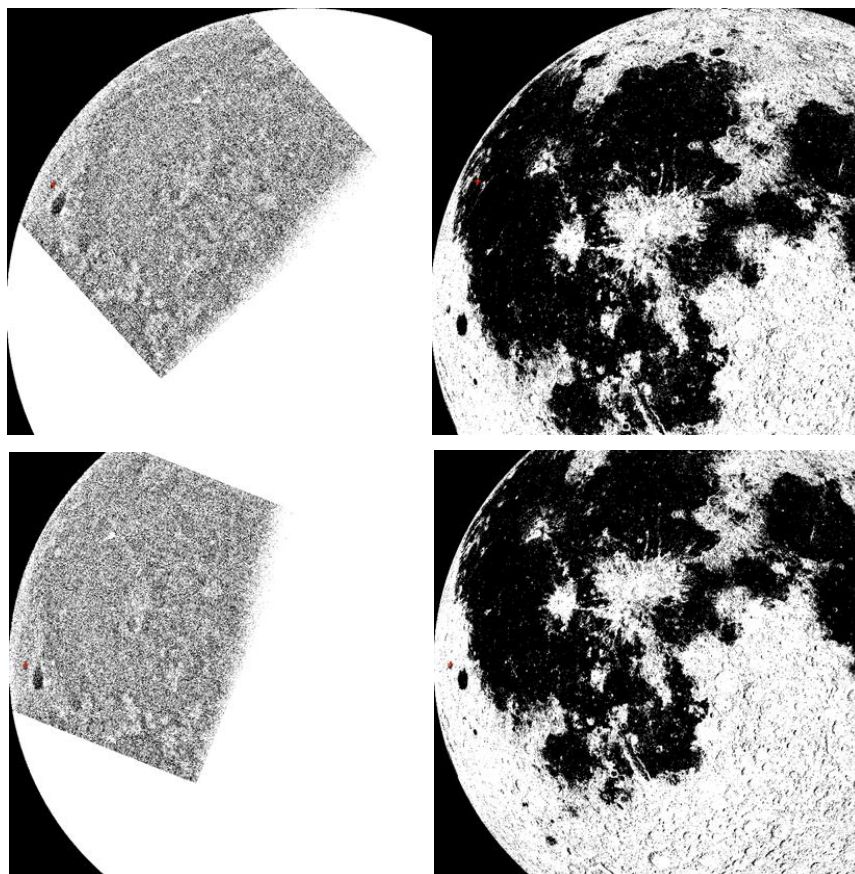
On the top left part of the screen is a metric labeled Matching pixels, which shows the percentage of the colored pixels that are matching (blue/(blue+orange)). This updates after each adjustment and is one way to judge your moves.

Unfortunately, this metric is unreliable on the northwestern hemisphere due to Ocean Procellarum causing false positive matches, as well as after shifting the image due to the lunar circles not aligning. It is best used for small adjustments.

On the top right part of the screen there are some options to track your movements:

- [Undo] and [Redo] buttons to undo and redo one move.
- [Reset to initial] to set the original rotation angle calculated automatically.
- [Move history] shows the last 5 moves. For rotations, shows the angle and the matching pixels %. For shifts, only shows the shift amount and direction.

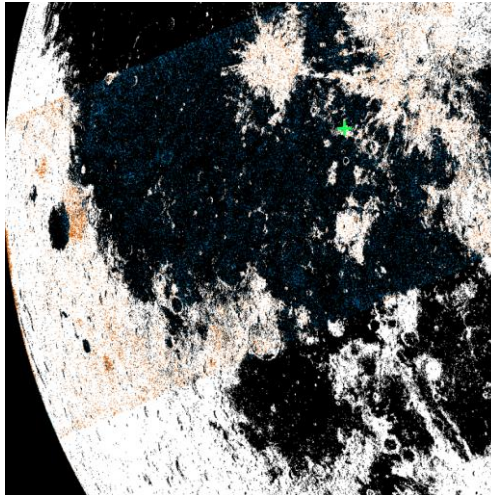
Another way to track your movement is by creating a mark. By clicking anywhere on the image and then [Create mark] on the bottom left part of the screen, a red cross mark is added on the images. [Remove mark] erases the mark. The mark belongs to the rotation image, but it is also visible on the lunar and correlation images. The mark follows the movements of the rotation image (rotating and shifting) so you can mark, for example, Riccioli crater on the rotation image and attempt to move it to its correct position. Note that clicking [Undo], [Redo], [Reset to initial] or [Flip vertically and retry] will remove the mark.



Example: Marking Riccioli crater on the rotation image (top left) and its corresponding wrong position on the background Moon image (top right). After rotating the image, Riccioli crater is at the correct position (bottom).

#### 4.3.6.3 Lunar features size not matching

A common problem that appears is that the lunar features of the rotation image may not be the same size as the same features on the Moon image. In this case it is impossible to match the images well.



Example: Grimaldi crater appears larger on the rotation image (orange) than on the moon (black).

The reason this happens is if the radius found from circle fitting is wrong, because it directly influences the scaling of the images:

- If the lunar features on the rotation image are larger than on the moon, the radius found was too small.
- If the lunar features on the rotation image are smaller than on the moon, the radius found was too big.

In these cases, on the left part of the screen there is a button labeled [Go back to circle fitting] which allows you to return to the circle fitting screen to try again and find a different radius.

#### 4.3.7 Complete localization

Clicking [Complete localization] on the correlation screen will display the results of localization on a pop-up window and ask to proceed to write the results to files.

If a directory with multiple events was selected for localization, the next event will automatically begin. This will also happen if you close the window at any point during localization.

If a directory with multiple events and a detection results csv file was selected, the csv file will be written at the end, after all events were finished.

## 4.4 Results

The program creates a new directory called `localization_results` inside the event directory, and writes the results in there. If an error occurred during localization, an `errorlog.txt` file is also written inside the results directory describing the error.

### 4.4.1 *Logger file*

A file called `localization_logger.txt` contains the localization results and more information:

- Path of the event folder
- Time and date localization started
- Results of localization (lunar coordinates of impact flash in degrees)
- Lunar coordinates of the center of the lunar disc observed
- Angular diameter of the lunar disc observed (arcminutes)
- Pixel scale of camera ( $\mu\text{m}$ ), if telescope focal length was given
- Radius calculated (pixels) based on pixel scale, if telescope focal length was given
- Center of circle found (pixels) based on the observation images
- Radius of circle found (pixels)
- Rotation angle (degrees)
- Offset (pixels): shift amount on x and y axis
- Impact location (pixels) on the correlation image
- Time and date localization stopped

If localization is stopped before it completes, only the folder path, starting and stop time will be written.

### 4.4.2 *Images*

Inside the results directory 9 images will be written:

- The impact frame
- Average of all event frames
- Filtered observation image (black and white)
- Result of edge detection (sobel filter)
- Result of limb detection
- Observation image with colored circle found
- Observed lunar disc
- Rotated observation image
- Correlation image



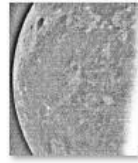
0-impact-frame.  
png



1-stacked.png



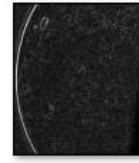
2-blurred.png



3-removed-light.  
png



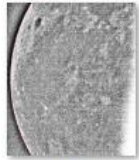
4-gauss.png



5-sobel.png



6-limb.png



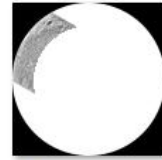
7-circleEdge.png



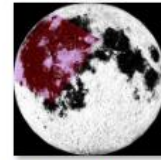
8-map.png



9-fit.png



10-rotated.png



11-correlation.png