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## A2.2. Toolkit: PASCAL Manual

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This manual provides a comprehensive guide on how to visualise and analyse the scientific data acquired by the StAnD Meteor Camera Kit, dedicated to the detection of bright meteors (i.e. fireballs and bolides) during night-time. Calibration and fireball data are analysed using PASCAL, namely the PRISMA and StAnD All-Sky Camera Analysis Laboratory. The document provides installation instructions, a description of the main components of PASCAL, and a step-by-step guide to triangulate the three-dimensional trajectory and to determine the dynamics of a fireball observed by at least two PRISMA or StAnD stations.

**Language:** English

**Suitable for age:** 7-18 years

**Keywords:** Meteors, bolides, fireball network, all-sky cameras

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## 1. Rudiments of Meteor Data Analysis

The rationale behind the observational efforts of meteor and fireball networks such as PRISMA and StAnD is to determine the **geometrical, physical, and orbital parameters** of the observed meteoroids based on the precise tracking of the three-dimensional trajectory of the meteors (mostly fireballs and bolides) detected in the Earth's atmosphere.

These results enable us to understand whether meteorite fragments are expected to have fallen onto the ground and, most importantly, to estimate their area of fall, called **strewn-field**. Furthermore, gathering statistics of such events allows probing the population of Near-Earth Objects (NEOs) and their orbital distribution in the vicinity of the Earth's orbit.

Therefore, the primary scientific data from the PRISMA and StAnD networks consist of video recordings of fireballs and bolides (referred to as **detections**). A set of two or more detections of the same fireball is then called an **event**. Along with event data, all stations in the network collect calibration data to perform continuous positional (**astrometry**) and intensity (**photometry**) calibration of the sensors.

All data from the PRISMA and StAnD networks can be analysed using **PASCAL**, the **PRISMA All-Sky Camera Analysis Laboratory**, an application specifically developed for this purpose by the authors of this document (INAF – Osservatorio Astrofisico di Torino) and written in IDL (Interactive Data Language, NV5 Geospatial Solutions).

### 1.1. Analysis of Calibration Data

The analysis of event data begins with the astrometric and photometric reduction of the videos, which involves determining the fireball's position and intensity as a function of time. This is made possible by analysing the calibration dataset of each camera that detected the event. This dataset consists of 5-second exposure images acquired every 10 minutes throughout the night, in which **stars up to magnitude +5** are typically visible, with an average of a few hundred stars per image (see also the Meteor Camera Kit Manual, Section 4.2.5).

The measurement of the positions and fluxes of these stars, combined with a comparative analysis against high-precision astronomical catalogues, enables the determination of the camera's **astrometric and photometric calibration**. This calibration consists of a set of mathematical relationships linking the measured quantities — namely, the stars' positions on the focal plane (expressed in pixels) and their fluxes (expressed in analog-to-digital units, ADU, per second) — to their true positions in the sky, expressed in alt-azimuthal coordinates (altitude above the horizon,  $h$ , and azimuth with respect to the North,  $a$ ) and their apparent magnitudes,  $m$ .

Such mathematical relationships, and in particular the values of their parameters, are therefore derived from the analysis of the calibration data and then applied to the event data. It is worth noting that these parameters can vary from night to night or over longer timescales, often exhibiting seasonal variations driven by temperature changes.

The calibration process enables the determination of the fireball's position in the sky and its apparent magnitude from a single detection, expressed in standardised units that allow these measurements to be combined with those obtained from other stations in the network. Further details are provided in [Barghini et al. \(2018\)](#) and [Barghini et al. \(2019\)](#).



## 1.2. Analysis of Fireball Data

Each fireball event detected by the PRISMA and StAnD networks (see also the Meteor Camera Kit Manual, Section 4.2.7) is analysed using a dedicated reduction pipeline comprising the following steps:

1. **Astrometric and photometric reduction** of each detection within the event, applying the calibration results (see [Section 1.1](#)). This step returns the alt-azimuthal coordinates ( $h$ ,  $a$ ) and the apparent magnitude  $m$  as a function of time for the entire event duration, also referred to as the *time of flight*.
2. **Triangulation of the fireball's atmospheric trajectory**, by combining the measurements of the celestial coordinates ( $h$ ,  $a$ ) of the fireball from all detections. This process yields the **three-dimensional trajectory** of the meteoroid during its visible flight through the Earth's atmosphere, usually expressed in terms of latitude, longitude, and altitude above ground level. Consequently, it is possible to estimate the most important physical observables of the event — namely, its **speed ( $v$ ) and absolute magnitude ( $M$ )** — as functions of time, or alternatively, as functions of altitude.
3. **Fitting of the observational data to a dynamic model**, which interprets the variations in speed and absolute magnitude as a function of several physical parameters. This is achieved by employing a **system of non-linear differential equations** that describe the physical processes governing the phenomenon. The parameters of this model are estimated through a fitting procedure, in which the model output is adjusted to match the observational data. These parameters are directly related to the **meteoroid's pre-atmospheric physical quantities** (including its mass, cross-section, size, and velocity). The results of the dynamic model can then be used to predict the evolution of these quantities throughout the fireball's atmospheric flight — for example, to estimate the final mass of the meteoroid and to assess whether or not meteorite fragments are likely to be recovered on the ground.
4. **Computation of the meteoroid's pre-atmospheric orbit** by backward extrapolation of its atmospheric trajectory, correcting for the atmospheric drag and the Earth's gravitational influence. This final step yields the orbital parameters of the meteoroid just prior to its encounter with Earth, enabling investigations into its source region within the Solar System.

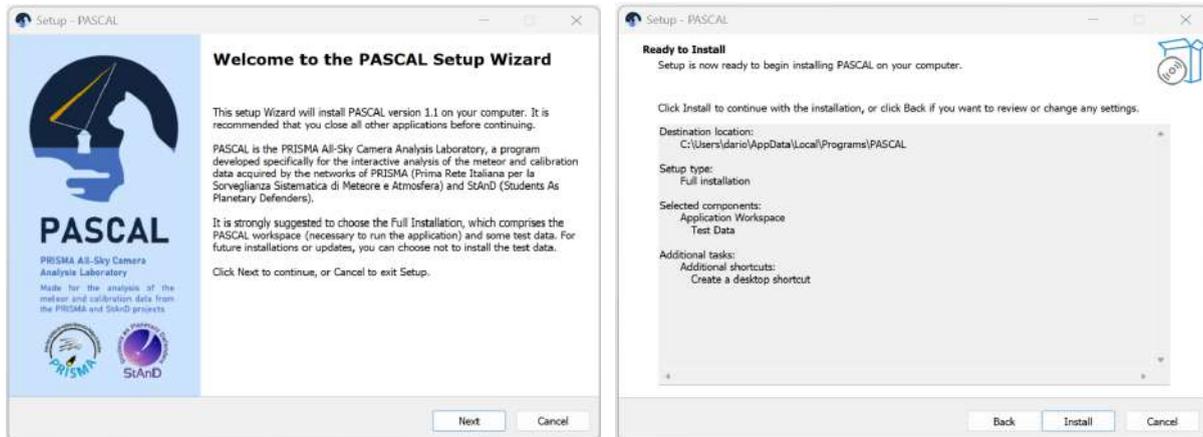
Further details on the event analysis performed on PRISMA data are provided in [Gardiol et al. \(2021\)](#).

## 2. Installation of PASCAL

PASCAL is currently distributed only for the Microsoft Windows operating system, and the installer is available for download on the StanD project website. After downloading, run the **setup wizard** by double-clicking the executable file (for example, *PASCAL\_setup-v1\_1.exe*). The user will be greeted with a welcome page (see [Figure 1](#), left panel).



Figure 1 – Screenshots of the setup wizard for the PASCAL application. The left panel shows a screenshot of the wizard’s welcome page, while the right panel displays the installation page.



The installation process is fully guided and consists of the following steps:

1. **Select *Destination Location***. The user will be prompted to select an installation directory for the application (by default, it will be installed in the *AppData\Local\Programs* directory of the current user’s profile).
2. **Select *Components***. The user can choose whether to install the application workspace (required to run PASCAL) and some test data. If this is the first time installing PASCAL, installing the workspace is essential. It is also highly recommended to install the test data, as this allows immediate testing of the application’s functionality and provides an example of how data should be organised within the workspace.
3. **Select *Additional Tasks***. The user can choose whether or not to create a desktop shortcut for PASCAL.
4. **Select *Workspace Location***. If the user chooses to install the workspace, the installer will prompt for its location. The workspace consists of a main directory, and the user can select where this directory will be created (by default, it is placed in the *Documents* folder of the current user’s profile) and choose its name (by default, it will be named *PASCAL*).
5. **Ready to Install**. A summary of all selected options is presented to the user (see [Figure 1](#), right panel).

After clicking the *Install* button on the last page, the application will be installed. At the end of the installation process, the user can choose whether or not to display the *ReadMe* file and/or launch PASCAL immediately.

## 2.1. PASCAL Workspace

The PASCAL workspace contains all the essential components and files required to run the application. It will be installed at the location specified on the *Select Workspace Location* page of the PASCAL setup wizard. To access it, navigate to the path chosen during installation. The workspace has the following folder structure:



- **PASCAL\archive\**. This directory stores the **compressed output of the data processing** performed by the PRISMA pipeline, formatted as *.tar.gz* archives for long-term storage. Even if test data were installed, this directory will initially be empty. It is used only when running the PASCAL submodule for the complete data processing available through the *File > Data process* menu (see [Section 3.2.4](#)).
- **PASCAL\atmosphere\**. This directory contains the **atmospheric and geomagnetic data, as well as external procedures** required for running the dynamic model module during event analysis. It is used only when running the PASCAL submodule for the complete data processing available through the *File > Data process* menu (see [Section 3.2.4](#)).
- **PASCAL\captures\**. This directory contains the **calibration data (captures)**, organised with a separate folder for each station (named using the station code, e.g. *ITPI01*). Within each station folder, the data are grouped by month of acquisition (e.g. *202505*) and stored in FITS file format. If the *Test Data* component was selected during installation, this directory will contain some test calibration data.
- **PASCAL\calibrations\**. This directory contains the **results of the calibration data processing**, with the same structure as the *captures* folder. Result files are provided in TXT and PDF formats. It is used only when running the PASCAL submodule for the complete data processing available through the *File > Data process* menu (see [Section 3.2.4](#)). If the *Test Data* component was selected during installation, this directory will contain the result files of the calibration test data.
- **PASCAL\events\**. This directory contains the **fireball (event) data**, organised into folders by month of acquisition (e.g. *202505*). Within each monthly folder, the data for each event are stored in a dedicated folder named with the event code (e.g. *20250501T235924\_UT*). Inside each event folder, the data from individual detections are each stored in a separate subfolder named after the corresponding detection code (e.g. *PINOTORINESE\_20250501T235924\_UT*). If the *Test Data* component was selected during installation, this directory will contain some test event data.
- **PASCAL\results\**. This directory contains the **results of the event data processing**, with the same structure as the *events* folder. Result files are provided mainly in TXT and PDF formats. It is used only when running the PASCAL submodule for the complete data processing available through the *File > Data process* menu (see [Section 3.2.4](#)). If the *Test Data* component was selected during installation, this directory will contain the result files of the event test data.
- **PASCAL\settings\**. This directory contains all the **configuration files required to run PASCAL** and its submodules. Its contents are organised as follows:
  - **PASCAL\settings\configurations\**. This directory contains all **configuration files and masks for each station**. If the *Test Data* component was selected during installation, this directory will also contain the configuration files and masks required to process the test data.
  - **PASCAL\settings\solutions\**. This directory contains astrometric and photometric calibration files (also referred to as *solutions*) to be used for the analysis of the fireball recordings from each station. If the *Test Data*



component was selected during installation, this directory will also contain the solutions required to process the test data.

- **PASCAL\settings\logos\**. This directory contains the logos of PASCAL and of the PRISMA and StAnD projects.
- **PASCAL\settings\templates\**. This directory contains some template files. It is used only when running the PASCAL submodule for the complete data processing available through the *File > Data process* menu (see [Section 3.2.4](#)).
- **PASCAL\settings\configuration.ini**. This file contains all configuration parameters and workspace paths required to run the PASCAL application. If the *Application Workspace* component was selected during installation, the configuration file is automatically adjusted to **match the local workspace path** specified by the user. In this case, the path to the configuration file is **stored in the current user's Windows Registry** and will be automatically loaded each time PASCAL is launched; otherwise, the user will be prompted to select the configuration file manually.
- **PASCAL\settings\solutions.ini**. This file contains a **two-column list of the stations** recognised by PASCAL. Each row represents a station: the first column contains the **station code** (e.g. *ITPI01*), and the second column contains the **station name** (e.g. *PINOTORINESE*). When opening a new image (calibration or fireball data), PASCAL verifies that the image FITS header reports a code and name matching one of the entries in this file. When adding data from a new station, the user must edit this file and add a new row for that station.
- **PASCAL\settings\catalog.txt**. This file contains the astrometric and photometric catalogue of stars used for the analysis of calibration data.

### 3. PASCAL Interface Description

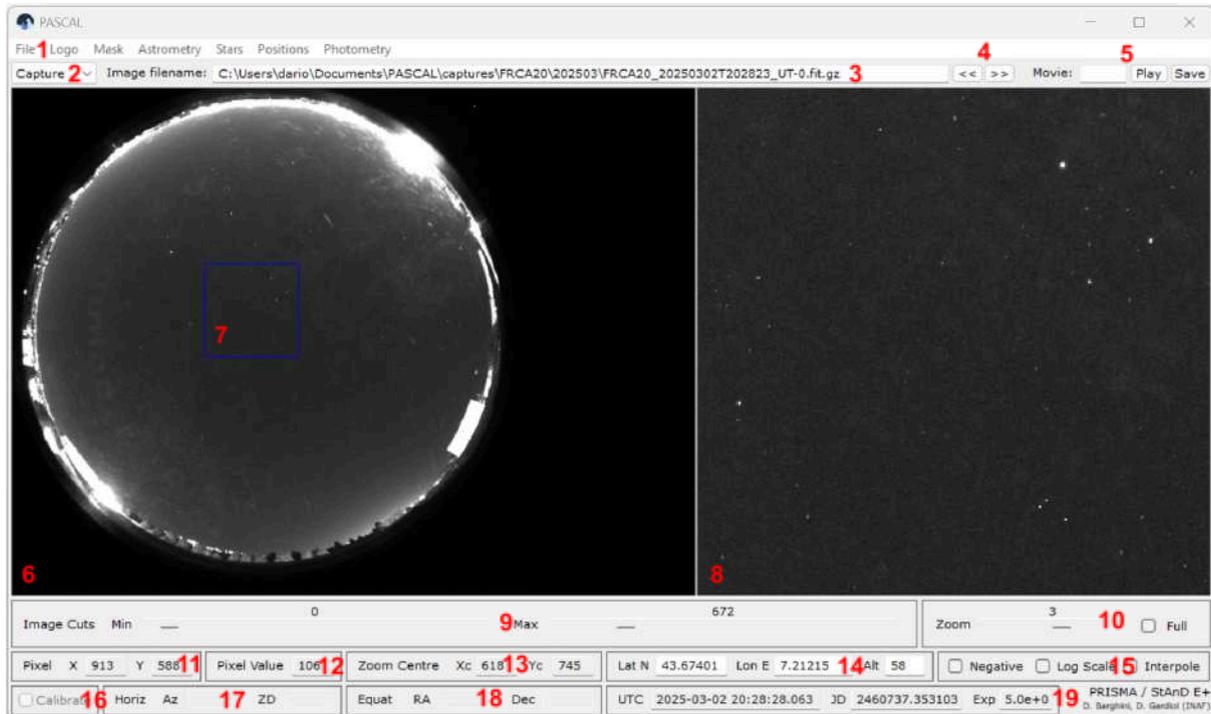
To launch the PASCAL application, search for and select *PASCAL* from the Windows Search bar on the taskbar, or double-click the PASCAL desktop icon if you created a shortcut during installation. At startup, a welcome window will appear (as shown in [Figure 2](#), left panel); click the *PASCAL* button to proceed. A second, similar window will then appear ([Figure 2](#), right panel); click the *Click To Continue* button to complete the launch process and start PASCAL.

Figure 2 – Screenshots of the welcome windows of the PASCAL application launcher.





Figure 3 – Screenshot of the main window of the PASCAL application, showing a calibration frame from the StAnD station in Nice (FRCA20 - Nice, Collège Frédéric Mistral).



### 3.1. Main Window

If PASCAL launches successfully, the user will be greeted with the main application window, as shown in [Figure 3](#). If the application cannot locate the *configuration.ini* file, a file browser window will **prompt the user to select a valid one**. If the selected configuration file has an incorrect format, PASCAL may close unexpectedly, so caution is advised when manually editing this file.

The main window presents several components, highlighted in [Figure 3](#) and listed in the following.

#### 3.1.1. Main Menu Bar

It provides access to all the **main modules, functions, and options of PASCAL**, organised into seven sub-menus (*File, Logo, Mask, Astrometry, Stars, Positions, and Photometry*). All entries are described in detail in [Section 3.2](#) to [Section 3.5](#).

#### 3.1.2. Mode Dropdown Menu

It displays the **current mode of the widget**, i.e. the type of image currently shown. Images can be from calibration data (in which case the dropdown menu displays *Capture*) or from fireball data (in which case it displays *Detection*). The current mode determines which PASCAL functionalities are active. The user can change the mode by selecting the desired option from this dropdown menu; however, note that detections must follow a strict folder structure according to the Freeture format (see [Section 3.2.2](#)).



### **3.1.3. Current File**

A text box displaying the **full path to the image file currently loaded** and displayed in PASCAL. The user can edit this path to load a different image. After editing it, the user must press *Enter* on the keyboard to load the new image.

### **3.1.4. Next/Previous File**

Two buttons to **browse to the previous (<<) and next (>>) image** FITS files in the current directory.

### **3.1.5. Play/Save Movie**

A combo widget to **play and save an animation by browsing through the image** FITS files available in the current directory. In the left text box, the user can specify the number of frames to include in the animation (e.g. entering *50* will include the next 50 frames relative to the current one), optionally followed by a comma and the number of milliseconds to set as the delay between consecutive frames (e.g. entering *50,10* will create an animation of 50 frames with each frame displayed for 10 ms).

Clicking the *Play* button displays the animation in the widget only. Clicking the *Save* button plays the animation in the widget and, once completed, prompts the user to choose a path and filename to save the output as a GIF file, along with a PNG image showing the integrated track resulting from the animation.

### **3.1.6. Main Draw Window**

It is the main component of the application, where the **current image is displayed in full size and grayscale**. The image visualization settings can be adjusted using the image sliders (see [Section 3.1.9](#)) and the display option buttons (see [Section 3.1.15](#)).

When moving the mouse over the window, the **(x, y) coordinates** of the cursor on the image are shown in the pixel position text boxes (see [Section 3.1.11](#)), and the corresponding **image pixel value** is displayed in the pixel value text box (see [Section 3.1.12](#)).

If the user clicks on the window with the left mouse button, the center of the zoom box (g) is moved to the clicked position, and the zoomed view window (h) is updated accordingly.

### **3.1.7. Zoom Box**

A blue box superimposed on the main draw window (see [Section 3.1.6](#)) that highlights the **portion of the image displayed in the zoom draw window** (see [Section 3.1.8](#)). The size of the zoom box can be adjusted using the zoom slider (see [Section 3.1.10](#)).

### **3.1.8. Zoom Draw Window**

A square draw window displays the **portion of the image enclosed by the zoom box** (see [Section 3.1.7](#)), using the same grayscale and display options as the main draw window (see [Section 3.1.6](#)). Hovering or clicking with the mouse in this window produces the same effects as in the main draw window.



### **3.1.9. Image Sliders**

Two sliders to adjust the **minimum and maximum values** for the current image displayed in both the main and zoom draw windows. Since PRISMA and StAnD network images are stored in 12-bit format, the default range is from 0 to 4095 ADU.

### **3.1.10. Zoom Settings**

A slider that allows the user to adjust the **size of the zoom box** highlighted by the blue square in the main draw window (see [Section 3.1.6](#)) and displayed in the zoom draw window (see [Section 3.1.8](#)). The slider ranges **from 5** (maximum half-size of  $15 \times 2^5 = 480$  pixels) **to 0** (minimum half-size of  $15 \times 2^0 = 15$  pixels).

Regardless of the slider value, selecting the *Full* button expands the zoom box to include the full image while preserving its square aspect ratio.

### **3.1.11. Pixel Positions**

Two textboxes that report the **x and y coordinates of the pixel** currently under the cursor, either in the main draw window or in the zoom draw window.

### **3.1.12. Pixel Value**

A textbox that reports the **image value of the pixel** currently under the cursor, either in the main draw window or in the zoom draw window.

### **3.1.13. Zoom Centre**

Two textboxes that report the **x and y coordinates of the centre of the currently selected zoom**, as highlighted by the blue square in the main draw window (see [Section 3.1.6](#)) and displayed in the zoom draw window (see [Section 3.1.8](#)).

### **3.1.14. Geographical Coordinates**

Three textboxes that display the geographical coordinates of the current image (**latitude, longitude, and altitude above ground level**), as read from the FITS file header. These values are also used for ephemeris computations (see [Section 3.5](#) and [Section 3.6](#)) and to compute the equatorial coordinates reported in the corresponding textboxes (see [Section 3.1.18](#)). The textboxes are editable, allowing the user to **correct inaccurate coordinates** from the FITS header. To make such modifications effective, the user must press *Enter* on one of the three textboxes.

### **3.1.15. Display Options**

Three toggle buttons allow the user to adjust the display options of the current image in both the main and zoom draw windows:

- **Negative:** inverts the grayscale palette, switching from a black to a white background;
- **Log scale:** applies a logarithmic stretch to the color scale;
- **Interpole:** smooths the image using a sub-pixel interpolation filter.



### **3.1.16. Calibrate Button**

A toggle button enables the **computation of celestial coordinates** based on the current astrometric solution (see [Section 3.5](#)). The resulting coordinates are displayed in the textboxes to the right of the button, showing both the horizontal coordinates (see [Section 3.1.17](#)) and the equatorial coordinates (see [Section 3.1.18](#)). The button will automatically deselect if the astrometric solution is modified manually or if a different image is loaded.

### **3.1.17. Horizontal Coordinates**

Two textboxes that report the values of the horizontal coordinates, **azimuth and zenith distance** ( $z$  or  $zd$ , which is the angle complementary to the altitude  $h$ ), of the pixel currently under the cursor according to the current astrometric solution, if the *Calibrate* button (see [Section 3.1.16](#)) is selected.

### **3.1.18. Equatorial Coordinates**

Two textboxes that report the values of the equatorial coordinates, **right ascension** (indicated as  $ra$  or  $\alpha$ ) **and declination** ( $dec$  or  $\beta$ ), of the pixel currently under the cursor according to the current astrometric solution, if the *Calibrate* button (see [Section 3.1.16](#)) is selected.

### **3.1.19. Time and Exposure**

Three textboxes that report the **timing data for the current image**, namely the UTC date and time, the Julian Date, and the exposure time of the image (in seconds).

## **3.2. File Menu**

Through this menu, the user can carry out some basic operations and to launch the *Data process* submodule of PASCAL for the complete analysis of PRISMA and StAnD data.

### **3.2.1. Load Config**

This menu item allows the user to **browse, select, and load a new configuration file**, or a new version of the current one, replacing the current PASCAL settings (see [Section 2.1](#)). Once clicked, a file browser dialog will open to **select an INI file**. If the chosen file is not in the correct format, PASCAL may close unexpectedly; therefore, caution is advised when manually editing the configuration file.

### **3.2.2. Open Detection**

This menu item allows the user to load a frame from a Freeture detection of a fireball into PASCAL. After clicking the button, a file browser dialog will open to **select an FITS file**.

A Freeture detection is stored in a directory following the convention:

**NAME\_YYYYMMDDTHHMSS\_UT** (e.g. *NICE\_20250113T222012\_UT*)

The same naming convention applies to events (i.e. the collection of two or more detections of the same fireball recorded by different stations) but without the station name prefix:

**YYYYMMDDTHHMSS\_UT** (e.g. *20250113T222012\_UT*)



It should be noted that two stations of the network may detect the same fireball at slightly different starting times; therefore, the time reported in the event code may differ by a few seconds from those reported in the detection codes of the same event.

For a detection to be correctly loaded into PASCAL, the directory must comply with the standard Freeture structure; otherwise, the detection will not be loaded in PASCAL. In particular, the folder must contain the following mandatory elements:

- ***fits2D***: a folder containing the **detection frames**, organized as individual FITS files named *frame\_XXX.fit* (e.g. *frame\_000.fit*, *frame\_001.fit*, ... *frame\_253.fit*);
- ***positions.txt***: a three-column TXT file reporting the **(x,y) positions of the fireball for each frame** where it was detected by Freeture. The columns are, in order: frame number, (x, y) coordinates, and UTC date/time string. For example:

```
[...]  
191      (622;456)      2025-03-03T03:29:18.0532  
192      (624;452)      2025-03-03T03:29:18.0866  
193      (626;448)      2025-03-03T03:29:18.1198  
[...]
```

When opening a detection, the user must select a starting frame. Afterwards, it is possible to **browse through all the detection frames** using the *Next/Previous* buttons (see [Section 3.1.4](#)), or by directly editing the frame number in the *Current file* textbox (see [Section 3.1.3](#)).

Loading a detection enables the *Positions* menu (see [Section 3.7](#)), which allows the user to view and edit the contents of the *positions.txt* file in order to analyse the apparent path of the fireball in the night sky as recorded by the all-sky camera.

### **3.2.3. Open Capture**

This menu item allows the user to **load a calibration image into PASCAL**. After clicking the button, a file browser dialog will open to **select a FITS file**.

For this option, the file does not need to follow any specific naming convention. In general, any image saved in FITS format can be loaded into PASCAL through this option, provided that its header contains the following mandatory keywords:

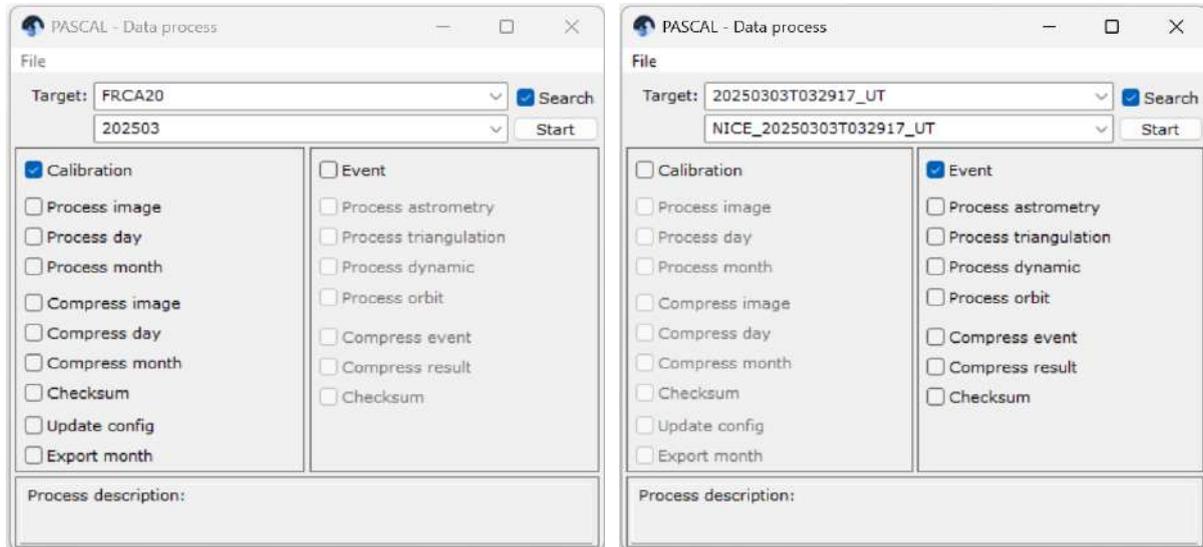
- ***TELESCOP***: the station name (e.g. *NICE*);
- ***DATE-OBS***: the UTC date and time of the observation in FITS format (e.g. *2025-03-03T03:29:18.0532*);
- ***EXPOSURE***: the exposure time of the image, expressed in seconds;
- ***SITELAT and*** : the geographic latitude of the station, expressed in decimal degrees;
- ***SITELONG***: the geographic longitude of the station, expressed in decimal degrees;
- ***SITELEV***: the altitude of the station, expressed in metres above the sea level.

If any mandatory keyword is missing, the image will not be loaded and an error message will be displayed, specifying the missing entry.

In addition, the station name reported in the *TELESCOP* keyword must be listed in the *solutions.txt* file (see [Section 2.1](#)); otherwise, the image will not be opened and the user will be prompted to add the missing station to that file.



Figure 4 – Screenshots of the *PASCAL Data Process* submodule window. The left panel shows the window when selecting calibration data processing and the right panel displays the event processing, both using the test data available with the PASCAL installer.



### 3.2.4. Data Process

This menu item launches the *Data Process* submodule of PASCAL, which opens a secondary window providing a graphical interface for executing the **PRISMA data analysis pipeline**. A screenshot of this window is shown in [Figure 4](#).

If the user selects either the calibration or the event module, the corresponding options will become available. The function of each option is briefly described in the *Process description* textbox at the bottom of the window when hovering over it with the mouse. A more in-depth overview of the **PRISMA pipeline and its functionalities** can be found on the [GitLab repository](#) of the source code and its [Wiki page](#).

The analysis target can be defined using the two *Target* textboxes (and their corresponding dropdown lists) located in the upper part of the window, depending on which module is currently selected:

- **Calibration module:**
  - The first line must be set to the **camera code** (e.g. *FRCA20*).
  - The second line must be set to the **day** (e.g. *20250310*) **or month** (e.g. *202503*) of the data acquisition to be processed.
- **Event module:**
  - The first line must be set to the **event code** (e.g. *20250303T032917\_UT*).
  - The second line may be **optionally set to the detection code** (e.g. *NICE\_20250303T032917\_UT*). If not set, the program will include all valid detections found inside the event directory.

The *Search* button, located on the right side of the target selection area, performs an automatic search of the data currently available in the PASCAL workspace and populates the two dropdown lists accordingly.



### 3.2.5. Exit

This button closes PASCAL. Alternatively, the application can also be closed using the “X” button in the top-right corner of the window.

## 3.3. Logo Menu

This menu becomes active only after a valid image has been loaded into PASCAL. Through this menu, the user can show or hide the project’s logo, as well as the positional and timing information, on the zoom draw window. These graphic elements will be also included in the exported track image and GIF animation (see [Section 3.1.5](#)).

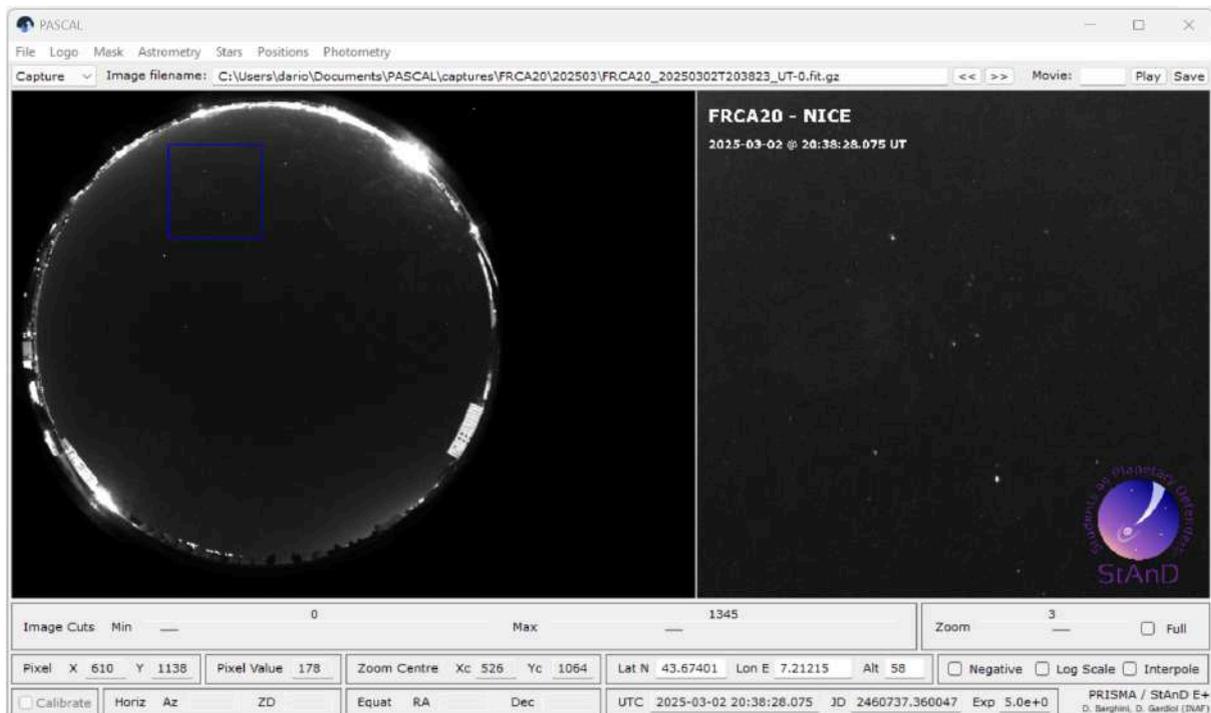
### 3.3.1. Show Logo

This menu item allows the user to **display the project’s logo** (either PRISMA or StAnD) in the bottom-right corner of the zoom draw window. An example of how the logo appears in the PASCAL interface is shown in [Figure 5](#).

### 3.3.2. Show Info

This menu item allows the user to display the **station code and name** in the top-left corner of the zoom draw window, and the **date and time of acquisition** of the current image on a second line right under it. An example of how this information appears in the PASCAL interface is shown in [Figure 5](#).

**Figure 5 – Screenshot of the main window of the PASCAL application, showing a calibration frame from the StAnD station in Nice (FRCA20 – Nice, Collège Frédéric Mistral). The project’s logo and the location and timing information are displayed by enabling the corresponding options in the Logo menu.**





### **3.3.3. Import Logo**

This menu item allows the user to **load a new logo** that will be displayed when the corresponding option is active (see [Section 3.3.1](#)). It includes three sub-options that allow loading different logo versions:

- **Black logo:** imports the version of the logo that will be displayed on a black background (when the *Negative* button is unchecked);
- **White logo:** imports the version of the logo that will be displayed on a white background (when the *Negative* button is checked);
- **Both logos:** imports both versions of the logo from one file (to be used when the logo has no separate black and white versions) that is assumed to have a transparent background.

## **3.4. Mask Menu**

This menu becomes active only after a valid image has been loaded into PASCAL. Through this menu, the user can **load and visualize a mask** (similar to the detection mask described in the Meteor Camera Kit Manual, Section 4.3.1) **and a superflat**. The latter is a composite image that can be used to **reduce spatial noise**, particularly in calibration frames, by suppressing the visualization of hot and dead pixels. It can also be computed directly through an option available in this menu.

The use of a mask and a superflat image is **recommended when performing the astrometric calibration of images** (see [Section 3.5](#) and [Section 3.6](#)), but they will be silently ignored during the fireball position and photometric analysis ([Section 3.7](#) and [Section 3.8](#)).

### **3.4.1. Load Mask**

This menu item allows the user to **load a mask BMP file**, similar to the one discussed for the Freeture configuration in the Meteor Camera Kit Manual, Section 4.3.1. In summary, the mask file is an image with the same dimensions as the sensor under consideration (1324 × 1324 pixels for the new-generation StAnD stations), where a pixel value of 0 (black) marks regions to be masked (i.e. excluded from all subsequent computations), and a value of 1 (white) marks regions to be preserved.

When a new mask is loaded through this menu item, it will be automatically displayed, and the *Show mask* option (see [Section 3.4.2](#)) will be checked by default.

If the *Test Data* component was selected during the installation of PASCAL (see [Chapter 2](#)), example mask files are available in the directory `PASCAL\settings\configurations\` for the StAnD stations included in the installed dataset.

Using this option allows, most importantly, the **masking of the portion of the image close to the horizon** when searching for stars (see [Section 3.6](#)), which is typically affected by light pollution from the surrounding environment and may otherwise cause false positives in the star search algorithm.



### **3.4.2. Show Mask**

This menu item allows the user to **show (if checked) or hide (if unchecked) the mask** currently loaded in the main and zoom draw windows of PASCAL. If no mask is loaded (i.e. the *Load mask* item is unchecked; see [Section 3.4.1](#)), clicking this item will have no effect.

In addition to controlling the mask visibility, the toggle status of this item also determines whether the mask is considered in the options of the *Astrometry* and *Stars* menus (e.g. whether the mask is applied during the star-finding process; see [Section 3.5](#) and [Section 3.6](#)).

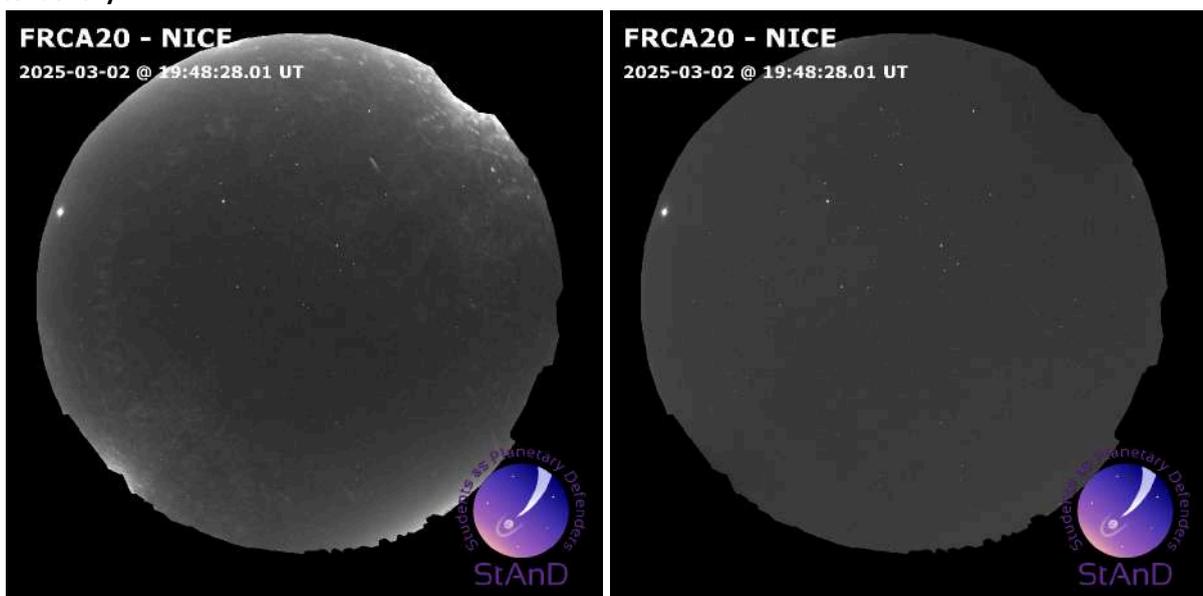
### **3.4.3. Compute Flat**

This menu item allows the user to compute a **superflat image** using the data contained in the directory of the image currently loaded in PASCAL. After selecting this option, the user will be prompted, through a file browser, to **select a series of FITS files from the current directory**. The recommended selection includes **at least ten images** acquired under good weather conditions and with the Moon below the horizon. These conditions can be verified before selecting this option through a simple visual inspection, by browsing the images (typically calibration frames) using the *Next/Previous* buttons (see [Section 3.1.4](#)).

From the selected images, PASCAL will compute a **median frame** that ideally encloses the relative response of each pixel. Once the computation is complete, the user will be prompted to choose a path and filename to save the resulting superflat image as a new FITS file. If needed, it can be visualized as a standard FITS image by loading it into PASCAL as a capture.

To improve the results of the superflat computation, it is recommended to perform this operation with an appropriate mask loaded and visible, by checking the first two options of the *Mask* menu (see [Section 3.4.1](#) and [Section 3.4.2](#)).

Figure 6 – Comparison between the “raw” and “flat” versions of a calibration image acquired by the StAnD station in Nice (FRCA20 – Nice, Collège Frédéric Mistral) during the night of 02/03/2025. The flat correction effectively removes the influence of nearby lights on the horizon, most stray light (including that caused by internal reflections within the optical system), and hot pixels. In the “flat” version, stars become much easier to identify.





#### **3.4.4. Load Flat**

This menu item allows the user to **load a superflat image** corresponding to the image currently loaded into PASCAL. The normalization to the selected superflat is performed through a **pixel-wise division of the image by the superflat**. We refer to the normalized image as “flat” because the resulting sky background will appear uniform and hot and dead pixels will be corrected.

The flat version of the image can be displayed instead of the original (“raw”) version by checking the *Show flat* item (see [Section 3.4.5](#)). When a new superflat is loaded through this menu item, the flat version of the image will be automatically displayed, and the *Show flat* option will be checked by default. An example of the comparison between the “raw” and “flat” version of the same calibration image is shown in [Figure 6](#).

#### **3.4.5. Show Flat**

This menu item allows the user to **show (if checked) or hide (if unchecked) the flat version of the current image**, computed using the currently loaded superflat, in the main and zoom draw windows of PASCAL. If no superflat is loaded (i.e. the *Load flat* item is unchecked; see [Section 3.4.4](#)), clicking this item will have no effect.

In addition to controlling the visibility of the flat image, the toggle status of this item also determines whether the superflat correction is applied within the options of the *Astrometry* and *Stars* menus (see [Section 3.5](#) and [Section 3.6](#)), that is, whether flat normalization is applied during the star-finding process.

### **3.5. Astrometry Menu**

This menu becomes active only after a valid image has been loaded into PASCAL. Through this menu, the user can enable, toggle and execute all the astrometric computations on the current image. It serves as the main interface for **loading, displaying, editing, and saving the astrometric solution**. In calibration images, this solution will be based on the positions of stars detected in the image. For this reason, many of the items in this menu are **interrelated with those of the Stars menu** (see [Section 3.6](#)).

For the sake of clarity, the term *solution* refers to the set of physical parameters used to **convert the coordinates of a source measured in instrumental units** on the focal plane, that is,  $(x, y)$  in pixel units, **into sky angular coordinates**, such as horizontal or equatorial coordinates. In some cases, the term *solution* may also refer to the **photometric solution**, which similarly consists of a set of parameters used to convert the **intensity of a source measured in instrumental units** (such as ADU per second) on the focal plane **into apparent magnitude units**.

#### **3.5.1. Activate**

This menu item **enables all other items in the Astrometry menu** – except for the *Load solution* (see [Section 3.5.2](#)) and *Reset solution* (see [Section 3.5.3](#)) items, which are always active – or disables them when clicked a second time. If no solution file has been previously loaded, PASCAL will automatically **load a predefined solution** and display a warning message.



### 3.5.2. Load Solution

This menu item allows the user to **load a new astrometric solution** in the form of a TXT file with a predefined and fixed format. After clicking this item, a file browser will prompt the user to select the desired file. A solution file can be also loaded **before activating the astrometry module** (see [Section 3.5.1](#)).

If the *Test Data* component was selected during the installation of PASCAL (see [Chapter 2](#)), **example solution files are available** in the directory `PASCAL\settings\solutions\` for the StAnD stations included in the installed dataset. Note that these solution files are those produced by the complete data processing pipeline (see [Section 3.2.4](#)) and may slightly differ from those generated using the *Save solution* item (see [Section 3.5.6](#)). Both file versions are fully compatible with PASCAL.

An example of a solution file is shown in [Figure 7](#). The first six lines of the file contain **important metadata**, listed in the following order: the station code and date of the solution; the configuration file used by the data processing pipeline to compute the solution; the **astrometric model** and the **number of stars** used in the computation; and the **standard deviation of the residuals** in azimuth and zenith distance derived from the position of the stars used to compute the solution. If the solution was exported through PASCAL, the header will contain **three additional lines related to the photometric calibration**, listed in the following order: the standard deviation of the magnitude residuals, the zero-point magnitude, and the correction factor associated with the photometric solution.

As shown in [Figure 7](#), each line following the header reports the **value of the parameters of the solution** (and the corresponding error, if provided) whose physical meaning can be understood through the use of the *Astrometry* submodule of PASCAL (see [Section 3.5.4](#)).

**Figure 7 – Screenshot of the content of a solution file for the the StAnD station in Nice (FRCA20 – Nice, Collège Frédéric Mistral), provided with the PASCAL installation is the user selected the *Test Data* component. The solution was computed through the complete data analysis pipeline over a daily statistics (from the night of 02/03/2025) of about 18 thousand stars.**

```
FRCA20_20250302_astro_solution.txt
1 FRCA20_20250302
2 config = FRCA20_20250202.ini
3 model = proj_rotz_expl_asym
4 ns = 18563.
5 sd_az = 1.93 amin
6 sd_zd = 2.93 amin
7 -----
8
9 a0 = 4.322362e-01 ± 1.013836e-05 rad
10 xo = 6.370093e+02 ± 1.730345e-02 px
11 yo = 6.469374e+02 ± 1.718083e-02 px
12 xz = 6.353480e+02 ± 6.836295e-03 px
13 yz = 6.500758e+02 ± 6.881603e-03 px
14 v = 2.235668e-03 ± 2.542034e-07 rad/px
15 s = 3.654308e-03 ± 2.354537e-05 rad
16 d = 6.857992e-03 ± 1.030439e-05 1/px
17 j = 1.451411e-03 ± 1.939584e-05 rad
18 phi = 1.416124e+00 ± 1.340949e-02 rad
```



### 3.5.3. Read Solution

This menu item allows the user to **reset the astrometric model and the parameters of the solution** (for both astrometry and photometry) to their default values. An informational message will be displayed if the pre-existing solution was loaded or modified by the user.

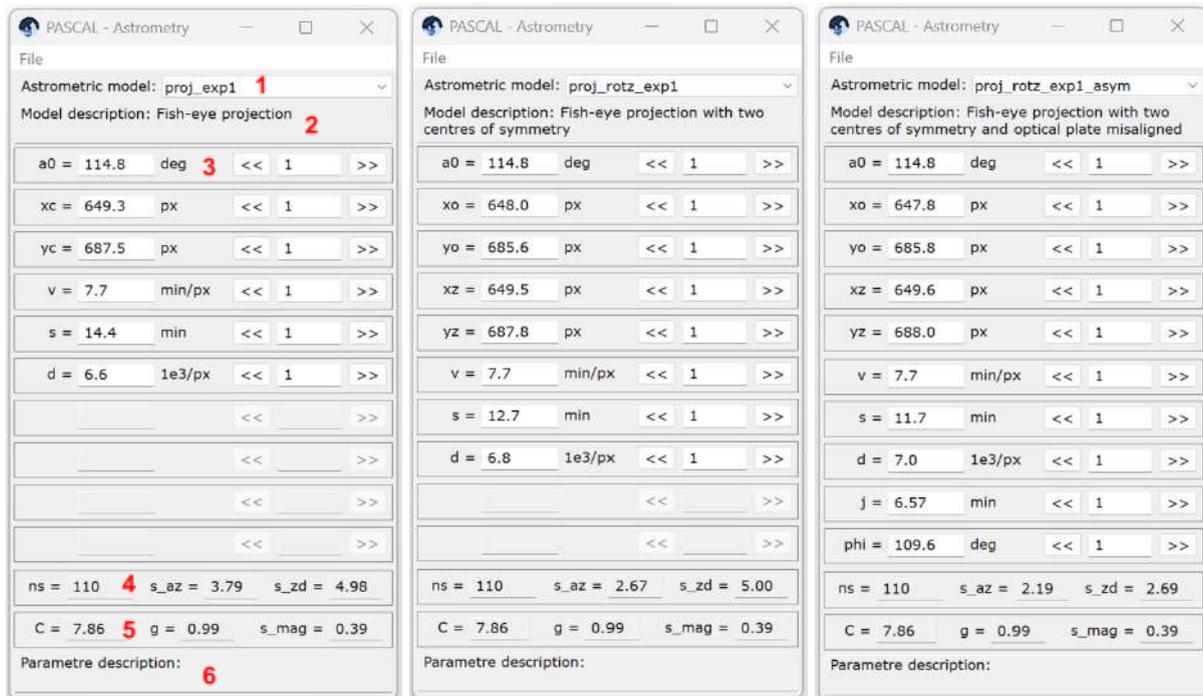
### 3.5.4. Edit Solution

This menu item launches the **Astrometry submodule of PASCAL**, which opens a secondary window providing a graphical interface for **modifying the parameters of the current astrometric solution**. A second click on this menu will close the currently opened submodule and destroy the window. Some screenshots of this window, shown for three different astrometric models loaded, are provided in [Figure 8](#).

The various components of the window of this submodule are as follows:

1. **Astrometric model:** a dropdown menu allowing the user to **select the astrometric model from four available options**. The supported models are:
  - a. **proj\_asin1** – the standard fish-eye projection;
  - b. **proj\_exp1** – a symmetric projection with an exponential distortion model;
  - c. **proj\_rotz\_exp1** – an extension of the previous model including two centres of symmetry (the optical centre and the zenith direction);
  - d. **proj\_rotz\_exp1\_asym** – an extension of the previous model that incorporates an asymmetric distortion of the azimuth angle on the focal plane.

**Figure 8 – Screenshots of the Astrometry submodule of PASCAL opened for three different solutions. The numbers shown in the left panel correspond to the description provided in [Section 3.5.4](#). Depending on the selected astrometric model, a different number of parameter rows will be activated. From left to right, the models increase in complexity and accuracy, as shown by the decreasing values of the astrometric residuals.**





2. **Astrometric model description:** a textbox displaying a short description of the current astrometric model.
3. **Parameters table:** a table displaying the **values of all the parameters** included in the current astrometric solution. Each row reports, from left to right, the **parameter name** (i.e. symbol or abbreviation), its **current value and measurement unit**, together with a set of two buttons and an editable textbox allowing the user to **increase or decrease the current value** according to the step specified in the textbox. When hovering the mouse over the parameter name, its description is displayed in the textbox at the bottom of the window.
4. **Astrometry information:** three textboxes reporting the value of some parameters summarizing the **quality of the astrometric current solution**. From left to right, these are: the number of stars used to determine the solution ( $ns$ ), the standard deviation of the azimuth residuals ( $s_{az}$ ), and the standard deviation of the zenith-distance residuals ( $s_{zd}$ ), both expressed in arcminutes. Lower values of these standard deviations indicate a better-quality astrometric solution, as they represent the **average offset** between the actual position of a source and the position computed by the astrometric model. These values are displayed only if the solution was computed from a fit over a set of stars associated with catalogue positions, and therefore the *Match stars* option of the *Stars* menu is active (see [Section 3.6.5](#)), or if it was loaded from a solution file produced by PASCAL (see [Section 3.5.2](#)). If the user modifies the solution manually (e.g. through the parameters table), these values will be erased.
5. **Photometry information:** three textboxes reporting the value of the photometric parameters associated with the current solution. From left to right, these are: the photometric zero-point magnitude ( $C$ ), the photometric correction factor for the magnitude scaling ( $g$ ), and the standard deviation of the magnitude residuals ( $s_{mag}$ ). The zero-point magnitude  $C$  represents the instrumental magnitude, defined as  $m_s = -2.5 \cdot \log_{10}(F_s)$ , of a source with apparent magnitude  $m = 0$  (where  $F_s$  is the instrumental flux of said source, typically expressed in ADU/s units). Knowing the values of  $C$  and  $g$ , one can estimate the apparent magnitude of a source as  $m = C + g \cdot m_s$ .  
  
The standard deviation of the magnitude residuals indicates the precision of this conversion based on the current values of  $C$  and  $g$  shown in the textboxes. Lower values of this standard deviation correspond to a higher-quality photometric solution. These values are displayed only if the *Match stars* option of the *Stars* menu is active (see [Section 3.6.5](#)) or if the solution was loaded from a solution file produced by PASCAL (see [Section 3.5.2](#)).
6. **Parameter description:** a textbox displaying the description of the parameter over which the user's mouse is currently hovering.

### **3.5.5. Fit Solution**

This menu item allows the user to **automatically determine the optimal values of the solution parameters** (for both astrometry and photometry calibrations) **based on the current match** between the detected stars and their catalogued positions and magnitudes



(see [Section 3.6.5](#)). This procedure is typically referred to as a “fit”, hence the name of this menu item.

This option will be available only if the *Match stars* item of the *Stars* menu is selected (see [Section 3.6.5](#)). Moreover, for the fit to be successful, the **number of matched stars must exceed the number of parameters** in the current astrometric model. It is recommended to have **at least several tens of matched stars** before attempting to fit the solution.

If the fit is successful, the values of the astrometric and photometric parameters displayed in the *Astrometry* submodule will be updated to the optimal solution (see [Section 3.5.4](#)), and all related options and submodules will be refreshed accordingly. The **quality of the resulting solution** can be assessed by examining the **astrometric and photometric residual plots** (see [Section 3.5.9](#) and [Section 3.5.10](#)). The standard deviations of these residuals are reported in the corresponding textboxes of the *Astrometry* submodule (see [Section 3.5.4](#)). If the fit fails, an error message will be displayed, and the current solution will remain unchanged.

### **3.5.6. Save Solution**

This menu item allows the user to **save the values of the current solution’s parameters** – both astrometric and, if available, photometric – into a TXT file that can later be loaded back into PASCAL (see [Section 3.5.2](#)). After clicking this item, a file browser window will open, prompting the user to **select a location and filename** for saving the solution as a TXT file.

### **3.5.7. Show Alt/Az Grid**

This menu item enables the **visualization of the alt-azimuthal grid** on both the main window and the zoom window of PASCAL, based on the currently loaded astrometric solution. Clicking the item a second time hides the grid. The grid is displayed as thin dashed lines in white (or black if the *Negative* option is selected; see [Section 3.1.15](#)), as shown in [Figure 9](#).

The lines radiating from the centre (corresponding to the zenith direction and/or the optical centre, depending on the selected astrometric model) represent **azimuth isolines**, while the concentric circles represent **zenith distance isolines**. In the zoom window, each isoline is **labelled with its corresponding alt-azimuth coordinate**.

Users should note that generating and displaying the grid requires a non-negligible amount of computation time. Consequently, **browsing through images may be slower** than expected while this option is active.

### **3.5.8. Hide Grid Label**

This menu item **disables the visualization of the alt-azimuth grid labels** when the *Show alt/az grid* option is active (see [Section 3.5.7](#)). Clicking the item a second time restores the labels visualization.

### **3.5.9. Plot Astrometry**

This menu item allows the user to plot the azimuth (top panel) and zenith distance (bottom panel) **residuals between the measured and catalog positions of the stars** identified in the current calibration image (see [Section 3.6](#)). Consequently, this item is available only when the *Match stars* option of the *Stars* menu is active (see [Section 3.6.5](#)). The plots are displayed



in a new graphical window, from which the user can **edit and export** them in several formats. An example of this window is shown in the left panel of [Figure 10](#).

Together with the standard deviations of the azimuth and zenith distance residuals reported in the Astrometry submodule (see [Section 3.5.4](#)), these two plots can be used to **assess the quality of the current astrometric solution**. In particular, the magnitude of the residuals should remain smaller than the angular size of one pixel, which for the optics of the StAnD Meteor Camera Kits is approximately 7 arcminutes.

### 3.5.10. Plot Photometry

This menu item allows the user to plot the **scatter between the instrumental and catalog magnitudes** of the stars identified in the current calibration image (see [Section 3.6.5](#)), **along with the calibration line** (shown in red) defined by the current photometric solution (i.e. the zero-point and the magnitude scaling correction factor). Consequently, this item is available only when the *Match stars* option of the *Stars* menu is active (see [Section 3.6.5](#)).

The plots are displayed in a new graphical window, from which the user can **edit and export** them in several formats. An example of this window is shown in the right panel of [Figure 10](#).

Together with the standard deviation of the magnitude residuals reported in the *Astrometry* submodule (see [Section 3.5.4](#)), this plot can be used to **assess the quality of the current photometric solution**. In particular, the scatter of the data points around the calibration line should not exceed 0.5 mag.

**Figure 9** – Screenshot of the main window of the PASCAL application, showing a calibration frame from the StAnD station in Nice (FRCA20 – Nice, Collège Frédéric Mistral) with the *Show alt/az grid* option of the *Astrometry* menu enabled. Grid labels are automatically displayed for each isoline and can be hidden using the *Hide grid labels* option in the same menu. The Orion constellation is visible in the upper-right portion of the zoom draw window.

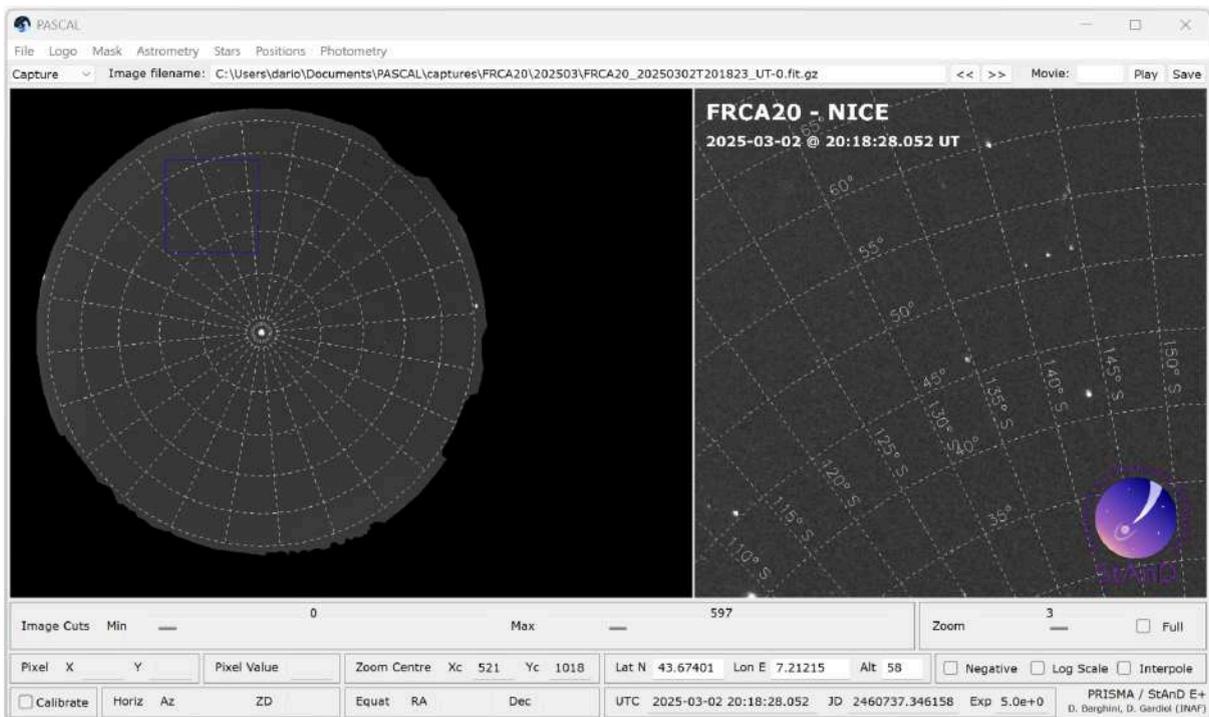
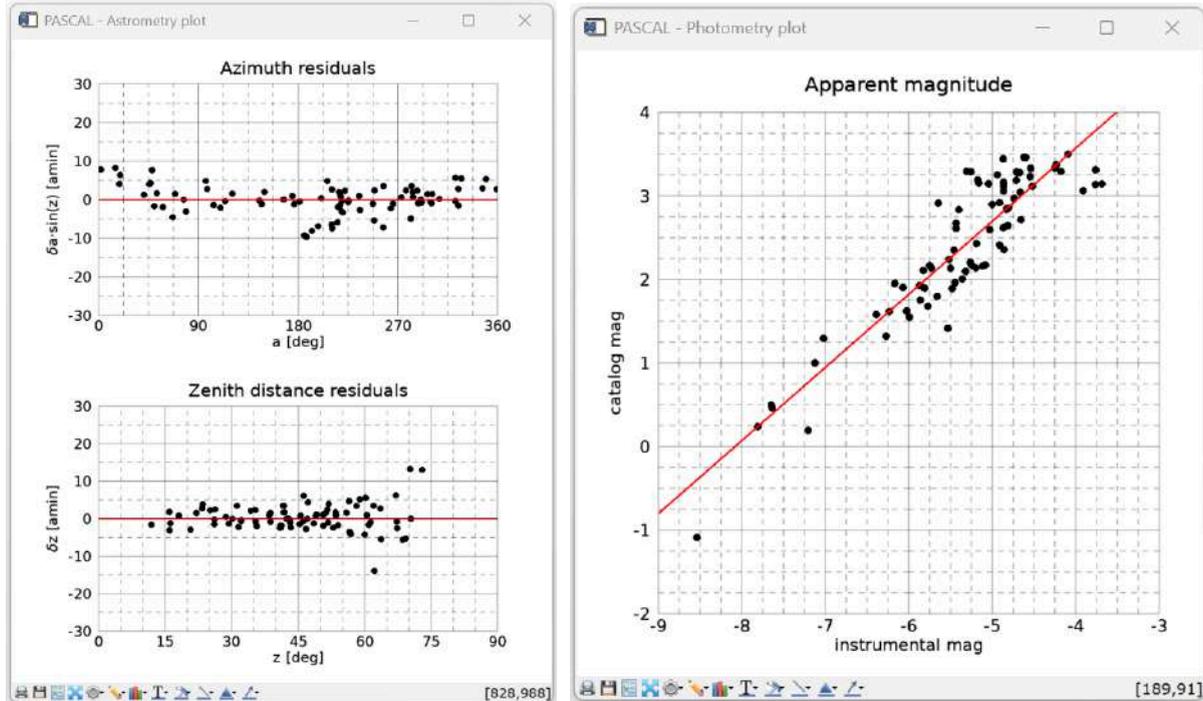




Figure 10 – Screenshot of the astrometry and photometry plots produced by PASCAL for the calibration of the image shown in Figure 43. On the left panel, the astrometry plot displays the azimuth and zenith distance residuals (in arcminutes) between the measured and catalogued positions of the detected stars, illustrating the quality of the current astrometric solution. On the right panel, the photometry plot shows the relation between instrumental and catalog magnitudes for the detected stars, illustrating the magnitude conversion defined by the current photometric solution. The standard deviations of the residuals shown in these plots are reported in the corresponding boxes of the *Astrometry* submodule (see [Figure 8](#)).



### 3.6. Stars Menu

This menu becomes active only after a valid calibration image has been loaded into PASCAL. Through its items, the user can perform all operations related to the **detection and identification of stars in the current image**. The core functionality provided by this menu is the comparison between the measured positions of detected sources and the corresponding entries in the stellar catalog preloaded in PASCAL (see [Section 2.1](#)), using the **current astrometric solution**. For this reason, many of the items in this menu are **interrelated with those of the *Astrometry* menu** (see [Section 3.5](#)).

#### 3.6.1. Find Stars

This menu item allows the user to **automatically detect stars** and, more generally, bright point-like sources, in the current image according to a set of configurable parameters (see [Section 3.6.6](#)). The positions of the detected stars are highlighted on both the main and zoom draw windows as **small red circles**. An example of the output of this function is reported in [Figure 11](#).

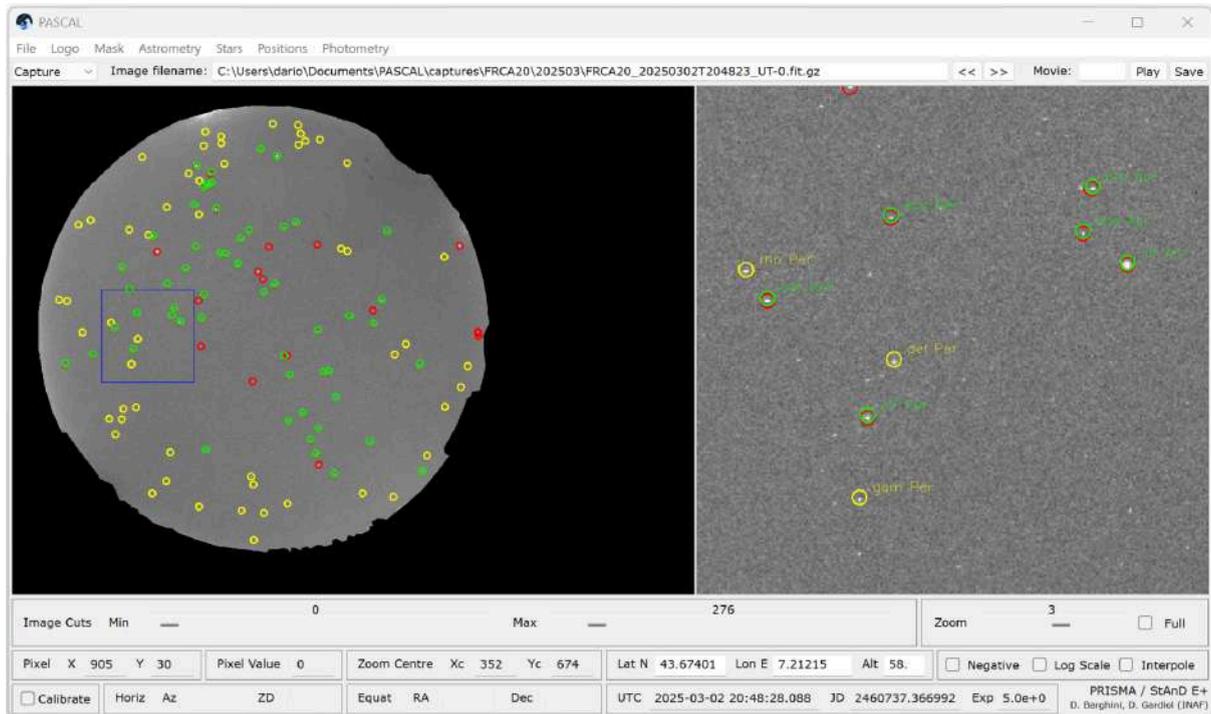
Before performing this operation, it is highly recommended to **load and display both a mask and a superflat**, in order to minimize the effects of nearby lights on the horizon, stray light, and hot pixels, all of which may in some cases mimic the signal of stars (see [Section 3.4](#)). If



these conditions are not met, a warning message will be displayed, informing the user that the results of the automatic star detection may be unreliable.

While this option is active, stars will also be automatically detected when a new image is opened. If no stars are found, the menu item will be automatically deselected and a warning message will be displayed.

**Figure 11 – Screenshot of the main window of the PASCAL application, showing a calibration frame from the StAnD station in Nice (FRCA20 – Nice, Collège Frédéric Mistral), with the *Find stars*, *Show catalog*, *Show IDs*, and *Match stars* options of the *Stars* menu enabled. Detected stars are displayed as red circles, while catalog stars are shown as yellow circles. Catalog stars that have been successfully matched with detected star positions are highlighted in green. The identifier of each catalog star is displayed as a label on the upper-right side of the corresponding circle, in yellow or green depending on whether a match was found.**



### **3.6.2. Stars Table**

This menu item opens a table displaying the **main properties of the detected stars** (see [Section 3.6.1](#)) and **their association with entries from the stellar catalog** preloaded in PASCAL (see [Section 3.6.3](#)). An example of this table is shown in [Figure 12](#). Each row corresponds to one detected star and is **ordered from brightest to faintest** according to the instrumental flux. From left to right, the table columns report:

1. the **progressive identification number** of the star;
2. the **X-coordinate** of the star centroid on the image, expressed in pixels;
3. the **Y-coordinate** of the star centroid on the image, expressed in pixels;
4. the **instrumental flux** of the star, expressed in ADU/s;
5. the **identifier of the stellar catalog entry** matched to the star (abbreviated name of the constellation and star, or code if no proper name is available);



6. the **azimuth** of the matched catalog entry, expressed in degrees;
7. the **zenith distance** of the matched catalog entry, expressed in degrees;
8. the **apparent magnitude** of the matched catalog entry.

Columns 5 - 8 are populated only if the *Match stars* item is enabled (see [Section 3.6.5](#)), and only for stars for which a valid catalog match has been found according to the current settings (see [Section 3.6.6](#)).

### 3.6.3. Show Catalog

This menu item allows the user to **display the positions of stellar catalog entries** on the current image according to the currently loaded astrometric solution (see [Section 3.5](#)). These positions represent **where stars are expected to appear** if the astrometric solution is sufficiently accurate and precise. Catalog positions are highlighted on both the main and zoom draw windows as **small yellow circles**. If a **catalog entry is successfully matched** with a detected star in the current image, the corresponding circles are **displayed in green** instead (see [Section 3.6.5](#)). An example of the output of this function is shown in [Figure 11](#).

### 3.6.4. Show IDs

This menu item allows the user to **display the identifier of each stellar catalog entry** shown in the current image as a small text label, displayed in yellow (or in green if the catalog entry has been matched with a detected star). If the *Show catalog* option is selected (see [Section 3.6.3](#)), the labels are **shown on the upper-right side of the corresponding circles** in the zoom draw window, only when the zoom level is lower than 4 (see [Section 3.1.10](#)).

Figure 12 – Screenshot of the *Stars table* window of the PASCAL application, showing the results of the stars finding and catalog matching algorithm for a calibration frame from the StAnD station in Nice (FRCA20 – Nice, Collège Frédéric Mistral).

#	X [px]	Y [px]	Flux [1/s]	ID	Az [deg]	ZD [deg]	Mag
28	505.17	1065.82	1.734e+02	eps Ori	225.54	55.10	1.62
29	500.52	376.67	1.681e+02	alf UMi	359.17	46.14	2.11
30	792.67	338.28	1.668e+02				
31	552.10	885.08	1.664e+02	mu. Gem	230.99	29.03	2.91
32	642.91	1158.17	1.571e+02	bet CMa	205.44	65.50	1.89
33	494.79	1060.11	1.504e+02	del Ori	227.21	54.88	2.14
34	399.85	806.92	1.499e+02	iot Aur	269.19	36.68	2.83
35	792.38	432.49	1.432e+02	gam UMa	54.03	38.77	2.43
36	537.86	887.79	1.393e+02	eta Gem	233.95	30.19	3.30
37	790.79	685.12	1.371e+02	alf Lyn	113.80	18.37	3.25
38	264.69	692.01	1.336e+02	bet Per	294.01	52.02	2.10
39	512.51	1094.25	1.317e+02	iot Ori	222.92	59.26	2.67
40	1055.23	598.69	1.230e+02	bet Leo	102.47	56.63	2.16
41	206.57	623.43	1.209e+02	gam01 And	302.95	61.50	2.24
42	583.90	859.20	1.188e+02	eps Gem	225.76	24.09	3.19



### 3.6.5. Match Stars

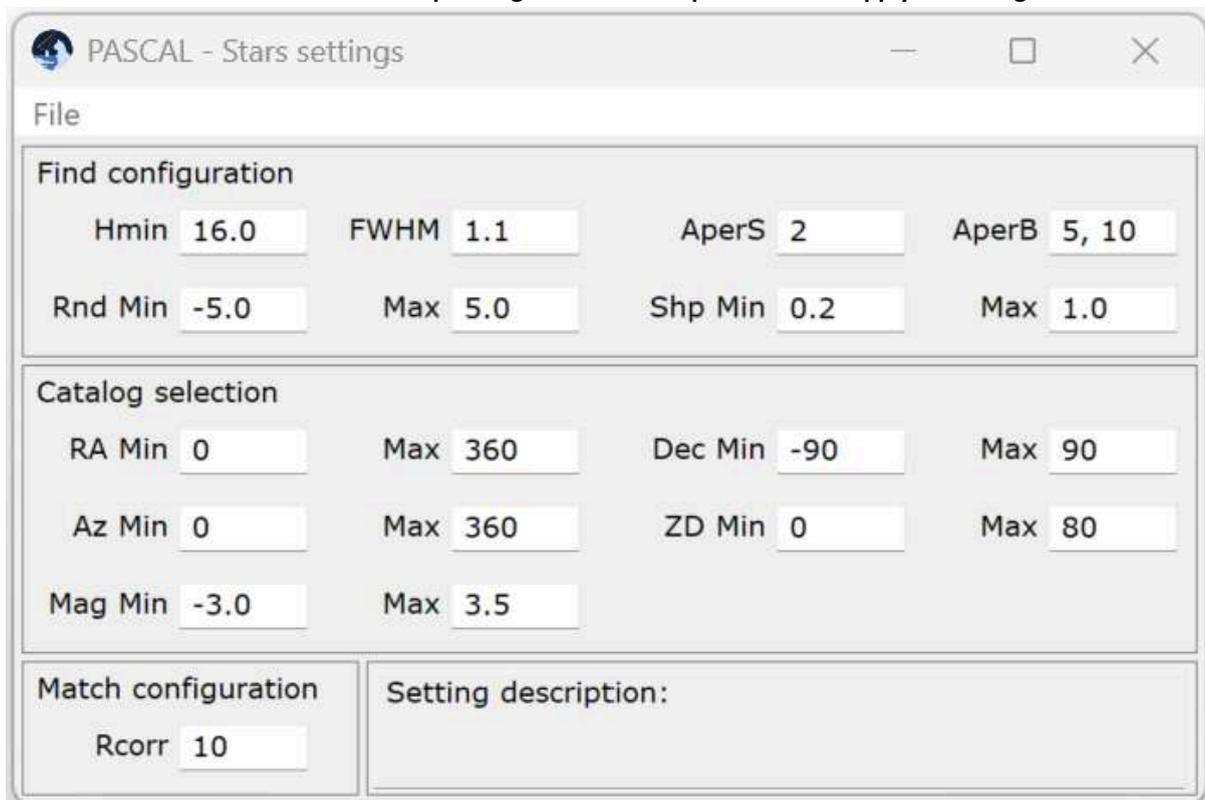
This menu item allows the user to **automatically match the positions of detected stars** (see [Section 3.6.1](#)) in the image with entries from the stellar catalog preloaded in PASCAL (see [Section 3.6.3](#)). Consequently, this item is active only if both the Find stars and Show catalog options are currently selected. The matching is performed using a **nearest-neighbour approach** between the lists of detected and catalog star positions, based on their mutual distance and within a **default maximum separation of 10 pixels**, which can be adjusted in the settings (see [Section 3.6.6](#)).

When a match is successful, the corresponding **catalog star circle and label are displayed in green** in both the main and zoom draw windows, and the associated catalog data are reported in the Stars table (see [Section 3.6.2](#)). An example of the result of this matching is shown in [Figure 11](#) and [Figure 12](#).

### 3.6.6. Open Settings

This menu item launches the *Stars settings* submodule of PASCAL, which allows the user to **edit various parameters controlling the behaviour of the Stars menu** and its main functions. A screenshot of this window is shown in [Figure 13](#). All parameters are listed with a descriptive label and an editable textbox containing the corresponding value. When the user hovers the mouse over a label, a short description of the associated parameter is displayed in the lower part of the window, under the *Settings description* section.

Figure 13 – Screenshot of the *Stars settings* submodule of the PASCAL application, showing the main configuration parameters for the *Find stars*, *Show catalog*, and *Match stars* options of the *Stars* menu. The user can edit these values in the corresponding textboxes and press Enter to apply the changes.





To modify one or more of these parameters, the user must edit their values in the corresponding textboxes and **press Enter** to apply the changes. The most important settings that can be adjusted are:

- **Hmin** (under the *Find configuration* section): the **minimum detection threshold for stars**, expressed as a multiple of the root mean square of the sky background. Lowering this value (default is 16) allows fainter stars to be detected, while increasing it restricts detection to brighter stars. It is not recommended to set this parameter below 4.
- **Mag Max** (under the *Catalog selection* section): the **maximum apparent magnitude of catalog stars to be displayed** when the *Show catalog* option is enabled. Increasing or decreasing this value (default is 3.5) includes fainter or brighter catalog stars, respectively. The user should note that the stellar catalog preloaded in PASCAL contains stars up to +6 apparent magnitude, while the brightest star, Sirius ( $\alpha$  CMa), has a visual magnitude of about -1.5.
- **Rcorr** (under the *Match configuration* section): the **maximum allowed distance between detected and catalog stars for a valid match** when using the *Match stars* option. Decreasing or increasing this value (default is 10 pixels) enforces a stricter or looser matching criterion, respectively. A recommended range for this parameter is between 5 and 20 pixels.

### 3.7. Positions Menu

This menu becomes active only after a valid detection frame has been loaded into PASCAL. Through its items, the user can perform operations related to the **identification and positioning of the fireball** in each frame of the recorded detection video. The starting point for this process is the information provided in the ***positions.txt* file**, which contains approximate fireball positions for each frame where it was detected, **automatically computed by Freeture**. The items in this menu allow the user to **refine and improve the accuracy** of these estimates.

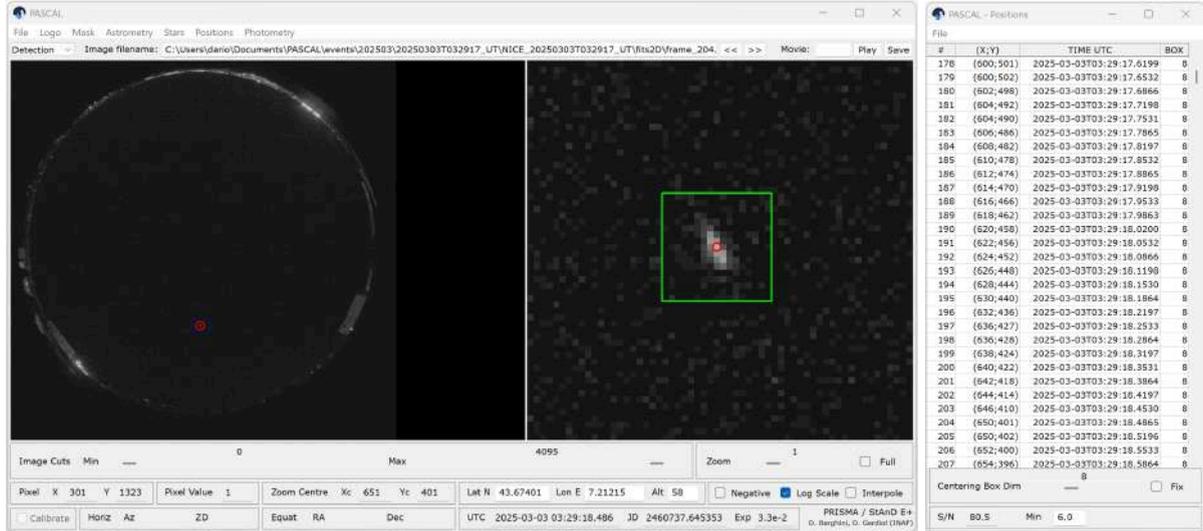
#### 3.7.1. Load

This menu item allows the user to **load the list of fireball times and positions** stored in the *positions.txt* file (see [Section 3.2.2](#)), which is automatically generated by the Freeture detection software. When this file is loaded for the first time, **a new TXT file named *newpositions.txt* is created** in the detection folder as a copy of *positions.txt*. All user modifications are saved in this new file, leaving the original positions file unchanged.

The contents of the positions file are displayed in the ***Positions* submodule of PASCAL**, which opens automatically when this menu item is selected. The submodule consists of a table reporting, for each frame, the progressive frame number, the  $(x, y)$  position, the UTC time, and the box half-size (see [Section 3.7.2](#)). An example of the PASCAL main window together with the *Positions* submodule is shown in [Figure 14](#). Clicking the item a second time will unload the positions list and close the *Positions* submodule of PASCAL.



Figure 14 – Screenshot of the main window of the PASCAL application showing a detection frame from the StAnD station in Nice (FRCA20 – Nice, Collège Frédéric Mistral), capturing a fireball observed on 3rd March 2025 at 03:29:17 UT, with the *Positions* submodule activated (*Load* and *Show box* options enabled). In both the main and zoom draw windows, the fireball ( $x, y$ ) position is marked by a small red circle. In the zoom draw window, the green box highlights the image region used for the S/N computation. The table displayed on the right lists the *Positions* table, reporting all frames included in the detection along with their relevant data.



If the detection frame currently loaded in PASCAL is present in the positions list, a **small red circle is displayed around the ( $x, y$ ) position** specified in the file (see [Figure 14](#)). The user can edit the current position by right-clicking on a new ( $x, y$ ) location in the zoom draw window, provided that the zoom level is lower than 3 (see [Section 3.1.10](#)). If the user right-clicks on the exact position already displayed, the current frame is removed from the positions list.

### 3.7.2. Auto Centre

This menu item enables the **automatic re-centering of the current fireball position**. The computation is performed when the item is first activated and every time a new detection frame is loaded into PASCAL. Clicking this item a second time disables this functionality. The re-centering algorithm follows this specifications:

- The new fireball position is computed using a **barycentric calculation** within a box centered on the current ( $x, y$ ) position. If the current frame does not have an associated position, the computation starts from the temporally closest position available in the positions list;
- The **half-size of the box** used to define the region on the image for the barycentric computation is specified in the last column of the positions table. This value can be adjusted using the *Centering Box Dim* slider located below the table in the *Positions* submodule window (see [Figure 14](#)). It is recommended to keep the box size large enough to fully enclose the fireball image. When loading a new frame, the box half-size is reset to the value specified in the table. Alternatively, the box size can be kept fixed across frames by enabling the *Fix* button located to the right of the slider.



- The algorithm evaluates the **signal-to-noise ( $S/N$ )** ratio at the computed position, defined as the ratio between the fireball flux and the root mean square of the sky background fluctuations. The resulting signal-to-noise ratio is displayed in the  $S/N$  textbox at the bottom of the *Positions* submodule window. If the  $S/N$  value falls below the minimum threshold (shown and editable in the adjacent *Min* textbox), the current frame is automatically removed from the positions list.

### **3.7.3. Show Box**

This menu item allows the user to **visualise the box used for automatic centering and  $S/N$  computation**. The box is displayed in green on the zoom draw window (see [Figure 14](#)). Clicking this item a second time disables the centering box visualisation.

## **3.8. Photometry Menu**

This menu allows the user to **perform aperture photometry measurements on the image** currently loaded in PASCAL. Aperture photometry is a standard technique used in astronomy to **measure the flux (light intensity) of objects in images**. In its standard implementation, aperture photometry requires the definition of three radii that determine the regions over which fluxes are computed:

- **Source aperture:** the radius of the circular region, centered on the target source, over which the gross source flux is integrated.
- **Sky aperture:** the inner and outer radii of an annular region concentric with the source aperture, used to estimate the average sky background flux per unit area. This background contribution is then scaled and subtracted to obtain the net source flux.

In our case, the primary application of aperture photometry is the measurement of the **light curve (LC) of a fireball** recorded by one or more stations of the network. However, the same functionalities can also be used to measure the flux of stars in calibration images.

### **3.8.1. Activate**

This menu item **activates the *Photometry* submodule of PASCAL**, by opening a new window, as shown in [Figure 15](#). The submodule window includes a draw panel that displays the image region currently loaded for the aperture photometry computation.

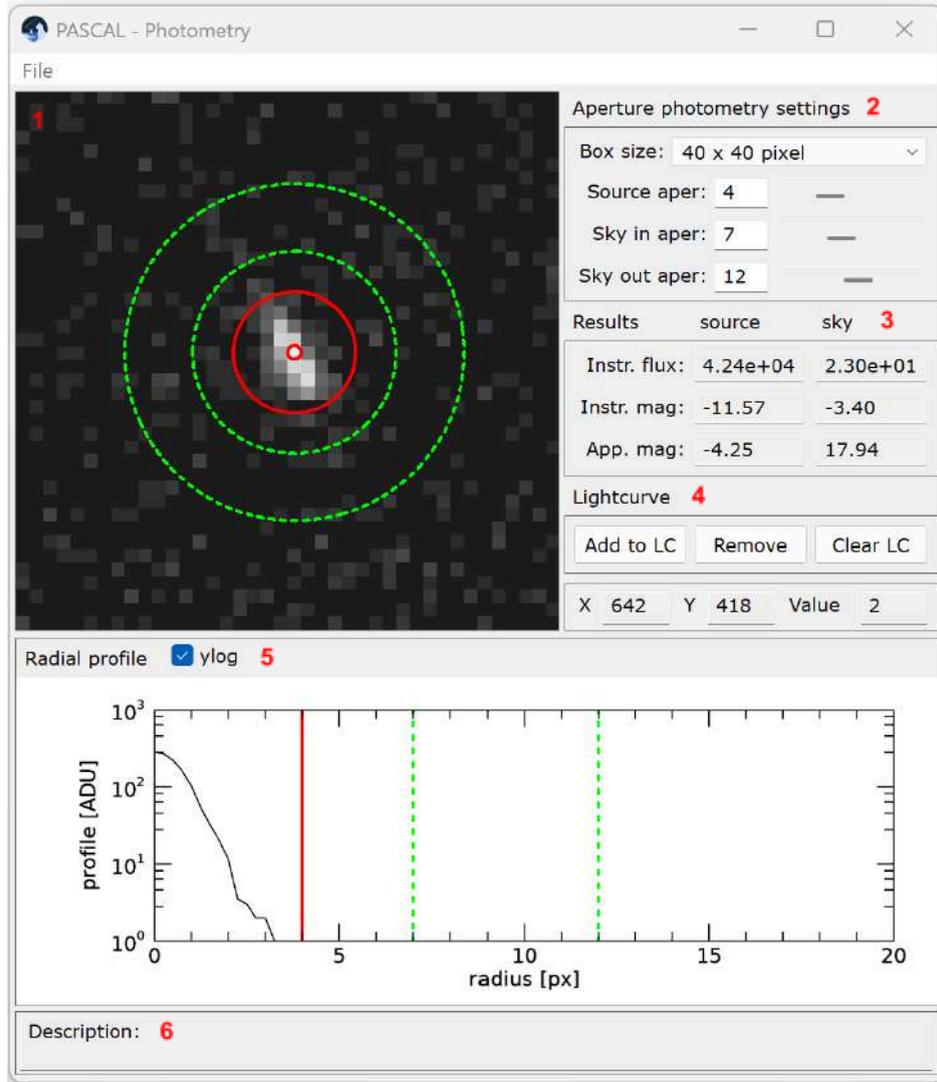
To start the measurement, the user can **select the centre of the object** directly from the zoom draw window in the main PASCAL interface by right-clicking on the desired  $(x, y)$  coordinates when the zoom level is lower than 3 (see [Section 3.1.10](#)). Once selected, the position will be displayed as a small pink circle in both the main and zoom draw windows.

If the image currently loaded in PASCAL corresponds to a detection, the positions list has already been loaded, and the current frame is included in that list (see [Section 3.7](#)), the *Photometry* submodule will automatically open already centred on the estimated fireball position. In this case, the user should be aware that right-clicking on the zoom draw window will simultaneously update the fireball position and recenter the aperture photometry.

In addition, it is also possible to **store individual measurements in the lightcurve**, which acts as a collection of flux and magnitude values as a function of time. This feature enables, for example, the **visualization of the fireball lightcurve** as a function of time.



Figure 15 – Screenshot of the *Photometry* submodule window of the PASCAL application, showing the details of the aperture photometry analysis for a single frame of a fireball observed on 3 March 2025 at 03:29:17 UT and recorded by the StAnD station in Nice (FRCA20 – Nice, Collège Frédéric Mistral). The screenshot also includes the index of all submodule components, as described in [Section 3.8](#).



The main elements of the *Photometry* submodule are the following:

- 1) **Aperture draw window:** a draw panel displaying the square region of the currently loaded image used for the aperture photometry computation. The aperture radii cannot exceed half the size of this box. The central pixel is marked by a small red circle, while the source aperture is shown as a solid red circle and the inner and outer background apertures are shown as two dashed green circles. The user can right-click on any pixel within this image to change the centre used for the aperture photometry computation and move the corresponding box.
- 2) **Aperture photometry settings:** a panel for configuring the settings of aperture photometry measurements. The user can select the box size from five available square dimensions (10, 20, 40, 80, and 160 pixels) and adjust the three aperture radii.



The radii can be modified either by entering values in the dedicated textboxes or by using the sliders located to the right of each textbox.

- 3) **Results:** a panel displaying the results of the aperture photometry measurement for both the source and the sky background fluxes. Specifically, the panel reports the **instrumental flux** (respectively in ADU/s for the source and ADU/s/pixel for the sky background), the **instrumental magnitude** (respectively in mag and mag/pixel), and the **apparent magnitude** (respectively in mag and mag/arcsec<sup>2</sup>). The apparent magnitude is provided only if a valid astrometric and photometric solution is currently loaded in PASCAL (see [Section 3.5](#)).
- 4) **Lightcurve:** a panel with three buttons to manage the measurements stored in the current lightcurve, which can be displayed in two separate plots for the source and sky background fluxes (see [Section 3.8.2](#) and [Section 3.8.3](#)). From left to right:
  - **Add to LC:** add the current aperture photometry measurement to the lightcurve. If a measurement for the current image is already present in the lightcurve, it will be replaced.
  - **Remove:** remove from the lightcurve the aperture photometry measurement corresponding to the current image.
  - **Clear:** clear all measurements from the LC.
- 5) **Radial profile:** a draw panel that displays the radial profile of the aperture photometry region, centred on the photometry centre selected by the user. The radial profile is computed as the average of the image pixel values at increasing radial distances, from 1 pixel up to half the size of the selected box. The three **aperture radii are overplotted on the panel** as vertical lines, using the same colours shown in the aperture draw window. The visualisation of the radial profile is useful for **assessing the appropriateness of the chosen apertures:** the source aperture should include all the signal from the selected source, while the sky background region should be sufficiently far from the source to avoid contamination from the source flux, nearby sources, or stray light.
- 6) **Description textbox:** a textbox displaying a short description of the parameter or panel currently under the mouse cursor. A similar textbox is also provided below the lightcurve panel, displaying the  $(x, y)$  coordinates and the corresponding counts value of the pixel in the image shown in the aperture draw window.

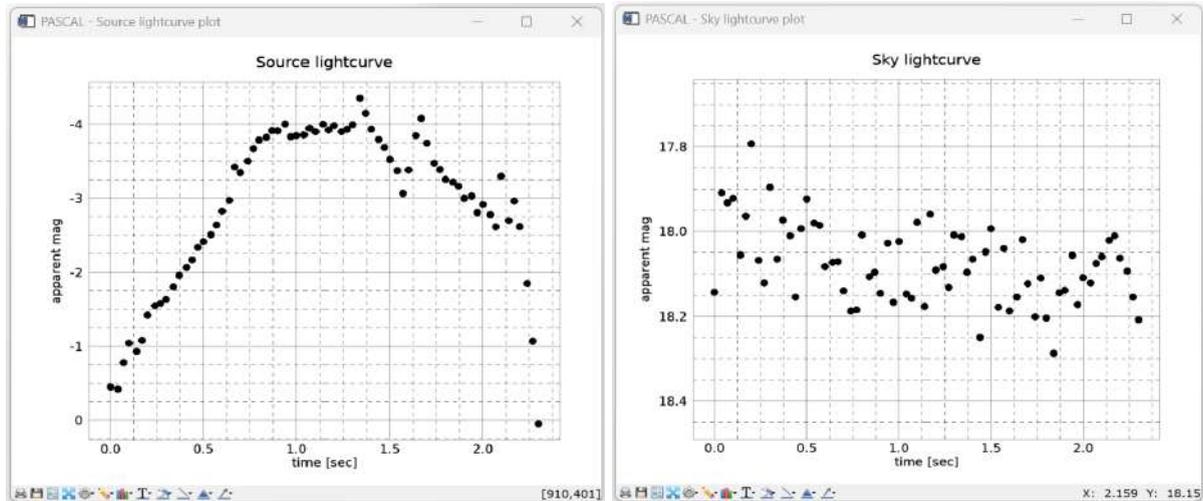
### **3.8.2. Plot Source LC**

This menu item allows the user to generate a **plot of the source lightcurve** currently stored in the memory of PASCAL. The plot is displayed in a new graphical window, from which the user can **edit and export** it in several formats. An example of this window is shown in the left panel of [Figure 16](#).

By default, the x-axis of the plot reports the time elapsed from the earliest image, expressed in **seconds for detection frames and in minutes for calibration images**. The y-axis displays the instrumental magnitude by default, or the calibrated apparent magnitude if a valid astrometric and photometric solution is currently loaded in PASCAL. Alternatively, the user can choose to display the instrumental flux using the dedicated option (see [Section 3.8.4](#)).



Figure 16 – Screenshot of the source (left panel) and sky background lightcurves (right panel) computed through the Photometry submodule of PASCAL for a fireball observed on 3 March 2025 at 03:29:17 UT and recorded by the StAnD station in Nice (FRCA20 – Nice, Collège Frédéric Mistral).



### 3.8.3. Plot Sky LC

This menu item allows the user to generate a **plot of the sky background lightcurve** currently stored in the memory of PASCAL. The plot has the same properties of the source lightcurve one, and an example of it is shown in the right panel of [Figure 16](#).

### 3.8.4. Plot Flux

This menu item allows the user to **choose whether to plot the instrumental flux** (when the item is checked) **or the instrumental/apparent magnitude** (when the item is unchecked) for both the source and sky background lightcurves.

### 3.8.5. Auto Add to LC

This menu item allows the user to **automatically add an aperture photometry measurement** each time a measurement is performed, without requiring the user to click the dedicated button in the *Photometry* submodule. Clicking this item again disables this functionality.

This option is particularly useful for **computing the lightcurve of a fireball** when used in conjunction with the *Load* item of the *Positions* menu (see [Section 3.7.1](#)). In this case, each time a new frame is opened, the centre used for the aperture photometry computation will automatically update to the fireball position specified in the positions list. To compute the complete fireball lightcurve, the user can then use the *Play* function of PASCAL to scroll through all detection frames (see [Section 3.1.5](#)).

## 4. PASCAL - Analysis of Calibration Data

The analysis of calibration data is typically performed to **determine the astrometric and photometric solutions required to triangulate a fireball event** observed by two or more PRISMA and/or StAnD stations. For this reason, the user must first identify and download calibration data acquired during a **suitable night with good weather conditions** for all cameras involved in the fireball recording. The PASCAL installer provides calibration and



fireball observational datasets for a few self-consistent cases, which can be used as tutorial examples.

Based on the information provided in [Chapter 2](#) and [Chapter 3](#), the **main steps required to complete the analysis of calibration data** for a single station using PASCAL are summarised below:

1. Load one calibration image acquired during the night under consideration using **File > Open Capture** (see [Section 3.2.3](#)).
2. Adjust the dynamic range displayed in the image using the **Image Cuts Min / Max** sliders to properly visualise the stars (see [Section 3.1.9](#)). If needed, use the zoom panel to focus on a specific region of the image (see [Section 3.1.8](#)).
3. Load an appropriate mask using **Mask > Load Mask** in order to remove disturbance lights (e.g. along the horizon) from the image (see [Section 3.4.1](#)). For the PASCAL tutorial data, example masks are provided in the PASCAL workspace (located by default in the user's Documents folder) under *settings/configuration*.
4. Identify a set of at least 10 - 20 images, preferably acquired without Moon contamination in the field of view, and compute a superflat based on these images using **Mask > Compute flat** (see [Section 3.4.3](#)). Then, load the resulting superflat using **Mask > Load flat** (see [Section 3.4.4](#)).
5. Activate the astrometric functions using **Astrometry > Activate** (see [Section 3.5.1](#)).
6. Detect the stars visible in the current image using **Stars > Find stars** (see [Section 3.6.1](#)), and enable the visualisation of the stellar catalog using **Stars > Show catalog** (see [Section 3.6.2](#)).
7. If an astrometric (and photometric) solution TXT file is already available, it can be loaded directly at this stage using **Astrometry > Load solution** (see [Section 3.5.2](#)). Pre-computed solutions for the PASCAL tutorial data are provided in the PASCAL workspace under *settings/solutions*.
8. Use **Astrometry > Edit solution** (see [Section 3.5.4](#)) to manually adjust the solution parameters and improve the alignment between detected stars (red circles) and catalog stars (yellow circles).
9. To confirm the associations, use **Stars > Match stars** (see [Section 3.6.5](#)), which highlights in green the catalog stars that have been successfully matched. Aim to obtain at least several tens of correctly matched stars, uniformly distributed across the field of view.
10. Optionally, refine the solution by selecting **Astrometry > Fit solution** (see [Section 3.5.5](#)), which optimizes the astrometric and photometric parameters based on the current star matches. The quality of the resulting solution can be evaluated using **Astrometry > Plot astrometry** (see [Section 3.5.9](#)) and **Astrometry > Plot photometry** (see [Section 3.5.10](#)).
11. **Browse through other calibration images** of the station from the same night, in order to verify that the derived solution is appropriate for different frames.
12. Export the final solution using **Astrometry > Save solution** (see [Section 3.5.6](#)). The saved solution can later be loaded during the analysis of the fireball detection data.



## 5. PASCAL - Analysis of Fireball Data

### 5.1. Detection Analysis

Once all the stations involved in the detection of the fireball in analysis have been calibrated, as outlined in [Chapter 4](#), it is possible to analyze the video of the fireball captured by each station to then combine these results and triangulate the three-dimensional trajectory of the fireball. To facilitate the implementation of this activity in the context of a classroom, we will consider a **simplified version of the triangulation method**, using only the astrometric data from the first and last frames of each detection video.

Based on the information provided in [Chapter 2](#) and [Chapter 3](#), the **main steps required to perform the analysis of a fireball detection** for a single station using PASCAL are summarised below:

1. Open a detection frame using **File > Open detection** (see [Section 3.2.2](#)).
2. Load the fireball positions via **Positions > Load** (see [Section 3.7.1](#)), then navigate to the first frame listed in the table.
3. Adjust the displayed dynamic range using the **Image Cuts Min/Max** sliders (see [Section 3.1.9](#)) to properly visualise the fireball. Use the zoom panel (see [Section 3.1.8](#)) if needed to focus on a specific region of the image.
4. Verify and adjust the bolide positions in each frame using **Positions > Auto Centre** (see [Section 3.7.2](#)), or manually by right-clicking over the fireball image centre on the zoom panel. Check before and after the positions and extend the list as required.
5. Load the correct solution through **Astrometry > Load solution** (see [Section 3.5.2](#)).
6. Browse to the **first frame of the detection video** and take note of the UTC time, azimuth and zenith distance at the fireball position at this frame using **Astrometry > Show alt/az grid** (see [Section 3.5.7](#)). Alternatively, click on the **Calibrate** button (see [Section 3.1.16](#)) and then hover the mouse on the fireball centre, taking notes of the coordinates displayed on the bottom of the main window (see [Section 3.1.17](#)).
7. Repeat the same procedure for the **last frame of the detection video**, taking note of the final UTC time, azimuth and zenith distance angles.

### 5.2. Triangulation

Let us consider one of the examples provided as tutorial data in the PASCAL installer. These are the data of a fireball observed on 15 August 2025 at 01:30:30 UT by the StAnD stations in Muensterschwarzach (DEBY20) and in Weinheim (DEBW21). [Figure 17](#) shows a **reconstruction of the track of the fireball** as seen by the two stations.

Once the procedure described above has been completed for both the detections of this fireball, the following data should now be available and look like what is presented in [Table 1](#). It should be noted that, in this case, the starting times for the two cameras are not aligned. Therefore, it is necessary to **adjust the starting time** of DEBW21 to match that of DEBY20. After this adjustment, the fireball astrometric data will be as of [Table 2](#).



Figure 17 – Tracks of the fireball observed on 15 August 2025 at 01:30:30 UT by the StAnD stations in Muensterschwarzach (DEBY20 – Muensterschwarzach, Egbert-Gymnasium) and in Weinheim (DEBW21 - FTP01, FTP-Europlanet Office).



Table 1 – Astrometric data of the fireball shown in [Figure 17](#).

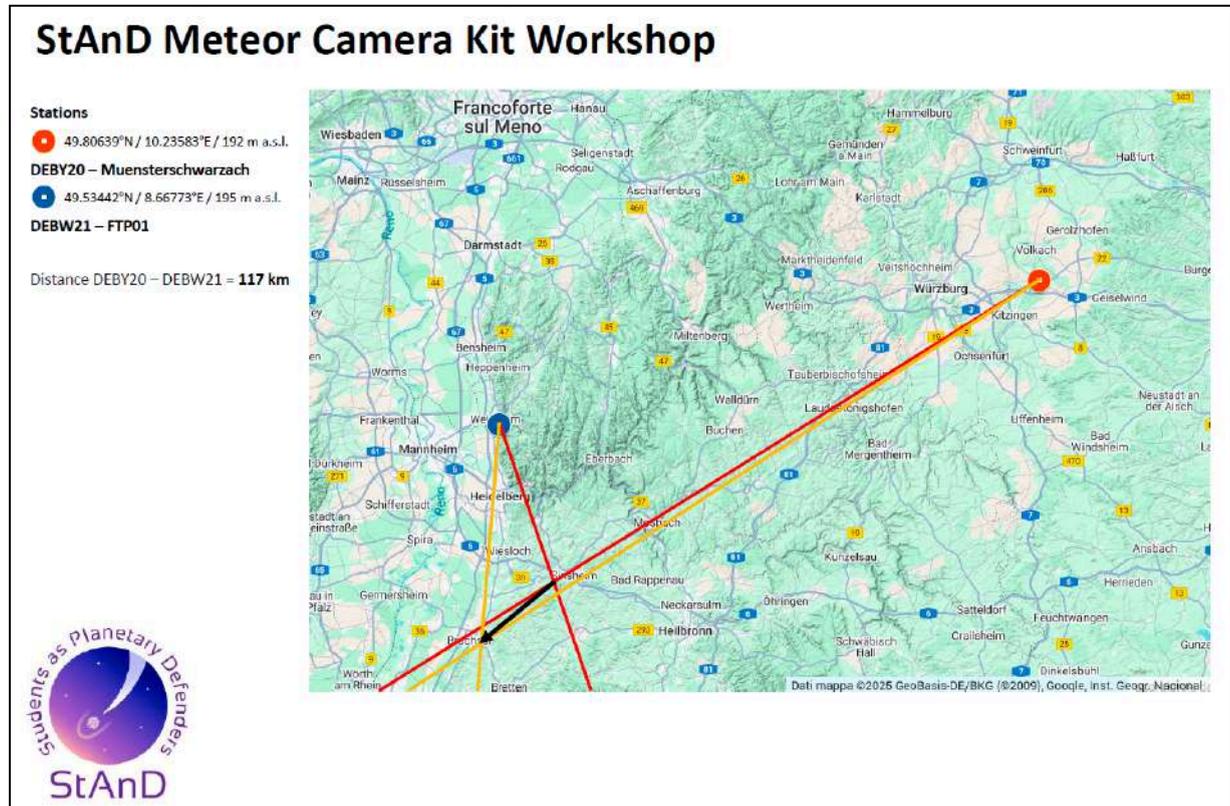
DEBY20 Muensterschwarzach	# frame	Time UTC	Azimuth	Zenith distance
First	179	01:30:31.11	238°	49°
Last	198	01:30:31.74	237°	62°
DEBW21 FTP01	# frame	Time UTC	Azimuth	Zenith distance
First	177	01:30:30.91	150°	17°
Last	202	01:30:31.75	185°	32°

Table 2 – Astrometric data of the fireball shown in [Figure 17](#).

DEBY20 Muensterschwarzach	# frame	Time UTC	Azimuth	Zenith distance
First	179	01:30:31.11	238°	49°
Last	198	01:30:31.74	237°	62°
DEBW21 FTP01	# frame	Time UTC	Azimuth	Zenith distance
First	183	01:30:31.11	161°	19°
Last	202	01:30:31.75	185°	32°



Figure 18 – Example of the map prepared for the triangulation of the fireball shown in [Figure 17](#). The red lines represent the lines of sight for the first frame of the fireball detection, while the orange lines correspond to the last frame. The intersections of the red and orange lines define the trajectory of the fireball projected on the ground, and it is indicated by the black arrow.



This operation can be done **on a printed map, using a pencil, ruler, and goniometer**. Alternatively, it can be performed on a computer, for example **in a document or slides editor** such as Microsoft PowerPoint, by using the *Insert > Shapes > Lines* function and adjusting each line's angle in the *Properties* tab to match the corresponding azimuth angle.

An example of this procedure is shown in [Figure 18](#), based on the data reported in [Table 2](#). The trajectory of the fireball projected on the ground (black arrow) is determined from the **intersections of the lines of sight** corresponding to the first frame (red lines) and the last frame (orange lines) of the detection.

Up to this point, only the azimuth data have been used, while the zenith distance has been neglected. Starting from the projected ground trajectory, these data can now be exploited to **estimate the initial and final heights of the fireball** by means of a simple geometrical approximation, thus retrieving the full three-dimensional trajectory. To do so, we consider a triangle whose base is the segment connecting, for example, the position of the DEBW21 station to the initial ground-projected coordinates of the fireball, as illustrated in [Figure 19](#). The vertices, sides, and angles of the triangle shown in [Figure 19](#) can be interpreted as illustrated in [Table 3](#).

The simplification lies in the fact that the triangle shown in [Figure 19](#) is not strictly planar, but should instead be treated as a spherical triangle. However, for the purposes of this analysis,



and considering the level of precision achievable through triangulation performed graphically on a printed map, the bias introduced by this approximation is negligible in most cases.

Figure 19 – Definition of the triangle used to estimate the altitude of the fireball, based on the triangulation results obtained from the map (see Figure 18) and on the measurement of the fireball zenith distance derived from the PRISMA and StAnD detection data and their astrometric analysis.

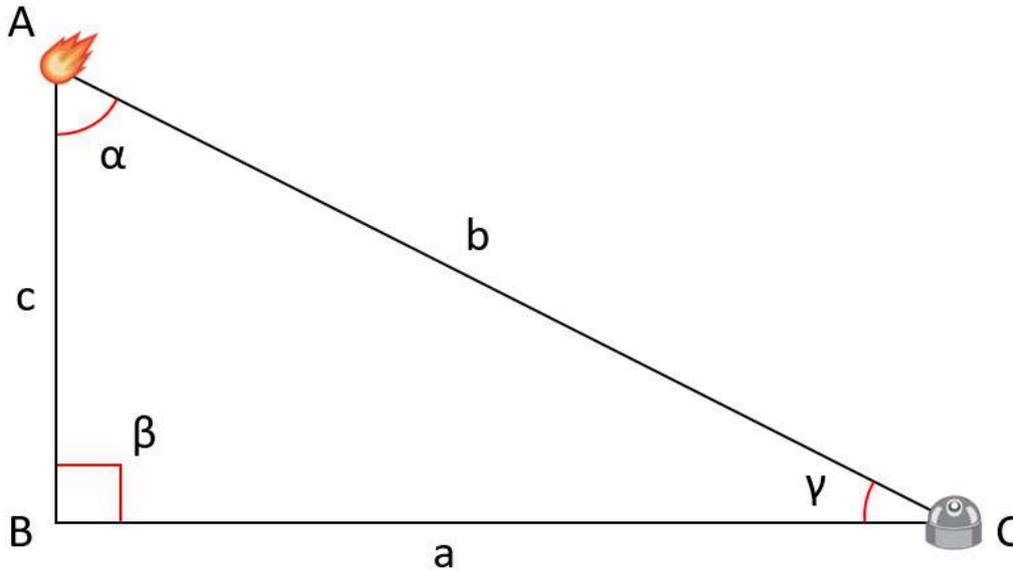


Table 3 – Physical meaning of the vertices, sides and angles of the triangle depicted in Figure 19.

VERTICES	SIDES	ANGLES
<b>A</b> = position of the fireball in the atmosphere	<b>a</b> = distance between the ground-projected fireball position and the camera	<b>α</b> = zenith distance of the fireball measured on the detection frame
<b>B</b> = position of the fireball projected on the ground	<b>b</b> = total distance between the fireball and the camera	<b>β</b> = 90° by definition
<b>C</b> = position of the camera observing the fireball	<b>c</b> = height of the fireball with respect to the ground	<b>γ</b> = 90° - α = altitude of the fireball measured on the detection frame

As evident from Table 3, the numerical values of **all the angles of the triangle are already known**. To fully solve the triangle, we can use the map in Figure 18 and scale it in order to measure side *a*, which in this case corresponds to the distance between the DEBW21 station (blue dot in Figure 18) and the starting point of the fireball trajectory projected onto the ground (the beginning of the black arrow in Figure 18).

To be able to **get the map scale into kilometers**, one can use the distance between the two stations DEBY20 and DEBW21, which is 117 km (as reported in the text of Figure 18). More generally, this distance can be obtained using any online mapping tool, provided the latitude and longitude of the stations are known. On the printed A4 version of the map, the distance



between the two stations, measured with a ruler, is about 12.3 cm. Given that their true separation is 117 km, this corresponds to a map scale of

$$s = \frac{12.3 \text{ cm}}{117 \text{ km}} \approx 0.1 \frac{\text{cm}}{\text{km}}$$

Using this scale, the length of side  $a$  of the triangle, which measures about 3.7 cm on the map, corresponds to a ground distance of approximately 37 km. We can now fully resolve the triangle by applying, for example, the **law of sines**:

$$\frac{a}{\sin \alpha} = \frac{b}{\sin \beta} = \frac{c}{\sin \gamma}$$

Using this relation, it is possible to derive a measure of side  $c$ , which represents the **initial height of the fireball** ( $H_i$ ). In particular, knowing side  $a$  and the angles  $\alpha$  (the initial zenith distance of the fireball measured from DEBW21, in this case  $19^\circ$ ) and  $\gamma$  (the initial altitude of the fireball measured from DEBW21, in this case  $71^\circ$ ), we obtain:

$$c = a \frac{\sin \gamma}{\sin \alpha} \rightarrow H_i \approx 37 \text{ km} \frac{\sin 71^\circ}{\sin 19^\circ} \approx 107 \text{ km}$$

The same procedure can be repeated to estimate the **final height of the fireball** ( $H_f$ ), by considering the corresponding triangle whose base is the segment connecting the position of the DEBW21 station to the final ground-projected coordinates of the fireball on the map shown in [Figure 18](#). From the map scale, the length of this base can be estimated to be approximately 45 km. Using the corresponding zenith distance angle of  $32^\circ$ , the final height of the fireball is then obtained as:

$$H_f \approx 45 \text{ km} \frac{\sin 58^\circ}{\sin 32^\circ} \approx 72 \text{ km}$$

We can now describe the **full cinematic of the fireball**. It lighted up at an initial altitude of 107 km over the city of Sinsheim on 15 August 2025 at 01:30:31.11 UT, travelling down to to a terminal altitude of 72 km in about 0.64 s, extinguishing at 01:30:31.74 UT over the city of Bruchsal, in the Baden-Württemberg land, Germany.

### 5.3. Fireball speed

It is then possible to estimate the **average speed of the fireball** by computing the total trajectory length travelled by the fireball and dividing it by the flight time. While the vertical distance can be calculated as  $H_i - H_f$ , the horizontal distance can be estimated by measuring, with a ruler, the length of the ground-projected trajectory on the map of [Figure 18](#) (black arrow) and scaling it to kilometres as described above. In this case, it measures about 2.2 cm on the map, corresponding to approximately 22 km.

The total trajectory length can therefore be calculated using Pythagoras' theorem as:

$$L = \sqrt{(22 \text{ km})^2 + (H_f - H_i)^2} \approx 41 \text{ km}$$

Then, the average fireball speed can be estimated as:

$$V = \frac{L}{\Delta t} \approx \frac{42 \text{ km}}{0.64 \text{ s}} \approx 66 \frac{\text{km}}{\text{s}}$$



#### 5.4. Meteoroid pre-atmospheric mass

A final step is to estimate the mass of the meteoroid that caused the fireball event by measuring its **absolute magnitude**  $\mathcal{M}$ , which represents the intrinsic luminosity of the astronomical object (or, in this case, of the fireball) at a given reference distance. For meteors, this reference distance is conventionally taken as 100 km. Therefore, starting from the apparent magnitude  $m$ , the absolute magnitude can be computed as:

$$\mathcal{M} = m + 5 \log_{10} \left( \frac{d}{100 \text{ km}} \right)$$

An approximation that can be applied in this context involves the **minimum absolute magnitude** (or **peak absolute magnitude**)  $\mathcal{M}_0$ , which corresponds to the absolute magnitude at the luminosity peak of the meteor. This approach is based on the work of [Verniani \(1973\)](#) and provides a rough estimate of the **pre-atmospheric mass** of the meteoroid (in kg units) as follows:

$$\log_{10} M_{\infty} = 2.63 - 0.4\mathcal{M}_0 - 4\log_{10} V_{\infty}$$

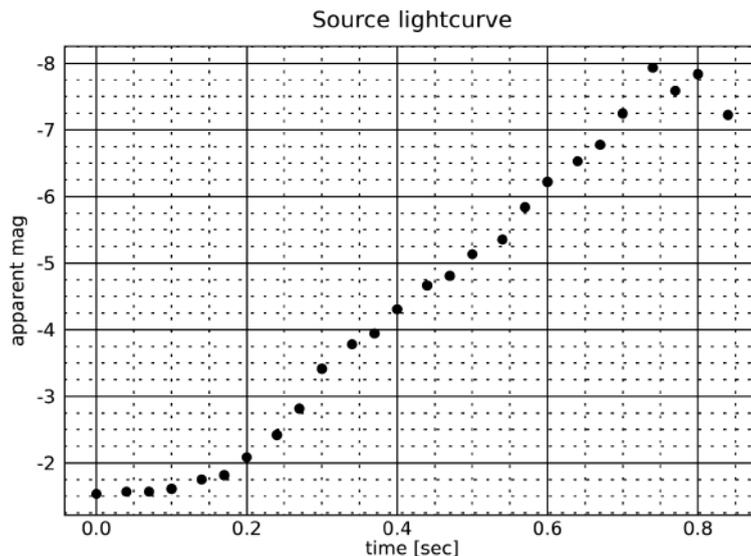
where  $V_{\infty}$  is the **pre-atmospheric speed** of the meteoroid (given in km/s units in the formula above), and can be approximated by the average fireball speed in our case. By using the *Photometry* submodule of PASCAL on the detection data of one station, we can compute the lightcurve of the bolide in terms of apparent magnitude. The lightcurve for the fireball under consideration computed from the data of the DEBW21 station is shown in [Figure 20](#).

For this fireball, the peak brightness occurred near the end of its luminous phase, with a recorded apparent magnitude of approximately -8. To determine the corresponding distance between the fireball and the DEBW21 station at that time, we can use the same triangle employed in calculating the final altitude of the fireball.

Then, the distance can be calculated using Pythagoras' theorem as:

$$d \simeq \sqrt{(45 \text{ km})^2 + (72 \text{ km})^2} \simeq 85 \text{ km}$$

Figure 20 – Lightcurve of the fireball observed on 15 August 2025 at 01:30:30 UT by the StAnD station in Weinheim (DEBW21 - FTP01, FTP-Europlanet Office), in units of apparent magnitude.





Therefore, the peak absolute magnitude can be estimated as:

$$\mathcal{M}_0 \simeq -8 + 5 \log_{10} \left( \frac{85 \text{ km}}{100 \text{ km}} \right) \simeq -8.3$$

In this case, the difference between the apparent and absolute magnitude is quite small, since the fireball was observed at a distance of 85 km, which is close to the reference distance of 100 km.

Finally, applying the formula of [Verniani \(1973\)](#), we can estimate the pre-atmospheric mass of the meteoroid as:

$$\begin{aligned} \log_{10} M_{\infty} &= 2.63 - 0.4 \cdot (-8.3) - 4 \cdot \log_{10}(66) \simeq -1.3 \\ &\rightarrow M_{\infty} \simeq 10^{-1.3} \text{ kg} \simeq 50 \text{ g} \end{aligned}$$

Such a small meteoroid mass, combined with its high entry speed, makes it highly unlikely that a significant portion survived the atmospheric passage, and therefore that meteorites reached the ground. As a rule of thumb, meteorites can potentially be recovered if the following conditions are met:

- A **significant pre-atmospheric mass**, typically at least a few kilograms;
- A **low entry speed**, generally below 20–30 km/s;
- A **low terminal height**, usually less than 30 km above the ground.

If these conditions are met, the event may warrant further investigation, and it becomes worthwhile to perform a full data analysis to determine the **meteoroid's kinematic, physical, and orbital properties** with greater precision and accuracy. In cases where it is estimated that a final mass exceeding a few tens of grams may have reached the ground, the potential meteorite recovery area, known as **strewn field**, is calculated. This computation takes into account the atmospheric conditions at the time, particularly the **profiles of wind speed and direction** in the fall area, derived from meteorological data.