

## “PI OF THE SKY” OFF-LINE EXPERIMENT WITH GLORIA

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**ABSTRACT.** GLORIA is the first free and open-access network of robotic telescopes in the world. Based on the Web 2.0 environment, amateur and professional users can do research in astronomy by observing with robotic telescope, and/or analyzing data acquired with GLORIA, or from other free access databases. The GLORIA project develops free standards, protocols and tools for controlling Robotic Telescopes and related instrumentation, for scheduling observations in the telescope network, and for conducting so-called off-line experiments based on the analysis of astronomical data. This contribution summarizes the implementation and results from the first research level off-line demonstrator experiment implemented in GLORIA, which was based on data collected with the “Pi of the Sky” telescope in Chile.

**KEYWORDS:** Telescope network, citizen science, Web 2.0, image processing, data analysis, robotic telescopes.

### 1. INTRODUCTION

GLORIA [1] (GLOBAL Robotic-telescope Intelligent Array) is an innovative citizen-science network of robotic observatories, which will give free access to professional telescopes for a virtual community via the Internet.

Contributions to GLORIA are made by 13 partners with 17 robotic telescopes scattered in 7 countries all over the world (see Fig. 1). This network will allow for continuous observations of celestial objects from different locations. When the object of interest sets in one location, an observer is able to continue observations from another location. This should allow her/him to observe an object even for 24 hours providing new quality in astronomical observations. In addition, there will often be an opportunity to observe celestial objects simultaneously from two or more observatories.

One of the challenges we have to face in designing the environment for GLORIA off-line experiments is dealing with huge amounts of data and a large variety of analysis tasks. LUIZA [2], an efficient and flexible analysis framework for GLORIA, has been developed based on a concept taken from High Energy Physics. The basic data classes, framework structure and data processing functionality are implemented, as well as selected data processing algorithms. The framework was used to implement the first GLORIA research level off-line demonstrator experiment, which is described in this contribution.



FIGURE 1. Location of observatories that contribute to the GLORIA project [1].

### 2. DEMONSTRATOR EXPERIMENTS

GLORIA allows users to run experiments in the network. These experiments can be divided into two general types:

- on-line experiments, for making observations with robotic telescopes. Experiments can involve teleoperation of the telescope or making scheduled sky observations in the network.
- off-line experiments, for analyses of the collected data on a basic level (for education or outreach) or doing more advanced image analysis (research level).

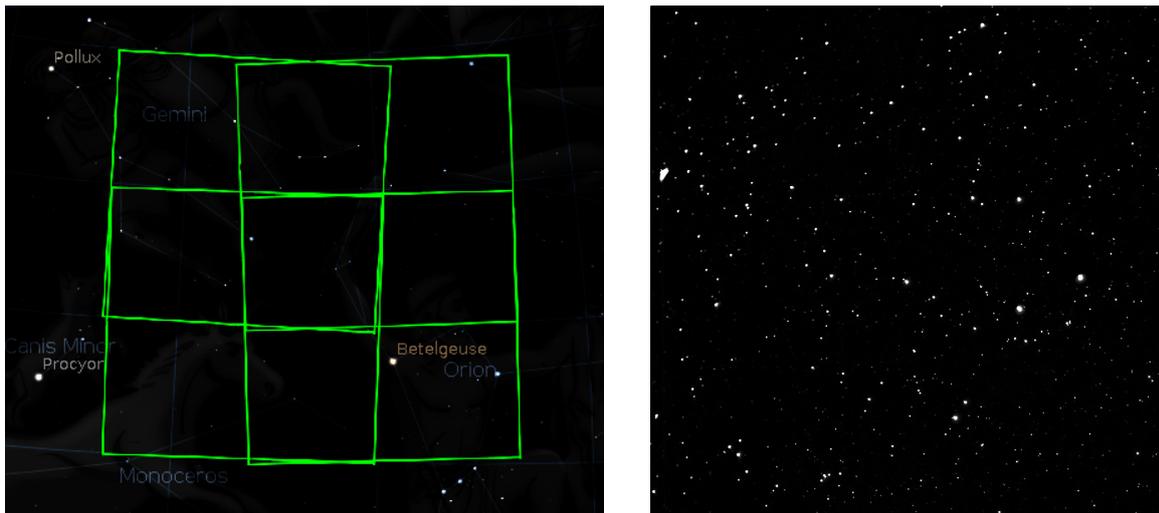


FIGURE 2. Fields of view selected for the off-line demonstrator experiment drawn on the Stellarium [4] map (left), and their common part, as seen on the “Pi of the Sky” image (right).

To present the network capabilities and the performance of the tools, demonstrator experiments have been created in both categories. To participate in these experiments, it is only necessary to create a user account via the project’s website [1], and then, after signing in, the user can choose among various on-line and off-line experiments.

The TAD (Telescopio Abierto Divulgacion) robotic solar telescope at the Observatorio del Teide in Tenerife (Canary Islands) was the first GLORIA telescope made available to users as an on-line demonstrator experiment. GLORIA provides the interface for users to schedule the observation time, and then to access and control the telescopes remotely, and make observations. The user gets almost full control over the telescope performance, including telescope pointing, focus adjustment, gain control and exposure settings.

### 3. “PI OF THE SKY” PROJECT

The “Pi of the Sky” project involves two observatories, one in Chile and the other in Spain [3]. In both observatories we use custom designed cameras with a  $2000 \times 2000$  pixel matrix and Canon lenses ( $f = 85$  mm,  $f/d = 1.2$ ). All cameras in Spain and one camera in Chile have only standard UV and infrared cut filters installed, while the second camera in Chile has an R Johnson-Bessel filter.

Data from “Pi of the Sky” was used to implement the research-level off-line demonstrator experiment for GLORIA, focusing on light curve reconstruction and classification of variable objects. The experiment is based on pre-selected data from the telescope in Chile. Analysis is done using the LUIZA framework, designed within GLORIA for efficient analysis of astronomical data.

The “Pi of the Sky” telescope takes sky images with 10 s exposure time. However, much better photometry accuracy is obtained from sums of 20 subsequent frames, corresponding to 200 s exposure time. Stacked

images taken from 2006 to 2009 at Las Campanas Observatory (LCO) and also in 2012 and 2013 at San Pedro de Atacama (SPdA), Chile, were selected for the demonstrator experiments. After visual inspection, and image pre-processing (see the following section) about 500 images remained. The field of view of “Pi of the Sky” cameras is  $20^\circ \times 20^\circ$ . Selected frames correspond to 4 overlapping observation fields, and the central region of about  $10^\circ \times 10^\circ$ , visible on all frames, was selected as the subject of the analysis. The chosen fields of view and their common part are shown in Fig. 2.

### 4. LUIZA FRAMEWORK

LUIZA is a simple modular application framework for development of image reduction and analysis tools. It is based on the following assumptions:

- (1.) each data (image) analysis can be divided into small, well defined steps, implemented as so called processors;
- (2.) each step has to have a well defined input and output data structure;
- (3.) by defining universal data structures we make sure that different processors can be connected in a single analysis chain;
- (4.) the processor configuration and parameters can be set by the user in run time in a simple steering file.

The LUIZA framework implements all basic data structures required for image analysis:

**GloriaFitsImage** — a class for storing FITS images, which uses the fitsio library for reading and storing images, and basic methods for image manipulation are implemented;

**GloriaFitsTable** — a flexible class for storing other data (integers, floats, strings, vectors of int/float);

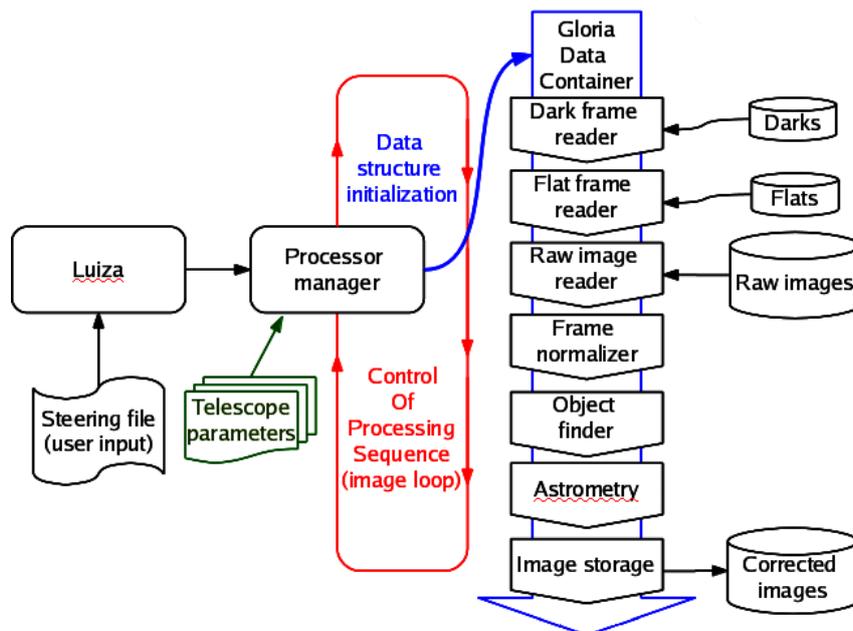


FIGURE 3. An example of the processing concept in the LUIZA framework.

**GloriaDataContainer** — an internal storage class in which images and tables are stored in collections; each collection has a unique name (string).

To use the LUIZA framework, each user has to create a steering file (GUI is provided), in which an analysis chain can be defined by selecting processors and defining their order. The steering file also allows the user to define input-output streams and set other processor parameters. Each LUIZA processor gets a pointer to a global GloriaDataContainer and will allow the user to create a new collection when reading data from a file or to analyse data stored in memory, and in the end the user will have the possibility to save analysis results to output files. An example scheme of image processing in the LUIZA framework is shown in Fig. 3.

## 5. IMPLEMENTATION OF THE EXPERIMENT

The “Pi of the Sky” images selected for the off-line demonstrator experiment are analysed within the LUIZA framework. Unfortunately, the full analysis chain, starting from a raw image and resulting in the light curve of the selected object, is quite time consuming. Therefore we decided to divide image analysis into two steps: image preprocessing, and object light curve reconstruction. Preprocessing (image stacking, dark subtraction, flat correction, object finding and astrometry) is done only once, while setting up the experiment and the object light curve reconstruction is run in response to each user request.

Object finding is done with the PixelClusterFinder processor. The algorithm searches for groups of pixels (called clusters) with a signal above the defined threshold. In the current analysis we use thresholds

of 8 and 3 times the noise level. To define the thresholds, the background level and the average noise level are calculated first. To correct for significant background variation over the frame, the background level is calculated in  $4 \times 4$  subframes and then interpolated. Finally, the cluster signal and the position on CCD is calculated. The output of the cluster finding processor is stored as a GloriaObjectList table. The astrometry processor is based on the Astrometry.net algorithm for finding the frame orientation and the transformation for calculating object positions in the sky. The processor analyses the GloriaObjectList table and calculates the parameters of the position transformation. In the final step, the positions of all objects in the list are calculated (Ra, Dec) and are added to the object list table. The final object lists are stored to binary FITS tables.

The light curve construction is based on coordinates specified by the user (from some range both right ascension and declination). However, when measurements from different fields are combined, this results in significant systematic effects. They most probably result from significant PSF deformations over the “Pi of the Sky” field of view and the dependence of PSF on the spectral type of the reference star (resulting from wide spectral acceptance of the “Pi of the Sky” apparatus — only a UV + IR cut filter is used). More precise calibration is obtained when a larger set of stars from the same part of the frame is used. After dedicated tests, we decided to use the “Pi of the Sky” reference star list, but to limit it to stars between 7 and 8.5 mag. One has to note that although “Pi of the Sky” measurements are normalized to V magnitude, there is a non-vanishing spectral dependence due to the wide spectral acceptance mentioned above. As a result, the “Pi of the Sky”

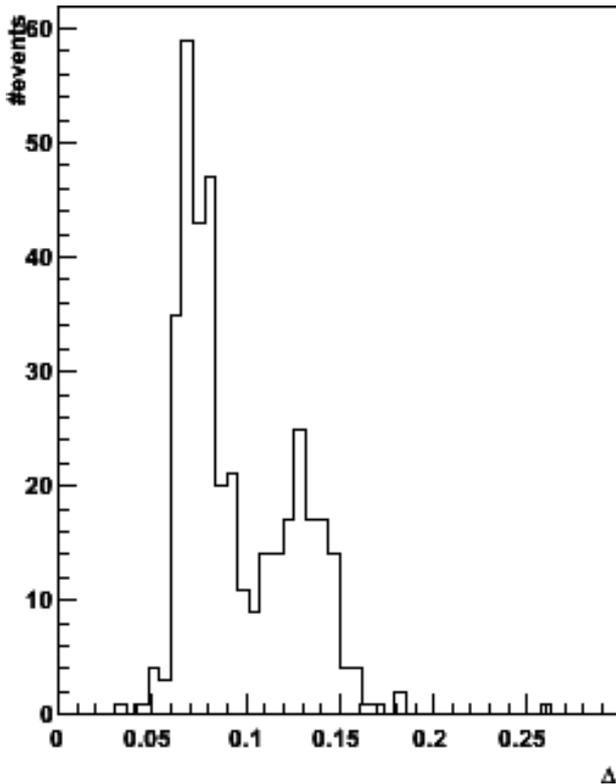


FIGURE 4. Distribution of the estimated calibration uncertainty  $\Delta$  for one constant star.

magnitudo coincides with that of the V catalogue only for stars with  $J - K \approx 0.4$ .

When multiple reference stars are selected, photometric calibration can be based on the average reference star magnitudo correction. An advantage of this approach is that the RMS of the difference between the reference star correction and the average correction,  $\Delta$ , can be used as an estimate of the photometry uncertainty. After applying the calculated correction to the object magnitudo, the measurement is added to the light curve with an HJD timestamp.

## 6. RESULTS

### 6.1. TESTS WITH CONSTANT STARS

The light curve reconstruction procedure was first tested on selected constant stars. The distribution of the estimated correction uncertainty  $\Delta$  for one of the considered stars is presented in Fig. 4. The distribution has a clear two-peak structure, indicating that for some frames the photometry accuracy was significantly worse, probably due to some systematic effects (or the object being near the edge of the CCD on some fields).

By using a cut  $\Delta < 0.1$  we can limit ourselves to the best measurements only. The result of such a cut is illustrated in Fig. 5, where the magnitudo distribution for the same selected star is presented before (dashed line) and after the cut (solid line).

The (properly adjusted) cut has a dramatic impact on the measurement. While reducing the event

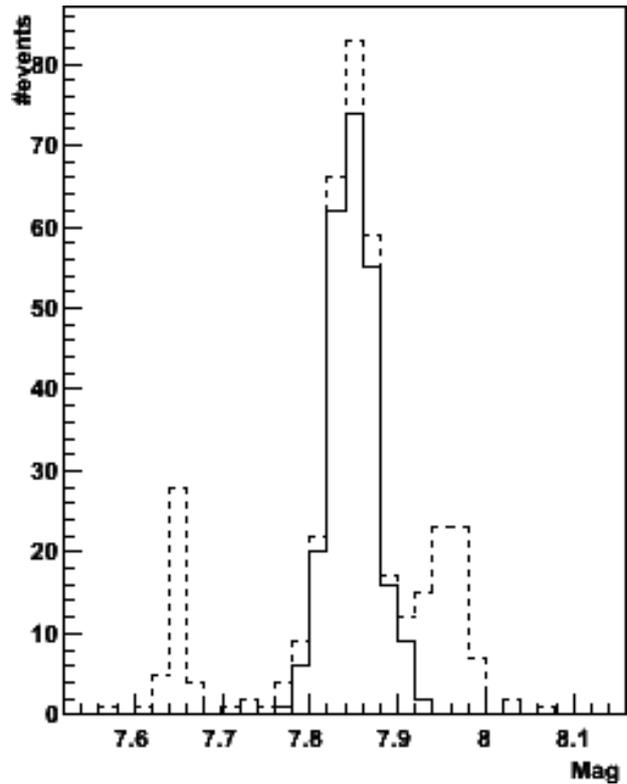


FIGURE 5. A magnitudo distribution for one constant star. The dashed line is before, and the solid cut is after the quality cut  $\Delta < 0.1$ .

statistics by about 30%, it also improves photometry quality (measurement spread) for the star by a factor of more than 4 (in terms of the RMS of the magnitudo distribution: from 0.111 mag to 0.026 mag).

### 6.2. VARIABLE STAR RECONSTRUCTION

An approach tested with constant stars was then applied to selected variable stars in the considered field. Regular variable stars were selected based on “Pi of the Sky” and Simbad [5] catalogues. For each star, after removing poor quality measurements with a cut on the estimated calibration uncertainty, a phased light curve was fitted. Selected results are presented in Figures 6 and 7. The fit, indicated by a green line, was performed with the CERN root package. The light curve was modelled with a Fourier series.

## 7. SUMMARY

The first on-line and off-line experiments in the GLORIA network are ready and are already available to users. The first off-line demonstrator experiment has been developed based on “Pi of the Sky” data collected at Las Campanas Observatory and at the San Pedro de Atacama Observatory (both in Chile). The data are pre-processed with LUIZA [2] — an efficient and flexible analysis framework. Fast light curve reconstruction, based on pre-processed data, is also done with LUIZA and is triggered by a user request sent via

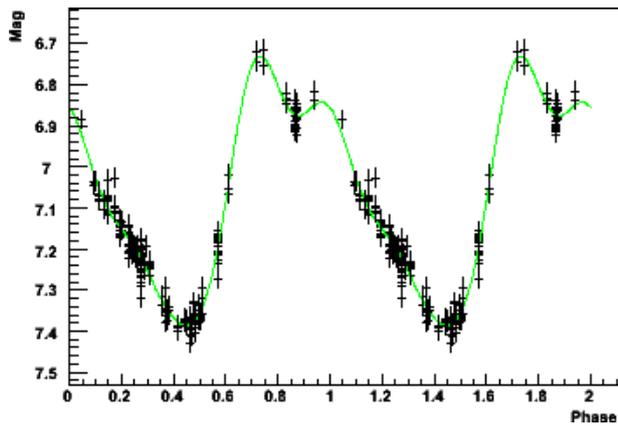


FIGURE 6. Light curve of W Gem, classical Cepheid ( $\delta$  Cep type), as reconstructed with LUIZA.

a web interface. After successful testing and tuning the experiment should be released soon on GLORIA's website [1].

#### ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement 283783. The research work has also been funded by the Polish Ministry of Science and Higher Education from 2011-2014, as a co-funded international project.

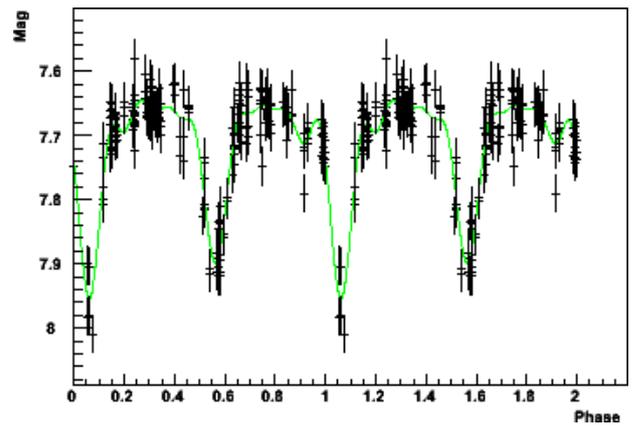


FIGURE 7. Light curve of V1388 Ori, eclipsing binary of Algol type (detached), as reconstructed with LUIZA.

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