Astrometric Calibration of All-sky Camera for Aircraft Spotting and Meteor Observations

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Abstract

All-sky cameras are a staple of astronomical and SLR observatories. They are environmental awareness tools, showing e.g. cloud presence, illumination conditions, and the laser beam direction. For actual positional tasks, these cameras require a star calibration to correct for their orientation, internal misalignments, and the optical behaviour of the lenses. This accomplished, they become precise measuring instruments that find new uses. We have performed the astrometric calibration of the all-sky camera that will be used for supporting SLR operations at Yebes Observatory, achieving sub-pixel positional precision and thus enabling several applications beyond mere situational awareness.

1. Introduction

For the new SLR station at the Yebes Observatory, an all-sky camera was purchased to aid observers in their operations. The primary function of these instruments in SLR stations is environmental awareness, e.g. detecting the presence and position of clouds, assessing the illumination conditions, the positions of the Sun and the Moon, and that of the laser beam. Due to the limited angular resolution and often moderate sensitivity of these cameras, their use for air safety purposes is at best secondary. Still, provided that a suitable calibration is performed, they can complement other safety systems providing positional information that can be employed, e.g. for validation purposes.

The astrometric calibration of these optical systems has been researched for meteor astrometry, where positional measurements of the same event by geographically distributed cameras are used for orbit determination. Several observational networks are currently deployed internationally for this purpose, employing different hardware setups but relying on the same principle.

We have implemented a calibration system for our camera following a selection of methods described in the literature, achieving sub-pixel positional precision (<2 arcmin RMS in Az/El). The calibration system requires no manual intervention after an initial coarse setup, and includes the steps of source extraction, selection, matching, and least squares fit of the camera model. A fully calibrated all-sky camera allows for pixel-perfect accurate overlays (e.g. in operational GUIs with predicted satellites or ADS-B relayed aircraft) as well as their use for meteor observations within dedicated networks. It also makes feasible to employ these cameras for complementary safety purposes.

2. Implementation

2.1 Hardware

The all-sky camera we have employed for these tests, which will be an auxiliary component of the future SLR station at Yebes, is an OMEA-8C, manufactured by Alcor System. Internally, this device uses a ZWO ASI294MC Pro camera, which combined with the optics mounted in the OMEA-8C package, provides a usable resolution of ~2800x2800 pixels, with an instantaneous field of view slightly larger than 4 arcmin. We employed the software included with the camera (Windows OS only) to collect the images, but this proved quite unreliable, limiting, and frustrating. The integration of the camera at the station will involve direct communication with the ZWO camera instead of using the software provided by Alcor System.

2.2 Calibration Model

The astrometric calibration of an all-sky camera is conceptually identical to the determination of a pointing model for a telescope mount. The encoder positions of the two axes of the mount are equivalent to the pixel positions in the images of the camera. The problem consists in the determination of the optimal parameters of a model that relates the instrumental coordinates (pixel or encoder positions) to sky coordinates. Of course, the specific mathematical form of the models employed are different, for they relate and correct for different physical effects.

The camera models must take into account the imperfect orientation of the device in the horizontal and vertical planes, the misalignment of the optical axis, the optical projection of the lense and its distortions, and possible misalignment of the internal sensor relative to the optical axis.

Solutions to the calibration of cameras with very large fields of view, which include all-sky cameras, can be found in the literature of the fields of computer vision and astronomy. The procedures followed in the computer vision domain usually involve the imaging of regular patterns (e.g. high contrast square grids) that are used to extract the camera parameters. The approach in the astronomical literature is to use the sources extracted from star fields, estimating both model parameters related to instrument as well as its orientation in space.

A popular model in meteor astronomy was given by Borovička et al, 1995 [1], with several improvements published since first proposed. More recently, Barghini et al, 2019 [2] reformulated some of the expressions, which together with a slightly changed strategy improved the estimability of the model parameters. Our implementation adopts features from both approaches, using the reformulated expressions from Barghini 2019, including an azimuthal correction present only in Borovička 1995, and adding a final 2D-spline empirical correction to further reduce the post-fit residuals.

The expressions employed follow, but interested readers should consult the references above to grasp of the mechanics of the model and the geometrical meaning of the variables:

$$r_\epsilon = \sqrt{(x_0 - x_z)^2 + (y_0 - y_z)^2}$$

$$E = a_0 + arctan(\frac{y_0 - y_z}{x_0 - x_z})$$

$$\epsilon = V r_\epsilon + S(\mathrm{e}^{D r_\epsilon} - 1)$$

x_0, y_0: plate coordinates of the optical axis

x_z, y_z: plate coordinates of the zenith

E, ϵ: distance between the optical centre and the zenith

These three expressions are the new parameterisation of the model given by Barghini 2019, which improve the estimability of the solution and allows for the determination of the zenith coordinates directly. This may be useful in some cases, especially in the initialisation stages, when valid initial guesses for the parameters are not available. Otherwise it is perfectly feasible to estimatex_z, y_zalong with the rest of the parameters.

$$r = \sqrt{((x-x_0)^2+(y-y_0)^2)} + A(y-y_0)cos(F-a_0) - A(x-x_0)sin(F-a_0)$$

$$b = a_0 - E + arctan(\frac{y-y_0}{x-x_0})$$

$$u = Vr + S(\mathrm{e}^{Dr}-1)$$

r : distance to the optical centre, with added term to remove azimuth-dependent scale variations (see Borovička 1995)

b,u : angles relating plate coordinates and projection coordinates in azimuth and zenith distance, respectively

Finally, the expressions for azimuth and zenith distance are:

$$Az = E + arctan(\frac{\sin u \sin b}{\sin u \cos b \cos\epsilon + \cos u \sin\epsilon})$$

$$Z_d = arccos(cosucos\epsilon - sinusin\epsilon cosb)$$

Thus, we have to estimate the plate constantsa_0, x_0, y_0; the camera constants *A, F*; the lens constants *V, S, D*; and the station constantsϵ, E. The coordinates of the zenith may be co-estimated or determined directly through the observation of meridian crossings (see Barghini 2019).

In addition to this, we have added an empirical correction to the solution, consisting in a 2D spline fitted to the post-fit residuals in azimuth and elevation obtained with the use of the model above. After performing multiple calibrations it was noticeable that the residuals presented a pattern, at the level of ~2 arcmin, which could not be removed via the introduction of additional parameters. This pattern was stable throughout time and therefore we concluded that it reflects physical characteristics of the camera/lens. Fitting the 2D surface removes this pattern almost completely, lowering the final RMS of fit to below 2 arcmin.

The system can be solved by univariate least squares, stacking the coordinates side by side, and can be written as$XB = Y$, where

X : partial derivatives of Az and Zd

B : vector of parameters

Y : residuals in (Az sin Zd) and Zd

2.3 Strategy

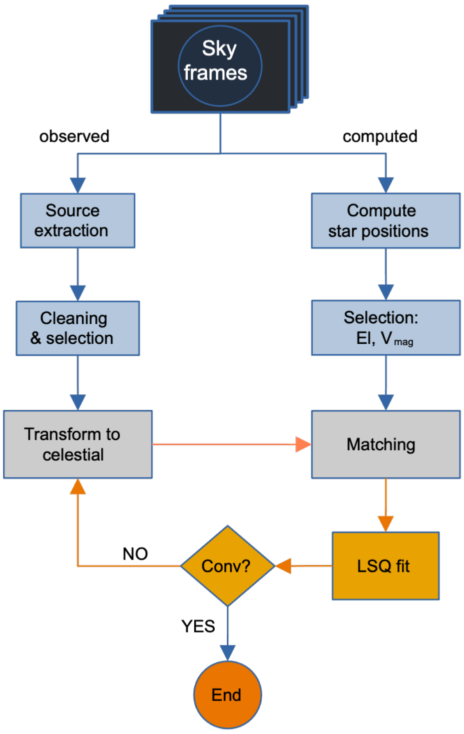
There are several difficulties and pitfalls to be aware of in order to perform the astrometric calibration succesffully:

- Highly non-linear model

- Very sensitive to the initial conditions
- Analytical Jacobian exists but is too cumbersome for practical use
- Initial parameter guesses mostly unknown

A consequence of this is that the initial setup of the system, with reasonable values for the solve-for parameters, require an iteration process with manual intervention, and possibly the use of a simplified model until stable convergence is achieved.

Afterwards, with coarse values for the model parameters available, the calibration process can be streamlined and perform without user intervention. For the automation of the source extraction we have used the software Sextractor [3], and for the computation of star positions Skyfield [4]. The least squares solver and the main program driving the whole proces is implemented in Python, using the Numpy, SciPy and Pandas libraries. The following diagram shows the structure of the process:

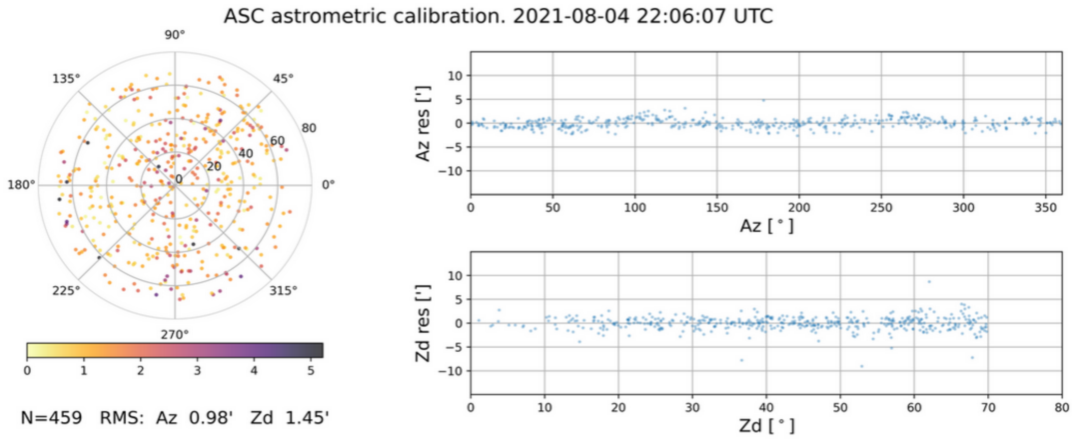


3. Results

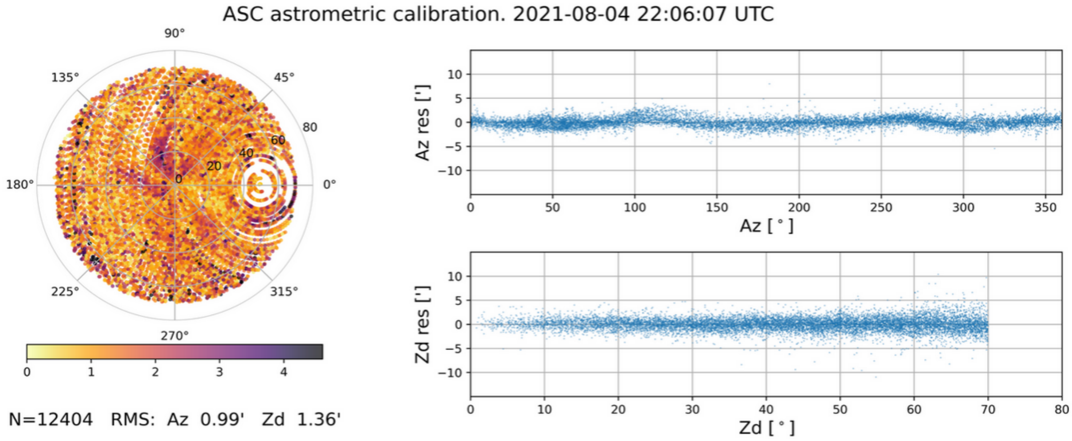
We have tested the calibration procedure with single frames of different exposures, from 10–45 seconds. All exposure times are satisfactory, although the star magnitude and therefore number of sources available obviously decreases with exposure time. It is also feasible to accumulate the sources extracted from different frames, and perform the calibration with a very large number of observations that ensures a virtually perfect coverage of the celestial hemisphere. The accumulation of frames taken during the night is a necessity to estimate the empirical correction to remove certain patterns in the residuals.

The figures below show the post-fit residuals in polar projection and in azimuth and elevation obtained with a single frame (459 sources extracted) and after accumulating

27 frames collected throughout a single night (12400 sources). The RMS of the fit is about 1 arcmin, which is ~4 times lower than the pixel FOV of the camera, therefore achieving sub-pixel positional precision.


ASC astrometric calibration. 2021-08-04 22:06:07 UTC

N=459 RMS: Az 0.98' Zd 1.45'


ASC astrometric calibration. 2021-08-04 22:06:07 UTC

N=12404 RMS: Az 0.99' Zd 1.36'

The quality of the calibration is maintained at all elevations, which is notable for these camera devices, whose optical projection and associated distortions are most conspicuous and difficult to model at large zenith distances close to the horizon.

4. Applications

The alignment of the images obtained with all-sky cameras is usually performed only coarsely. This is acceptable for some of the operational uses of these devices (e.g. operator sky awareness). In richer applications, the sky images can be augmented with graphic overlays that include e.g. the positions of objects such as ADS-B detected aircraft, satellite orbits, and celestial grids. The quality of this kind of user interfaces benefits from the availability of positional precisions at the pixel level.

Beyond the mere display of information over sky images, astrometrically calibrated cameras could be employed for air safety purposes. A possible application in this regard is the validation of positional data obtained through other methods (FLARM, ADS-B, other cameras), although in principle they could also be used as a safety tool on their own right, complementing other existing instruments.

Applications outside the field of SLR include the integration of calibrated devices in meteor sensing networks, which use the data collected simultaneously by several cameras to calculate the trajectories of meteors in the upper layers of the atmosphere, as well as the possibility of using these cameras as sky quality monitors, with an additional photometric calibration.

References

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