LSST Astrometric Science

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Large Synoptic Survey Telescope

Short-exposure observations from Subaru, Gemini, and SOAR support the preliminary conclusion (Monet et al., BAAS 36, 1531, 2004) that a a single 10-second exposure in 1.0 arcsecond seeing can provide a differential astrometric accuracy of about 10 milliarcseconds. A single solution for mapping coefficients appears to be valid over spatial scales of up to 10 arcminutes, and this result suggests that numerical processing can proceed on a per-sensor basis without the need to further divide the individual fields of view into several astrometric patches. The expected astrometric accuracy after 10 years of LSST observations should therefore be around 1.0 milliarcseconds for parallax and 0.2 milli-arc-seconds/year for proper motions.

LSST Requirements for Astrometry

- The science goals for astrometry with the LSST require that positional accuracy of a ***single*** observation be of the order of 10 milli-arc-seconds or better.
- The large field of view and relatively short exposure time put LSST into a regime where there is little astrometric heritage.
- This poster presents the results of examining the astrometric accuracies that can be obtained from short exposure (typically 15 seconds) CCD observations from three different large aperture telescopes: Subaru, SOAR, and Gemini-South. Observations of the same star field were taken at various zenith distances and atmospheric conditions.

Analysis

The stars in the fields under study are too faint to be included in high accuracy catalogs. Hence, the astrometric solution must provide estimators for the mean positions of all the stars (in pixel units and not necessarily in RA and Dec.), and transformations between the coordinate systems of each exposure and that of the mean system.

The centroid of each star was calculated by fitting a 2-dimensional Gaussian to the flux using an iterative, modified Marquardt descent (Bevington 1969) that fits for five free parameters (amplitude, background, column position, row position, and width of the Gaussian). This algorithm is fast, robust, and has a long astromeric heritage for accuracy in a variety of applications. Once the centroids for all stars on all frames have been computed, those for a single frame are chosen as the first approximation for the mean coordinates. Given these, the transformations between each frame and the mean can be computed, and new values for the mean coordinates are computed. So long as the frames are reasonably similar, this iteration converges and is independent of the choice of which frame is used for the first guess.

For these studies, the model for centroiding each stellar image was held constant, but three different models were used for the astrometric mapping.

1. The "constant" model assumes that the coordinate system of each frame differs from that of the mean by only a constant shift. The underlying assumption is that the exposures have averaged over the atmospheric effects, that the telescope and camera scale and orientation were constant, and that only the mean position of the fields changed from frame to frame. In general, few optical systems and sky conditions are this stable, but this solution gives a bound for how bad the observing conditions were.

2. The "linear" model assumes that the mean coordinate system can be computed from a scaled rotation of each exposure. It has three free parameters in each axis:

$X_{mean} = A + Bx_i + Cy_i$ with a similar expression in Y_{mean}.

This model assumes that whatever changes occurred between exposures are small and that a linear expansion provides sufficient accuracy.

3. The "cubic" model is the extension of the linear model:

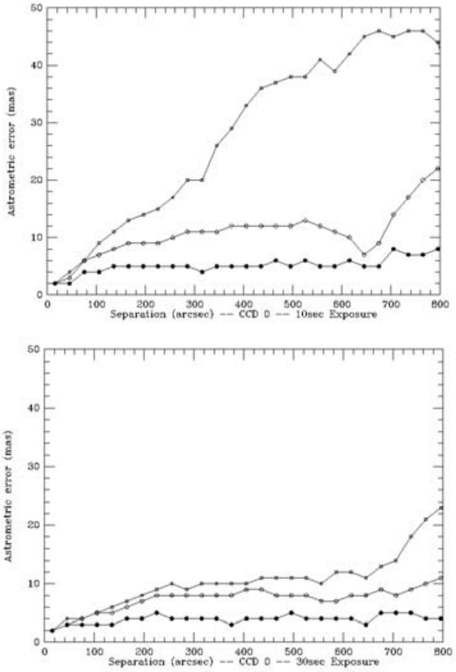
$$X_{mean} = A + Bx_i + Cy_i + Dx_ix_i + Ex_iy_i + Fy_iy_i + Gx_ix_ix_i + Hx_ix_iy_i + Ix_iy_iy_i + Jy_iy_iy_i$$

and a similar expression in Y_{mean}.

Under normal circumstances, the cubic model is sufficient to map most optical and other astrometric distortions. The usual explanation for significant cubic terms is that they arise from atmospheric turbulence and become smaller as the exposure time increases.

The data used were from the public archive of Subaru data, which can be found at http://smoka.nao.ac.jp. The authors gratefully acknowledge the SMOKA science archive and the Astronomical Data Analysis Center operated by the National Astronomical Observatory of Japan for access to these data. The authors also thank the LSST Simulations Team, and those who collected the observational data.

For relatively sparse star fields, a powerful diagnostic is to compute the separation between all possible pairs of stars for each exposure after the transformation to the mean coordinate system. The growth of the error in the measurement of the separation as a function of the separation gives another clue about the role of unresolved atmospheric turbulence in the astrometric solution.



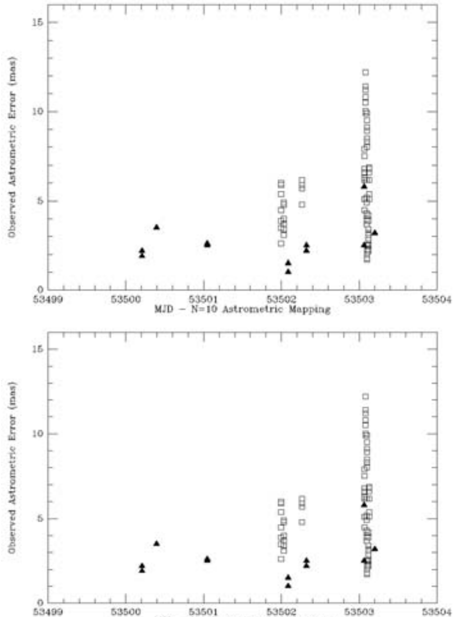
Figures 1a and 1b. Astrometric reductions of the Subaru Suprime-Cam data for 10-second (1a; above) and 30-second exposures (1b; below) using constant (☐), linear (○) and cubic (●) astrometric models.

The Subaru Suprime-Cam Data

The Subaru data show that there are significant changes in the apparent scale of the image. The linear astrometric model is much better than the constant model, but the cubic model offers only a modest improvement over the linear model. The size of the astrometric error appears to scale as 1/SQRT(exposure time) as predicted by the standard models of atmospheric seeing.

The SOAR and Gemini-South Data

As part of the LSST Simulation Group's observing campaign, many astrometric sequences were taken. The goal was to do astrometric solutions similar to those described above, but with a wider range of seeing, exposure time, and zenith distance. Figures 2a and 2b show the RMS astrometric error from a single fit to all stars rather than the growth of error as a function of separation.



Figures 2a and 2b: Astrometric error as a function of epoch (MJD) for constant (2a; upper) and cubic (2b; lower) astrometric models. Filled symbols (♦) show Gemini GMOS data and open symbols (☐) show SOAR SOI data.

Figures 2a and 2b show that the assumption of a cubic astrometric model reduces the RMS error by about a factor of two, and that errors similar to those seen in the Subaru data are seen for both SOAR SOI and Gemini GMOS data. The worst residuals seen are from the 60-second exposures taken with the SOAR SOI camera, and these have a typical error of about 10 milli-arc-seconds. The theory of seeing predicts that the errors should be reduced by 1/SQRT(exposure time) but this is not seen. It appears that all exposures shorter than 60 seconds have errors near 5 milli-arc-seconds. The source of this discrepancy is not known, but it may be the case that the cubic fit to the shorter exposure data is removing some of the astrometric distortions that cannot be fitted out of the longer exposure data.

Conclusion

- **The relative astrometric error in a single 15-second exposure taken in 1.0arc-second seeing will be in the range of 5 to 10 milli-arc-seconds when acubic (or possibly linear) astrometric model is used. This is consistent with the LSST Science Requirements Document.**

- **We expect astrometric accuracy to scale as:**
  10mas*(FWHM/1.0 arcsec)*SQRT(10/T_exp)

Thus the expected LSST median seeing of 0.7arcsec should deliver even better astrometry.

The SOAR and Gemini data were collected in a manner that may allow the astrometric impact of the seeing to be correlated with other observable attributes of the atmosphere. Since the accuracy of LSST astrometry scales with the error of a single observation, and because the volume of space measured with a particular uncertainty scales as the cube of the astrometric accuracy, it is important to develop an accurate prediction for LSST.

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