



## Kalman Filter for Calibrating a Telescope Focal Plane

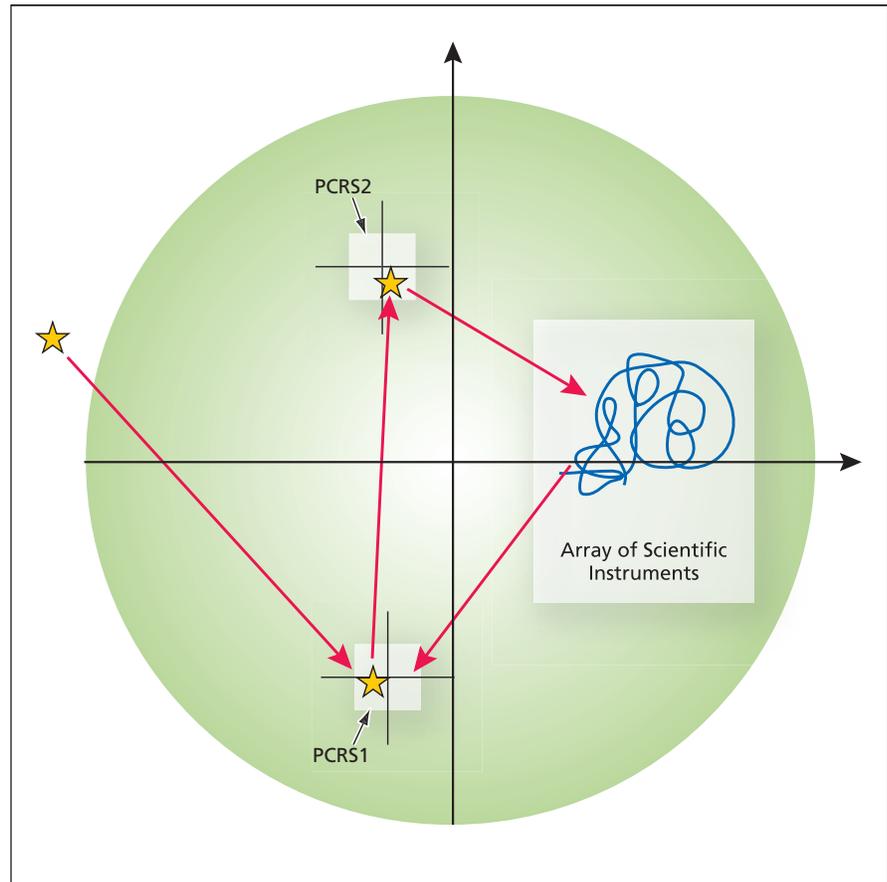
Optimal estimates of scientific and engineering calibration parameters are generated simultaneously.

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The instrument-pointing frame (IPF) Kalman filter, and an algorithm that implements this filter, have been devised for calibrating the focal plane of a telescope. As used here, "calibration" signifies, more specifically, a combination of measurements and calculations directed toward ensuring accuracy in aiming the telescope and determining the locations of objects imaged in various arrays of photodetectors in instruments located on the focal plane. The IPF Kalman filter was originally intended for application to a spaceborne infrared astronomical telescope, but can also be applied to other spaceborne and ground-based telescopes.

In the traditional approach to calibration of a telescope, (1) one team of experts concentrates on estimating parameters (e.g., pointing alignments and gyroscope drifts) that are classified as being of primarily an engineering nature, (2) another team of experts concentrates on estimating calibration parameters (e.g., plate scales and optical distortions) that are classified as being primarily of a scientific nature, and (3) the two teams repeatedly exchange data in an iterative process in which each team refines its estimates with the help of the data provided by the other team. This iterative process is inefficient and uneconomical because it is time-consuming and entails the maintenance of two survey teams and the development of computer programs specific to the requirements of each team. Moreover, theoretical analysis reveals that the engineering/science iterative approach is not optimal in that it does not yield the best estimates of focal-plane parameters and, depending on the application, may not even enable convergence toward a set of estimates.

In contrast, in the IPF Kalman-filter approach, no attempt is made to distinguish between engineering and scientific parameters. Hence, there is no need for separate engineering and scientific survey teams, separate software, and iteration between the teams. Instead, both engineering and scientific focal-plane parameters are estimated to-



The **Focal Plane Is Occupied** by two pointing-control reference sensors (PCRSs) and an array of scientific instruments. The telescope is maneuvered so that a star is first centroided on PCRS1, then centroided on PCRS2, then moved over to the array of scientific instruments to obtain a series of centroid measurements, then centroided again on PCRS1. This maneuver makes it possible to attain the main goal of the calibration, which is to establish the locations of the instruments in a telescope-pointing reference frame.

gether, using data taken in the same focal-plane survey. The main advantage is that the IPF Kalman filter offers greater efficiency and economy. In addition, the estimates generated by the IPF Kalman filter are optimal.

The IPF Kalman filter is a high-order square-root iterated linearized Kalman filter, which offers robust numerical conditioning and a capability to obtain high accuracy. The filter is parameterized for calibrating the focal plane and aligning the scientific-instrument photodetector arrays with respect to the telescope bore-sight, all to within a specified tolerance (in the original intended application, a focal-

plane radial standard deviation corresponding to 0.14 arc second in the sky). To obtain this level of accuracy, the filter utilizes 37 states to estimate desired alignments while also correcting for systematic errors expected to be caused by optical distortions, the scale factor and misalignment of a scanning mirror, thermomechanically induced drifts of alignments among telescope and instrument frames, and gyroscope bias and bias drift in all axes.

Other salient features of the IPF Kalman filter and algorithm include the following:

- The use of polynomial functions of time to characterize such time-depend-

ent behaviors as gyroscope drifts and thermomechanically induced alignment drifts. Because the polynomial coefficients are constant, this feature makes it possible to accommodate such behaviors while retaining the global re-linearization of the Kalman filter.

- A gyroscope-data pre-processing sub-algorithm makes it possible to compute and store gyroscope sensitivities in advance, thereby eliminating the need for repeated and time-consuming propagation of gyroscope sensitivities during each filter cycle.
- A parameter-masking capability offers the option of restricting estimation to an arbitrary subset of all the focal-plane parameters, thereby affording

flexibility to match calibration mathematical models of different levels of fidelity to different scientific instruments.

- A “multi-run” feature affords flexibility to estimate parameters by use of measurement data, which has been acquired during different observing sessions.
- An experiment design characterized by maneuvers illustrated in the figure provides for observability of all desired parameters and enables the use of the same Kalman filter for a variety of instruments.
- Measurements using observations of both visible and infrared sources can be included in the same set of calibration data.

- There is an option to process centroid information that is partial in the sense that it pertains only to position along a single axis of a photodetector array. Such information is obtained, for example, when calibrating the entrance aperture of spectrometer slit by first scanning a source across the narrow slit width, and then scanning the source along its length.
- The filter algorithm can be executed in one of several optional modes that offer compromises between accuracy and robustness.

*This work was done by Bryan Kang and David Bayard of Caltech for NASA’s Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1). NPO-40798*

## Electronic Absolute Cartesian Autocollimator

Readout is not materially affected by drifts in analog circuitry.

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An electronic absolute Cartesian autocollimator performs the same basic optical function as does a conventional all-optical or a conventional electronic autocollimator but differs in the nature of its optical target and the manner in which the position of the image of the target is measured. The term “absolute” in the name of this apparatus reflects the nature of the position measurement, which, unlike in a conventional electronic autocollimator, is based absolutely on the position of the image rather than on an assumed proportionality between the position and the levels of processed analog electronic signals. The term “Cartesian” in the name of this apparatus reflects the nature of its optical target.

Figure 1 depicts the electronic functional blocks of an electronic absolute Cartesian autocollimator along with its basic optical layout, which is the same as that of a conventional autocollimator. Referring first to the optical layout and functions only, this or any autocollimator is used to measure the compound angular deviation of a flat datum mirror with respect to the optical axis of the autocollimator itself. The optical components include an illuminated target, a beam splitter, an objective or collimating lens, and a viewer or detector (described in more detail below) at a viewing plane. The target and the viewing planes are focal planes of the lens. Target light reflected by the datum mirror is imaged on the viewing plane at

unit magnification by the collimating lens.

If the normal to the datum mirror is parallel to the optical axis of the autocollimator, then the target image is centered on the viewing plane. Any angular deviation of the normal from the optical axis manifests itself as a lateral displacement of the target image from the center. The magnitude of the displacement is proportional to the focal length and to the magnitude (assumed to be small) of the angular deviation. The direction of the displacement is perpendicular to the axis about which the mirror is slightly tilted. Hence, one can determine the amount and direction of tilt from the coordinates of the target image on the viewing plane.

In a conventional all-optical autocollimator, the target is a first reticle, a technician observes the target image through an eyepiece, and a second reti-

cle affixed to the viewing plane is used to measure the coordinates of the displaced image of the first reticle. In a conventional electronic autocollimator (which could be characterized more accurately as a conventional optoelectronic autocollimator), the target is a pinhole and a position-sensitive photodetector is placed at the viewing plane. The location of the bright pinhole image is measured by use of the position-sensitive photodetector along with analog readout circuits. The net outputs of these circuits are two sets of voltage differences nominally proportional to the displacement of the pinhole image along two coordinate axes ( $x$  and  $y$ ) in the viewing plane. Like all analog devices and circuits, the position-sensitive photodetector and its readout circuits exhibit thermal and spontaneous drifts,

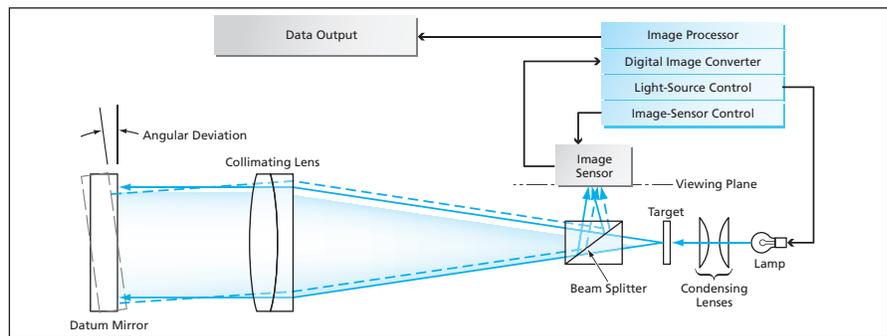


Figure 1. An **Electronic Absolute Cartesian Autocollimator** includes a conventional autocollimator optical system with a coded Cartesian-grid target, an image sensor, and a digital image-processing and control system.