Photometry
Subduing the Demons
The first rule of array imaging is repetition

- Multiple images allow systematic identification of outlier signals due to cosmic rays and other transients.
- They also allow replacing areas compromised by cosmic rays, latent images, hot or dead pixels, ghosting, etc. with real data.
- By dithering the pointing on the sky between exposures (moving the telescope slightly so the images fall on different parts of the array), the sky signal itself can be used to flatten the image (as discussed below). If the sky dominates the signal, then fringing effects are removed to first order, along with many other potential contributors to non-flatness.
- Properly sampled images are another form of repetition - more than one pixel contributes to the signal. Accurate photometry benefits from spreading the light over multiple pixels (which can also be done with dithering a lot).
Modern arrays often include non-active pixels that are electrically identical to those that detect photons. For CCDs, some benefit is obtained by overscanning the array, while for infrared arrays they are physical outputs called reference pixels. They can be used to correct the images for slow drifts in the electronics.

The second rule of imaging photometry is don't change anything

- Artifacts like MUX glow, pedestals, and many others will disappear from your reduced data virtually completely if you are careful to take all your data - science and calibration frames - in identical ways (for example, the identical exposure times and readout cadences)
- Detector arrays also perform better when they reach equilibrium, i.e., constant exposure times and readout cadences, plus constant temperatures, backgrounds, and etc.
Then you are ready to calibrate the data. This step must take into account the differing properties of the detectors in the array:

- pixel-to-pixel variations in amplifier offset
- pixel-to-pixel variations in dark current
- pixel-to-pixel variations in responsivity

Three unknowns require three sets of data:

- Offset frame (sometimes called bias frame): very short exposure, no signals
- Dark current frame: long exposure, no signals
- Response frame (sometimes called flat field): uniform illumination
For best results
• Dark current and response frames may need to be obtained close in time to the data frames
• It may be necessary to use identical integration times for dark, response, and data frames
• Response and data frames should be taken with illumination of identical spectral character
• Need a minimum of 3 frames on source – 5 or more is better – to be sure there are no transient bad pixels (e.g., cosmic ray hits)
A good strategy for imaging is:
• Take repeated exposures of the field, moving the source on the array between exposures
• Generate the response frame by a median average of these frames – sources will disappear because they do not appear at the same place on any two frames
• Obtain dark frames with the same exposure time as used for the data and response frames
• Subtract dark from data and response (also takes out offset); divide corrected data by corrected response
• Shift frames to correct for frame-to-frame image motions
• Median average again to eliminate bad pixels and cosmic rays, while gaining signal to noise on the source image

In general, the image reduction software will include standard or recommended procedures to generate the necessary calibration frames from your data, and to shift and add all your science frames into one high-quality image.
Is the job done?

Recall the list of possible array problems we discussed earlier. Some of them should be taken care of at this stage, although they might have required some extra processing: 1.) fringing; 2.) hot and dead pixels; 3.) cosmic ray hits; 4.) latent images; and 5.) MUX glow. The next to last item might require generating a special flat field frame designed to just capture the latents. You might also have to identify electrical and optical ghost images and other such effects and fix them by hand or with custom routines.
Astrometry
Today: How measurements are made
Thursday: Jane Morrison on how they are used
From “The Hipparcos and Tycho Catalogues,” ESA
The Strand Telescope (Naval Observatory, Flagstaff), optimized for photographic astrometry. It is 1.55 cm aperture, with a flat secondary ("folded Newtonian"). The primary is paraboloidal, f/9.8.
Measuring machines were used to scan plates to locate the stars.
Photograph plates work well for astrometry because they have many grains (pixels) that scatter the light and give an image not strongly influenced by a few dominant pixels.
A plate measuring machine systematically determines the density (exposure level) of a plate by scanning a light source over it on one side and a detector on the other.
A big advance required a new approach - Hipparcos. The satellite spins (2 hours for the entire sky) and its telescope compares two directions separated by about 50 degrees.
The telescope is a reflective Schmidt design, with the corrector split to divide the aperture between the two fields.
Upper - Hipparcos modulating grid, spacing 8.2 μm projecting to 1.208 arcsec on the sky.

Lower - star mapper used for the Tycho catalog, determining positions with accuracy about 25 times lower than through the grid, and measuring B, V photometry of them.

Satellite spun slowly, one revolution per ~ 2 hours so stars passed over these masks quite rapidly. The signal modulated by the mask was used to determine star positions.
An image dissector scanner was used with its sensitive area where a star was expected. It was read out 1200 times/second, that is, every 0.15"
Signal in the Hipparcos arm of the instrument as the grid lets through more and less of the star light. The phase of this oscillation gives a very accurate measure of the position of the star (to be compared with another one 50 degrees away on the sky).
But it's not going to be that easy. Here are three stars from each field, superimposed (left). But each will have some proper motion, so when they are sighted again they will have moved (center). And on top of that, they will have some degree of parallax (right). All these apparent motions need to be fitted to complete the job of getting astrometry.
Furthermore, the grid only gives accurate measurements in one coordinate. To get good positions, many sightings of the star need to be combined in a model.
The data were recently re-reduced to obtain significantly higher accuracy than the first time.

**Hipparcos, The New Reduction of the Raw Data**

Floor van Leeuven, Springer, 2007

(and in Vizier)

The new reduction of the Hipparcos data presents a very significant improvement in the overall reliability of the astrometric catalogue derived from this mission. Improvements by up to a factor 4 in the accuracies for in particular brighter stars have been obtained. This has been achieved mainly through careful study of the satellite dynamics, and incorporating results from these studies in the attitude modelling. Data correlations, caused by attitude-modelling errors in the original catalogue, have all but disappeared. This book provides overviews of the new reduction as well as on the use of the Hipparcos data in a variety of astrophysical implementations. A range of new results, like cluster distances and luminosity calibrations, is presented. The Hipparcos data provide a unique opportunity for the study of satellite dynamics. The orbit covered a wide range of altitudes, showing in detail the different torques acting on the satellite. One part of the book details these studies and their impact on the new reduction. It furthermore presents an extensive summary on a wide range of spacecraft and payload calibrations, which provide a detailed record of the conditions under which these unique Hipparcos data have been obtained.
Star positional accuracies over time, assuming a proper motion error of 2.5 mas per year.
From "The Hipparcos and Tycho Catalogues," ESA

Progress in astrometry

Errors of best star positions and parallaxes

From "The Hipparcos and Tycho Catalogues," ESA
Another modern method: very long baseline interferometry (VLBI)
Future Possibilities

The Space Interferometry Mission (SIM)
GAIA
A Michelson Astrometric Interferometer

Incoming Starlight

Extra pathlength

Astrometric baseline

Physical baseline

Siderostat

Compressor

Beam Splitter (Combiner)

Detector

Adjust Delay to equalize Pathlength for each arm
Sky Scanning Principle

- Spin axis: $45^\circ$ to Sun
- Scan rate: 60 arcsec $s^{-1}$
- Spin period: 6 hours

Figure courtesy Karen O'Flaherty
Gaia: Complete, Faint, Accurate

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<td>300 µarcsec at V = 20</td>
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Payload and Telescope

Two SiC primary mirrors
1.45 × 0.50 m² at 106.5°

Rotation axis (6 h)

Basic angle monitoring system

SiC toroidal structure (optical bench)

Combined focal plane (CCDs)

Superposition of two Fields of View (FoV)

Figure courtesy EADS-Astrium
**Focal Plane**

**Total field:**
- active area: 0.75 deg$^2$
- CCDs: 14 + 62 + 14 + 12
- 4500 x 1966 pixels (TDI)
- pixel size = 10 µm x 30 µm
  = 59 mas x 177 mas

**Sky mapper:**
- detects all objects to 20 mag
- rejects cosmic-ray events
- FoV discrimination

**Astrometry:**
- total detection noise: ~6 e$^-$

**Photometry:**
- spectro-photometer
  - blue and red CCDs

**Spectroscopy:**
- high-resolution spectra
  - red CCDs