Photogrammetry Primer

We often get general questions from panel members (especially new ones, who may not have encountered the subject before) about photogrammetry, how it works, and the many jargon terms that creep into our proposals. This document is an attempt to define the key terms and provide a working knowledge of what photogrammetry is and how it is used. We also invite the working group members to see an informal demonstration of our photogrammetric workstation when they visit us.

The short definition of *photogrammetry* is "the art and science of making measurements from images." Specifically, we measure the locations of features in the images (*image space*) and try to relate them to two other kinds of information: (a) the position, pointing, and detailed workings of the cameras or other sensors (photogrammetrists call all these kinds of data *orientation*); and (b) the locations of the features in the real world (*ground* or *object space*). There are different names and applications for the calculation depending on what quantities are unknown, but the calculations are all done as least-squares calculations to allow for noise in the data and the use of more observations than unknowns.

The simplest type of calculation is *intersection*, in which the orientation data are known and the ground coordinates unknown. Each image is a two-dimensional projection of the three-dimensional world, so if a feature (say, a rock) is observed at a given pixel this does not give its full ground-space location but does constrain that location to lie on a known curve (a geometric straight line for an ordinary optical image, or in a radar image actually a known circle). The equations relating image to ground space are sometimes called the *colinearity equations* in the case of an optical image.

The software needed to calculate the line from pixel coordinates or pixel from ground coordinates for a given sensor is called a *sensor model*. Both ISIS and SOCET SET require sensor models to be defined and use them in all types of geometric calculations involving images. Both systems require a short list of "plug in" subroutines to define a full sensor model. These include the routines that calculate image-to-ground and ground-to-image transformations (this part of the sensor model is sometimes called the *math model*) and various housekeeping routines. All framing cameras use one kind of sensor model (with different parameters such as focal length, etc.). Fundamentally different sensors such as pushbroom scanners (MOC) and radar (Magellan) each require their own appropriate sensor model. Within a single class of sensor that uses one sensor model, the different parameters (focal length, image size, distortion model) that characterize different instruments are sometimes referred to as the *camera model*.

Once a feature is measured in two images and the needed sensor model(s) are available, we solve for the intersection of the two corresponding lines to get the full ground coordinates. Of course, subject to noise in the measurements the lines may be skewed so we actually do a least-squares determination of the point where they come closest to meeting. Intersection calculations are used to make digital elevation models (*DEM*s): we use *automatic image matching* techniques to measure a dense set of corresponding points in two images and generate a dense set of points describing the ground. The SOCET SET module for doing this is called Automatic Terrain Extraction (*ATE*). An Interactive Terrain Extraction (*ITE*) module lets us check the DEM results overlaid on the images in stereo and edit them, vitally necessary because the automatching is not completely reliable and the human eye can do better. Both the automatcher and the eye look for patterns of several pixels in the image, so they produce an independent DEM point only every few pixels. The horizontal resolution of a DEM is therefore less than that of the images it comes from. DEM points are sometimes called *posts* and the DEM resolution is *post spacing*. The resolution of a DEM or an image can be called ground sample distance (*GSD*).

An important step in preparing images for either stereo viewing or automatching is *pairwise epipolar rectification*. This means resampling the two images so they are not only the same size and orientation, but so that the stereo parallax direction runs from side to side. If the images are not lined up in this way, they will not appear in depth on the stereo display (instead of seeing stereo, the viewer will get a splitting headache). Automatic stereomatching also depends on this kind of alignment so that it can search efficiently (along a line instead of over an area) for corresponding image patches. SOCET SET can supposedly do the pairwise epipolar rectification of images either as a preprocessing step (i.e., generating new image files on disk) or on the fly while displaying them and doing automatching, but we found that in some cases it works better to do it by preprocessing.

Other important types of intersection calculations are used to make maps from the images. Once the DEM is determined, we can intersect the lines of pixels with it to determine the ground coordinates of all the pixels. This process accounts for parallax when the image is non-vertical and is called *orthorectification*. The resulting image mosaics are called *orthomosaics*. If we have no DEM we can intersect the pixel lines with a *reference surface* such as a sphere or ellipsoid approximating the size and position of the planet and make an *unrectified* mosaic. The majority of planetary mosaics until recently were made this way and are not considered true "maps" by purists because they contain parallax distortions.

If all the orientation data were known to high accuracy, intersction would be the only kind of calculation we would need. But if the orientation data are off, the intersection will give wrong results from good image matches. Moving the cameras or changing their pointing will move the whole set of points in the DEM and distort it somewhat. To avoid this, we do a calculation where the orientation data are unknowns, solving for improved estimates of them. This is generally done with a much smaller set of image measurements than are needed to make up a DEM, maybe a handful per pair of overlapping images. If we know the ground coordinates of all the points the calculation is called a *resection* but this is obviously only practical on Earth. If we solve for some of the ground coordinates (even if others are known, e.g., from the much more accurate MOLA grid, or by tracking landers and identifying their landing points in images) as well as the orientation data, the calculation is called *bundle-adjustment*, or, if there are more than a single strip of images involved, *bundle-block adjustment*. Another related term is *aerotriangulation*. The features measured are called *pass-points* in general and *ground-points* if they have known ground coordinates. In Astrogeology we also refer to ground-points as *tie-points*, non-ground points as *match-points*, and the bundle-adjustment calculation as a *jigsaw* (after the PICS and later ISIS programs that do the calculation). Jigsaw is both a noun and a transitive verb ("I have to jigsaw these images before I make my mosaic."). The SOCET SET module for doing bundle-adjustment (and resection) calculations is Multisensor Triangulation (*MST*). It is aided by Automatic Point measurement (*APM*) and Interactive Point Measurement (*IPM*), which should be fairly self-explanatory.

So…why SOCET SET? ISIS includes the jigsaw program and it includes rudimentary automatic matching capabilities (programs findrx, qmatch, coreg3) that are used respectively to find *reseaux* (marks put on the focal plane of the TV cameras for calibrating distortions) in Viking/Voyager images, for refining pass-point measurements, and for lining up images of the same subject taken in different filters. It is possible to make DEMs with little more than these tools but there would be no way to validate the results against the stereo images or edit the DEM if the automatic matching is not successful. The commercial system provides a complete package with the modules mentioned and in particular the ability to display images and color graphics of the DEM in stereo and edit DEM posts and pass-points with a special 3D input device. The bundle-adjustment and matching modules are also more powerful in some ways than their ISIS equivalents. After some years of discussion and looking for alternatives, the USGS and PCGMWG concluded that buying a commercial stereo system offered advantages over trying to develop all these needed capabilities in ISIS. ISIS is still critical to the overall workflow; we ingest and calibrate the images in ISIS because we can write the mission-dependent code to do so, then pass the images to SOCET SET by using programs containing both ISIS and SOCET code. Although we can make mosaics and maps in SOCET SET we often pass the DEM data and orthorectified images back to ISIS to do these final steps.