PLANETARY CARTOGRAPHY, PHOTOGRAMMETRY, AND GEODESY:

AN INTEGRAL COMPONENT OF SUCCESSFUL MISSION PLANNING

USGS ASTROGEOLOGY SCIENCE CENTER

AND

THE NASA PLANETARY CARTOGRAPHY AND GEOLOGIC MAPPING WORKING GROUP

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OVERVIEW

Cartographic processing, which can be considered broadly as the integration of data from disparate images and other observations of a planetary body into a single coherent coordinate system, is a critical step in extracting the maximum scientific value from a spacecraft mission. The Discovery Announcement of Opportunity strongly encourages proposers to have a plan for the cartographic reduction of their data. In particular, though systematic cartographic processing of the data may sometimes be left to post-mission analysis programs, it is critical that mission teams arrange for the acquisition and analysis of the calibration data needed to produce high-precision, high-accuracy products for scientific interpretation. In addition, at least some of the returned data will likely need to be processed during the mission in order to address the scientific goals of the investigation. Because planetary cartography is a discipline of considerable complexity and long history, the expertise that proposal teams bring in this particular area is likely to vary widely. The goal of this document is therefore to give a brief overview of the planetary digital cartographic services that the USGS Astrogeology Science Center is available to provide when partnered with spacecraft mission teams. As described below, these services include development of remote-sensing instruments, data acquisition plans, spacecraft operations, radiometric and geometric calibration efforts, camera model development (including corrections for spacecraft jitter and optical distortions), data product generation (e.g., image mosaics, regional or global digital elevation models), data analysis and visualization tools, software and data processing workshops for team members, and data archiving operations that follow international cartographic standards. Because photogrammetry (the process of deriving quantitative geometric information from measurements on images) is at the heart of precision planetary cartography, we begin with a short primer on photogrammetric techniques and terminology before describing the specific capabilities that are available.

The Astrogeology Science Center develops and maintains the image processing software suite ISIS (*Integrated Software for Imagers and Spectrometers*). This system allows for scientific analysis and cartographic manipulation of planetary images. ISIS provides sophisticated tools for the derivation of topographic information from planetary image data, thus enabling the detailed 2- and 3-D characterization of planetary terrains at the scale of the input images. ISIS currently supports the following missions, although more are being added every year: Voyager 1&2, Viking 1&2, Mariner 9&10, Lunar Orbiter

3,4,&5, Apollo 15,16,&17 Metric camera, Clementine UVIS, NIR, HIRES & LWIR, Galileo SSI & NIMS, Cassini ISS, RADAR, & VIMS, Mars Global Surveyor NAC & WAC, Mars Odyssey THEMIS IR & VIS, Mars Reconnaissance Orbiter HiRISE, CTX, and MARCI, Mars Express HRSC, Messenger MDIS NAC & WAC, Lunar Reconnaissance Orbiter NAC, WAC, & Mini-RF.

In addition, the Astrogeology Science Center has been a world leader in photogrammetric topomapping of solar system bodies with stereo images since the 1970s. Like the production of non-topographic map databases now performed in ISIS, this work underwent a radical transition from partly analog to fully digital in the 1990s. 2007 marked ten years since the Astrogeology Science Center selected the commercial photogrammetric workstation software package SOCET SET ® (BAE Systems) for use in topomapping projects. The NASA Planetary Cartography and Geologic Mapping Working Group strongly supported the need for a centralized topographic map production program at USGS and fully endorsed the use of SOCET SET for this purpose. The commercial software, which provides unique capabilities for viewing stereo imagery and extracting quantitative topographic information, is fully integrated with the ISIS environment through interface software developed by Astrogeology staff members. As a result, stereo observations from a majority of the ISIS-supported sensors listed above can be used for topographic mapping.

Primer on Photogrammetry

Photogrammetry is at the heart of cartographic processing, whether primarily two-dimensional (e.g., production of image maps in ISIS) or three-dimensional (topographic mapping in SOCET SET). It involves relating the measurement of feature locations in images (*image space*) to two other kinds of information: (a) the position, pointing, and detailed workings of the cameras or other sensors; and (b) the locations of the features in the real world (*ground* or *object space*). 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 (e.g., 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).

Camera Models

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 well-defined sensor models for use in all types of geometric calculations involving images. All framing cameras use one kind of sensor model (with different parameters such as focal length, etc.). Fundamentally different sensors such as pushbroom scanners (e.g., the Mars Orbiter Cameras, HiRISE, LROC NAC) and radar (Magellan, Mini-RF) 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 referred to as the *camera model*. This is a mathematical algorithm that enables computation at any image pixel the latitude, longitude, pixel resolution, and a variety of sun-spacecraft-surface angles (e.g., phase, emission, incidence, solar azimuth, right ascension and declination). A camera model enables geometric rotation of pixels from the camera perspective to a map projection, thus allowing comparison among images acquired at different times and/or from different instruments (Figure 1). Once projected to a common coordinate system, regional and/or global image mosaics can be made comprising tens of thousands of individual images. Further, the availability of incidence, emission, and phase angles allows for photometric normalization of images taken under different lighting conditions that enables both scientific analyses and the creation of seamless mosaics. Finally, images acquired at different viewing geometries contain valuable stereo information that can be used to create digital elevation models at resolutions comparable to those of the images.

A key point is that a new camera or other sensor may or may not require the development of a new sensor model, but even in the case that the camera is sufficiently similar to past flight hardware that existing sensor model code can be used or adapted, it is *always* necessary to determine accurate parameter values for the new instrument. The accuracy and precision of all cartographic products depend critically on the determination of correct values for focal length, distortion, and so on. Estimation of these parameters is known as *camera calibration* or *geometric calibration* (to distinguish from calibration of the radiometric sensitivity of the instrument, a separate process that is usually also critical to obtaining quantitative scientific results from images). The data required to perform geometric calibration may be obtained before flight in the laboratory, during flight, or in some combination, but it is important to note that if adequate calibration data are not obtained at these times, the opportunity to produce accurate cartographic products—and thus to integrate the images with other data sets—is lost forever.

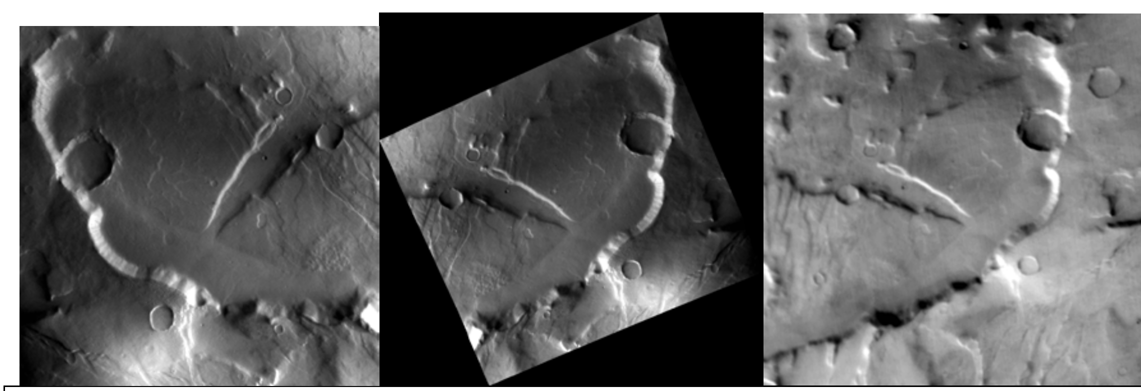

Figure 1. Dawn spacecraft Framing Camera (FC) image of Mars (left); same image map-projected with North towards the image top (right); Viking image of same region on Mars projected to match FC image.

Digital Elevation Models and Orthorectification

Once a feature is measured in two images and the needed sensor model(s) are available, one can solve for the intersection of the two corresponding lines to get the full ground coordinates. Intersection calculations are used to make digital elevation models (*DEM*s, also called digital topographic models or DTMs). A*utomatic image matching* techniques are used to measure a dense set of corresponding points in two images and generate a dense set of points describing the ground. An Interactive Terrain Extraction (*ITE*) module in SOCET SET provides a means to quality check and edit the DEM results overlaid on the images in stereo. This step is 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" (grid spacing) of a DEM or an image can be called ground sample distance (*GSD*).

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.

Bundle Adjustment

If all the orientation data were known to high accuracy, intersection would be the only kind of calculation we would need. But if the orientation data are off, the intersection will give incorrect 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, calculation is performed where the orientation data are unknowns, solving for improved estimates of them. If some of the ground coordinates are known along with their orientation data, the calculation is called *bundle-adjustment*. Or, if there are more than a single strip of images involved, it is referred to *bundle-block adjustment*. Additional well-characterized points may be available from laser altimeter data, or from known locations of landers in images. Such ground-points are often referred to as *tie-points*, and the bundle-adjustment calculation as a *jigsaw*.

ISIS includes the “jigsaw” programs and some automatic matching and DEMs generation capabilities, 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 past several decades of research in the photogrammetric community strongly indicate that matching errors are relatively common and manual validation and editing are still essential even for the most sophisticated matching algorithms that have been devised—algorithms that can be far more complex than those now implemented in ISIS. SOCET SET 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. Customized ISIS software is used to ingest and calibrate the images and then images are passed to SOCET SET by using programs containing both ISIS and SOCET code. Although maps are often produced in SOCET SET, DEM data and orthorectified mosaics can be sent back to ISIS, ArcGIS, and Adobe Illustrator for final processing.

ASTROGEOLOGY SCIENCE CENTER POSSIBLE SERVICES AND SUPPORT

The Astrogeology Science Center has nearly a half-century of experience in planetary cartographic and scientific analyses of planetary surfaces. Such expertise can improve the success of mission and instrument activities, particularly if implemented early in mission planning. With sufficient planning, the following areas of expertise can be provided through funded partnerships with Astrogeology:

1) *Advanced Mission Planning*: This activity includes development of new scientific instrumentation and spacecraft systems, general mission design of space missions, and research and development in mission operations and data analysis technologies. Astrogeology can supply staff to support mission planning (e.g., meeting and working group attendance) and through the development of materials requested by the mission development and planning office. Planning the acquisition and reduction of the laboratory and flight data needed to support geometric and radiometric calibration is a key function in which Astrogeology has experience across multiple missions.

2) *Flight Mission Support*: The focus of this activity is the support of on-going spaceflight missions. Services include mission planning, design, and simulation; real-time data analysis and press releases; and initial data cataloging and archiving. Data received by the flight missions is processed within by the Astrogeology Science Center for distribution to the Planetary Data System (PDS) and the scientific community at large.

3) *Analytical Software Systems Development*: This activity is devoted to the development of software systems for the large, complex data sets produced by flight missions, including multi/hyperspectral and imaging radar data. Software is developed to address the unique aspects of each data set such that they may be processed and distributed for use by the scientific community at large. In addition, software is developed to support other cartographic and mission support functions operated within the Program. Implementation of geometric sensor models, reduction of data to give precisely calibrated geometric parameters, and development of algorithms and parameters for radiometric calibration of images are major elements of the software development process.

4) *Digital Map Series and Database Development*: This activity includes production, publication, and distribution of digital image and topographic databases at global, regional, and local scales for the planetary bodies. Geometric and radiometric

calibrations developed at earlier stages are drawn on in this processing, and the tools of photogrammetry are used to ensure the accuracy of products. Detailed photometric modeling of planetary surfaces may also be used to generate uniform-appearing products from observations taken under a variety of conditions. Maps are produced in accordance with USGS map preparation and publication standards and are distributed in both digital and (less frequently) hardcopy form.

5) *Development of Digital Topographic Databases*: This activity focuses on the development and implementation of techniques to use planetary mission data to prepare topographic maps and digital elevation models of planetary surfaces.

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