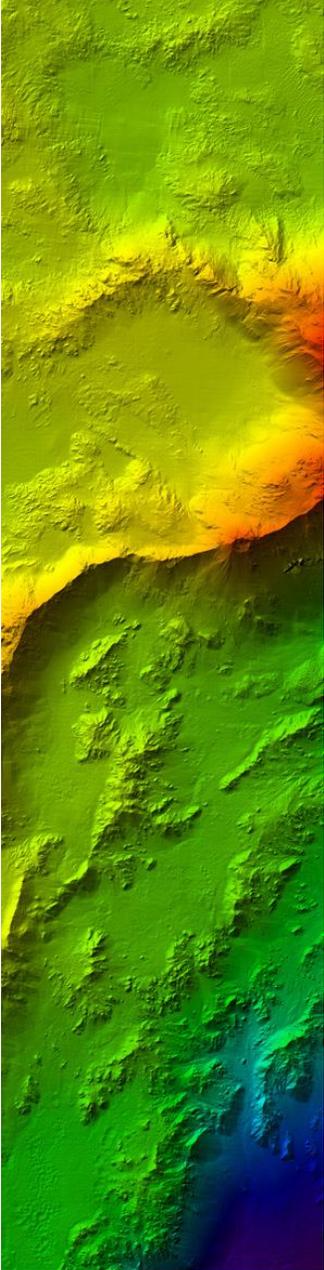


 **USGS**
science for a changing world
Astrogeology Research Program

BAE SYSTEMS



**HiRISE**

**Stereo Processing
of Planetary Stereo Imagery
using ISIS3 and SOCET SET®**

a Primer

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This Primer outlines the current procedures developed and used by the Photogrammetry team of the Astrogeology Science Center, USGS, for stereo processing using planetary stereo imagery, such as HiRISE (Kirk, et al., 2008). To follow these procedures at your own facility, you will need the following:

1. *Training datasets,*
2. *Astrogeology's in-house software and PERL scripts, and*
3. *Tutorials in a series of ZIP files.*
4. *ISIS installed and operational on home computers*
5. *SOCET SET[®] software installed and operation on specialized equipment*

All these files will be placed in a publicly accessible site.

The tutorials ZIP file includes the PowerPoint presentation file from latest training workshops on SOCET SET^{®1} processing for Planetary Stereo Imagery. The presentation file supplements this tutorial by providing some background on Astrogeology's photogrammetric processing methodologies, as well as helpful tips.

The intended audience for this tutorial is threefold. First, we have collected much of this information in our efforts to support colleagues who have set up digital photogrammetric workstations at their home institutions with the goal of using them for topographic mapping with planetary stereo imagery such as HiRISE images. Second, this document forms the basis of the preliminary training we provide to scientists who come to Flagstaff to use the Planetary Photogrammetry Guest Facility established by the USGS and the NASA Planetary Geology and Geophysics and Planetary Major Equipment Programs in 2009. Third, this tutorial is also used as training tool for Astrogeology Science Center members. **Throughout the text, you will find critical information highlighted in red text.** You will also find instructions in green text. These are in-house notes that can be ignored, or if applicable, adopted by your facility. *Note: until ISIS has the calibration and "balancing" software to produce balanced cubes from PDS images, our procedure starts with the balanced cubes produced by the HiRISE team at University of Arizona.*

Finally, this Primer is intended to help with processing generic planetary stereo imagery which includes examples for line scanners, framing cameras as well as other sensors. In using this Primer, it is essential to view it as a work in progress, since new techniques are continuously developed to meet changes in hardware needs and evolving software. We have included several step-by-step details for the new SOCET SET[®] user; and we continuously add tips and short cuts for the rather advanced and skilled users. If you have any good short cuts and suggestions to add to the tutorial, please let us know and we will incorporate your material with proper credit.

¹ SOCET SET is an acronym that stands for SOftCopy Exploitation Toolkit. SOCET SET is a trademark of BAE Systems

1. Photogrammetry

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 attitude of the cameras or other sensors (hence called *orientation*); and (b) the locations of the features in the real world (*ground or object space*).

There are different approaches and applications for how calculations are made, depending on which variables are known and which are unknown. Generally speaking, photogrammetric calculations are formulated using least-squares methods to handle random errors, noise, and blunder detection the observed (measured) data and to ensure better representative calculated variables.

1.1 The Colinearity Condition

The most fundamental theoretical formulation is based on the geometrical condition which stipulates that the camera station, termed as the perspective center, the image point, and the corresponding point on the ground, all form a straight line. This condition is called the Colinearity Condition. Using this condition as shown in Figure 1, the camera position and orientation data are assumed to be known, the image pixel coordinates of a particular points are measured, and object space coordinates of the corresponding point are unknown, and to need be calculated.

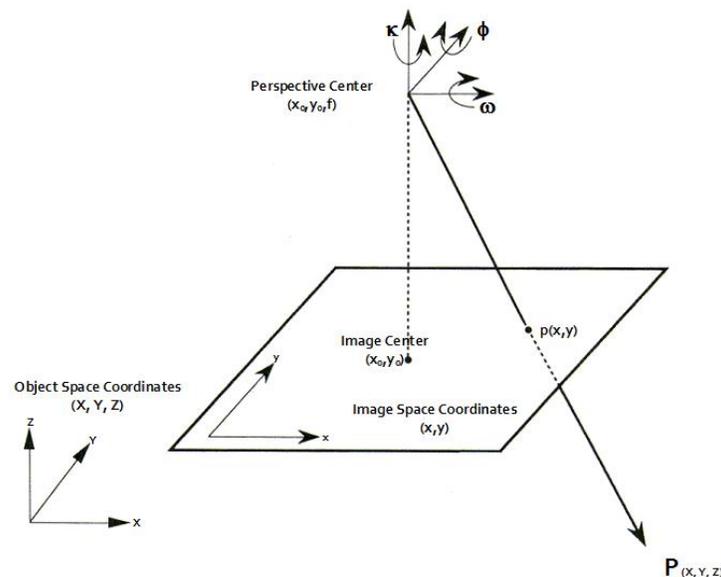


Figure 1 The Colinearity Condition showing the perspective center, the image point p , and the ground point P , all falling on a straight line.

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 straight line for an ordinary optical image, or in a radar image actually a known circle). The equations relating image to ground space are called the colinearity equations in the case of an optical image.

1.2 Sensor Models

A sensor model is a term that comprises the mathematical formulation (within a software package) that relates the measured image pixel coordinates $p(x,y)$ to the object space coordinates $P(X,Y,X)$ for a given sensor with known position and attitude. Both ISIS and SOCET SET require that sensor models be fully defined to carry out valid stereo processing of planetary images. This is achieved with specialized "plug in" subroutines that calculate image-to-ground and ground-to-image transformations and various housekeeping routines. The specific mathematical formulation of the sensor model that calculates these transformations is called the *math model*. Figure 2 shows two different kinds of sensors and a simplified model diagram. All framing cameras use one kind of sensor model (with different parameters such as focal length, resolution, etc.). Line scanners, such as the pushbroom sensor, use different sensor models as defined by the technical specifications of a space mission.

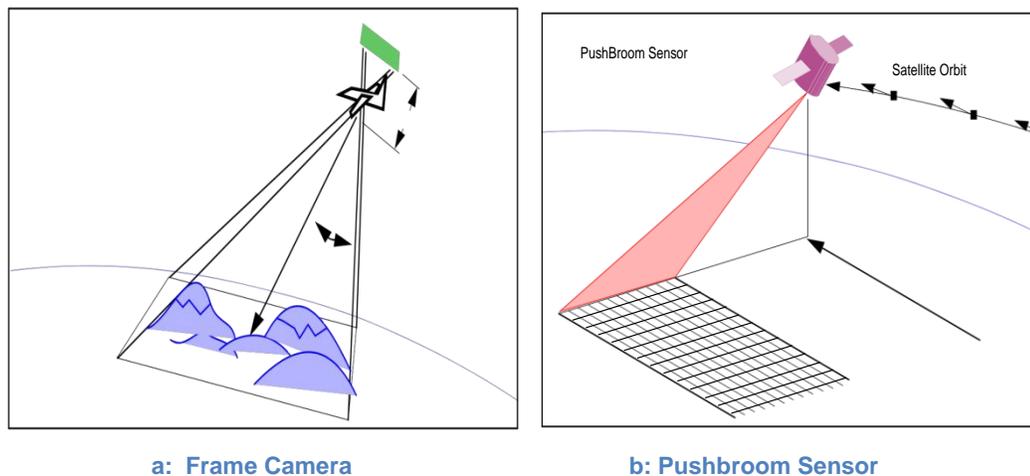


Figure 2 Simplified diagrams of two sensor models. a: frame camera, and b: pushbroom sensor.

Fundamentally, different sensors, such as pushbroom scanners (Mars Orbital Camera (MOC)) and radar (Magellan,) require their own appropriate sensor model. Within a single class of sensors that use one sensor model, the different parameters (focal length, image size, distortion model) that characterize different instruments are sometimes referred to as the *camera model*.

1.3 Surface Extraction, DEM, DTM, DSM, and TIN

Surfaces are represented by a series of values of elevation, often called digital elevation model (DEM), digital terrain model (DTM) or digital surface model (DSM). There is no common or standardized usage of the terms in scientific literature. A DSM is common to Earth surface, and includes man-made structures, such as buildings and other objects. A DTM represents the bare ground, hence mapping the footprints of buildings and man-made structures. A DEM is often used as a generic term for DSMs and DTMs, but only to represent elevation without any further definition about the surface. Also, DEM and DTM are used interchangeably.

For the purpose of this Primer, DEM is defined as a data file of elevation values that represent the terrain of an area of interest. Figure 3 shows a DEM of an area on Mars. DEM is generated over a grid of posts that covers the overlap area of the stereo pair of planetary images. The grid is formed by a fixed interval between elevation posts, and always referenced to a specific geographical reference system. This is usually either latitude-longitude or some planetary coordinate systems. In SOCET SET documentation, BAE systems uses the term DEM to refer to gridded topographic datasets, in which elevations at regularly spaced locations are stored as pixel values in what is essentially an image file (which has, however, a defined geographic or map coordinate system associated with it). They use the term DTM to subsume both gridded DEMs and triangulated irregular networks (TINs), which can contain any number and arrangement of height points. Heights at other locations in a TIN are evaluated by interpolating between the three nearest points.

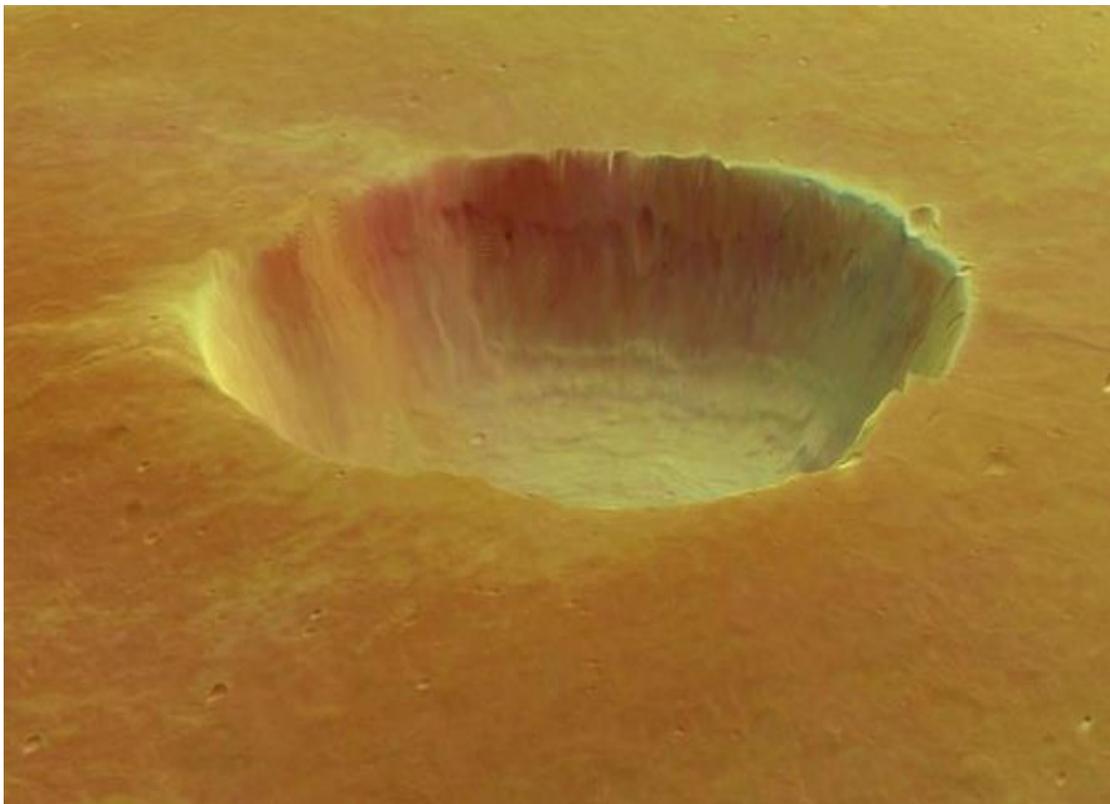


Figure 3. a DTM representation of an area on Mars. (Credit ESA/DLR/FU Berlin, G. Neukum)

To calculate an elevation value of a feature (represented by a point), the sensor model must be known, and then the image coordinates of that point, $p(x,y)$, are measured in the two overlapping images. The sensor model is then used to calculate for the elevation of the point in the object space. The geometric formulation for calculating the object space elevation is based on intersecting two lines that pass through the perspective centers (cameras) and the point located in both images. The intersecting lines, the perspective centers, and the point of the intersection in the object space, all form the epipolar geometry as shown in Figure 4.

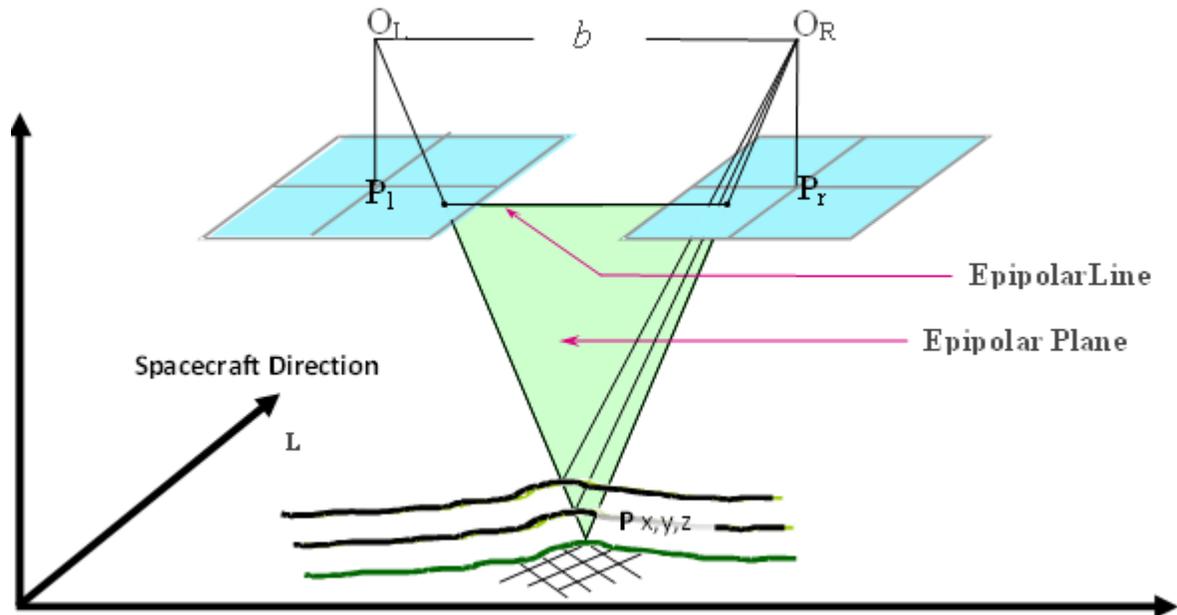


Figure 4. The epipolar geometry, formed by the perspective centers, the base line between them, the point in object space. The epipolar line is the intersection line between the epipolar plane and the overlapping images.

The epipolar plane is formed by the line of intersection of the image planes with the plane formed by the baseline joining the two perspective centers). This geometry is rather important because it is used to limit the search for corresponding (conjugate) points in the left and right images into one dimension. As shown in Figure 5, the search for conjugate points is limited to the epipolar lines

To locate the conjugate points, automatic image matching techniques are used along the epipolar lines. The same subroutine is used to generate the points that populate the whole grid of the DEM.

The SOCET SET modules for terrain extraction are NGATE (Next Generation Automatic Terrain Extraction) and AATE (Adaptive Automatic Terrain Extraction). An Interactive Terrain Extraction (ITE) module is used to check the DEM results overlaid on the images in stereo and edit them manually. This step is vital because automatic matching requires checking by a human operator. Both the automatic matching and the human eye-brain system look for similar patterns of several pixels in the image, so they produce an independent DEM point only every few pixels. The horizontal sampling distance of a DEM is therefore less the resolution of the images it is derived from. DEM points are sometimes called posts and the DEM sampling distance is

post spacing. The resolution of an image, and the grid spacing of a DEM, can both be called ground sample distance (GSD).

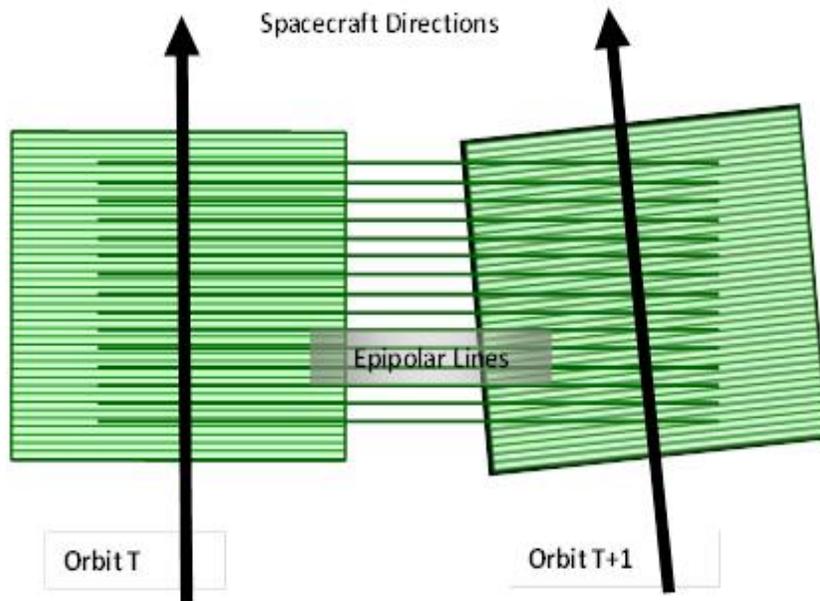


Figure 5. The epipolar geometry of an image pair is used to limit the search for conjugate points for elevations calculation into one dimension that is along the epipolar line

1.4 Orthorectification

Other important types of intersection calculations are used to make maps from the images. Once the DEM is produced, we can intersect the lines of pixels with it to determine the ground coordinates of all the pixels. This process accounts for relief distortion, as it compensates for the shift in pixel location based on its elevation. In orthorectification, DEM provides the elevation of a point, and the shift is calculated as a correction applied on the pixels of that location. The resulting image mosaics are called orthomosaics. If there is no DEM available, then a reference surface such as a sphere or ellipsoid approximating the size and position of the planet can be used to generate an unrectified mosaic. Most planetary mosaics, until recently, have been made this way and are not considered true orthophotos because they contain relief distortion.

If the exterior orientation parameters (i.e., camera location and attitude) were accurately known, simple intersection would be the only calculation required for orthorectification. If the exterior orientation parameters are only approximate, then the camera location will need to be adjusted to ensure that the image and the reference surface, or the DEM if available, are correctly aligned. To adjust the exterior orientation parameters, the camera location is assumed to be unknown. A set of points that are identifiable on both, the image as well as the planet surface, are then measured and the image coordinate $p(x,y)$, the object space coordinates, $P(X,Y,Z)$ are used to solve for the adjusted exterior orientation parameters. The object space coordinates are obtained from altimeter data of the planet, such as the Mars Orbiter Laser Altimeter (MOLA) and the Lunar Orbiter Laser Altimeter (LOLA). The process by which the exterior orientation parameters are adjusted, based on image measurements of known surface points, is called Bundle Adjustment.

1.5 Bundle Adjustment (Aerotriangulation)

To achieve bundle adjustment, image coordinates and the corresponding object space coordinates need to be measured for several points that are located in the overlapping areas of the planetary images. Aerotriangulation is the process of using all these measurements, and others, to be the input data for the bundle adjustment. There are three different kinds of points in aerotriangulation. Ground control points, GCP, are those points that have known object space coordinates, $P(X,Y,Z)$. Tie points are those points that are measured in two or more overlapping images with no object space coordinates available. Pass points are the same as tie points, but usually located on the side-lap of images. While such distinction between tie and pass points is more traditional in aerial photogrammetry than the in the planetary counterpart. The SOCET SET module for bundle adjustment (and resection) calculations is called MultiSensor Triangulation (MST). It is aided by Automatic Point measurement (APM) and Interactive Point Measurement (IPM) tools.

1.6 SOCET SET

The reason for using SOCET SET is that there are no comparable tools in ISIS at the present time. ISIS includes “jigsaw” (in ISIS3) and “randlsq” (in ISIS2) programs, which both include rudimentary automatic matching capabilities. In these two generations of ISIS, programs like “findrx,” “qmatch,” and “coreg” are used respectively to find reseaux (marks put on the focal plane of the TV cameras for calibrating distortions) some planetary image, such as Viking/Voyager images, for refining tie and pass point measurements, and for lining up images from different dates of different missions covering the same area.

These capabilities are intended to measure a rather sparse set of tie points, simply to ensure that overlapping images are properly aligned (or oriented) in relation to each other (hence called relative orientation). This procedure requires validation by the user to ensure that alignment is within the defined specifications. It is possible to generate DEMs with little more than these tools (by adding a layer of software to attempt matching at a dense grid of points) 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.

The bundle adjustment and matching modules are also more powerful in some ways than their ISIS equivalents; the matching error rate for SOCET SET ATE is likely to be well below that for the simpler ISIS matching algorithms, and that of the “next generation” ATE algorithm (NGATE) is expected to be even lower.

Astrogeology and the Planetary Cartography and Geologic Mapping Working Group (PCGMWG) concluded that acquiring a commercial photogrammetric production system, namely SOCET SET, offered advantages over trying to develop all photogrammetric capabilities in ISIS. ISIS is still critical to the overall workflow as it is used to ingest and calibrate the images in ISIS environment then pass the images to SOCET SET by using programs containing both ISIS and SOCET SET code. Although it is possible to produce maps in SOCET SET, it is preferred to pass the DEM data and orthorectified mosaics back to ISIS, ArcGIS, and Adobe Illustrator to do these final steps. Overall, Astrogeology’s approach to planetary mapping is the coupling of its in-house planetary image and cartographic processing package, i.e., ISIS with SOCET SET.

1.7 ISIS Processing Overview

ISIS and SOCET SET parallel each other in many respects: both import/export and processes images, have bundle-block adjustment capabilities, and produce cartographic products. Similar and differing functions are depicted in Figure 6. ISIS has mission-specific data ingestion and calibration software, along with a suite of special purpose application software, however it does not have stereo processing capabilities. While commercial off-the-shelf digital photogrammetric systems cannot handle most planetary data, software changes in only two areas are needed for them to do so: 1) input/output of planetary image data and supporting geometric information, and 2) in some cases, development of "sensor models" specifying the transformation between image lines/samples and object space for the variety of planetary sensors.

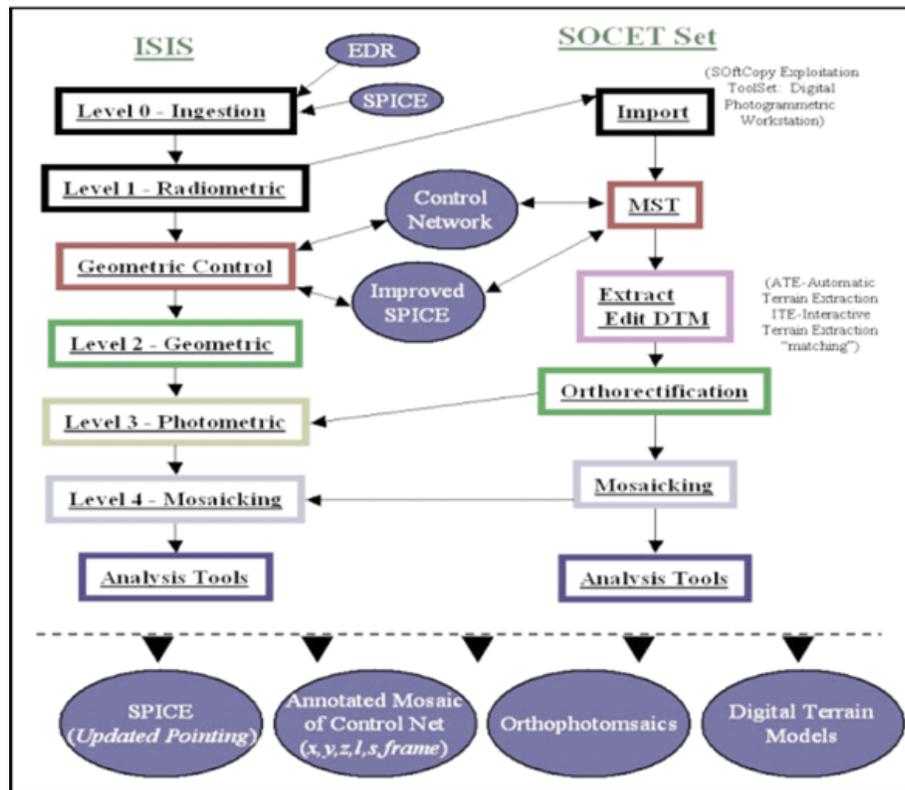


Figure 6 Flowchart of ISIS and SOCET SET for photogrammetric processing. Similar functionalities in both systems are coded with same colors.

1.8 SOCET SET Processing Overview

SOCET SET, along with specialized hardware provides many useful capabilities for mapping. These include functions such as import/export of common data formats, multi-sensor bundle-block adjustment, automatic extraction of digital topographic model (DTM) data, stereo display and interactive editing of DTMs, orthophoto generation and mosaicking, and image display and enhancement tools. These capabilities can be extended by programming with the SOCET SET Developer's Toolkit (DEVKIT). The Astrogeology Photogrammetry group has written programs to import planetary images and supporting data from ISIS into SOCET SET for stereo mapping. One of our goals for the next few years is to make it possible to use ISIS3 for all data sets for which we have developed a stereo processing capability. Newer sensors are generally processed and translated only in the ISIS3 system. At times, the unique properties of a sensor require the development of both translation software and a sensor model.

For pushbroom sensors, such as HiRISE, Astrogeology has determined (through processing multiple projects) that the SOCET SET Generic Pushbroom Sensor Model to be adequate. The generic framing camera sensor model supplied with SOCET SET functions with a wide variety of planetary framing cameras, including CCD, vidicon, and digitized film detector systems. In general, only synthetic aperture radar (SAR) imagers have required the development of custom sensor models.

1.9 Using DEM and Altimeter Track Points

For **planetary stereo imagery** stereo processing in SOCET SET, an appropriate geographic reference system is required, such as Geographic Coordinate system. As input parameters to a project in geographic coordinates, for instance in HiRISE, you will need an ographic latitude and positive east longitude reference point, and an approximate elevation range expected in the map area.

Additionally, to control a stereo pair to available DEM, the portion of the gridded data and the Altimeter Tracks that cover the project area are required. For example, in HiRISE, these datasets must also be in the ographic latitude and positive East longitude system. All the needed input parameters and DEM files based on the overlap area of the stereo pair can be obtained from various sources. In the case of HiRISE, simply run `hidata4socet.pl` from `<workdir>` as follows (**this will take an hour or two to run**):

1.10 Importing Images into SOCET SET

To import line scanner/pushbroom images into SOCET SET it requires running `import_pushbroom`. `import_pushbroom` will first import the raw image as a framing camera with unknown position and orientation. (This is a legacy approach when we ran ISIS and SOCET SET on the same platform and could not link to ISIS and SOCET SET libraries simultaneously.) Importing as a framing camera first converts the raw image into a format SOCET SET utilizes, creates a pyramid of reduced resolution images needed by SOCET SET,

and populates the Base-Sensor portion of a SOCET SET support file. (SOCET SET support files are detached image labels comprised of Base-Sensor keywords, followed by keywords specific to a sensor type, such as the generic pushbroom.) Once the images have been imported, import_pushbroom merges what we need from the support file created by the frame import, with the generic pushbroom keywords found in the *_keywords.lis file to create a generic pushbroom support file. Any framing camera support files are no longer needed and are deleted.

1.11 Creating a SOCET SET Project

For **generic planetary stereo imagery or HiRISE** stereo processing, create a project in Geographic Coordinates, using MARS2000 has the datum. For all SOCET SET projects, you must provide a rough estimate of the expected elevation range over the project area. Additionally, when working in Geographic Coordinates, you must enter a reference latitude and longitude coordinate (this is equivalent to the center_longitude and center_latitude of the equi-rectangular map projection.) The elevation range and reference latitude and longitude coordinate to enter can be found in the SOCET SET statistics file generated by hidata4socet.pl (in <workdir>/<ss_project_name>_SS_statistics.lis).

1.12 File Management

MST input files consist of an automatic triangulation file (*.atf), a ground point file (*.gpf), the support files of the images to be triangulated/adjusted (*.sup), and corresponding image point files (*.ipf) – one for each image.

When setting up MST, we are populating the *.atf file that contains links to the *.gpf, *.sup and *.ipf files, along with the image parameters we want to adjust. The *.gpf file and *.ipf files are populated as we measure image tie and control points. After points are measured, and a bundle adjustment is successfully performed, MST generates a report file (with the same name as the triangulation file, with a .rep extension.) If to save the adjustment solution, the *.sup, *.ipf, and *.gpf files are updated: The *.sup files are updated with the adjustments to the image parameters. The *.ipf files are updated with the image point errors. The *.gpf file is updated with ground point errors; additionally tie-points will have updated ground coordinates based on the new stereo geometry of the imagery.

Before controlling the images, it is strongly recommended to save a copy of the image support files in an 'original' directory/folder prior to making any adjustments. The support file contains the array of triangulation parameters adjusted for each image, and these values are used as the starting point for a subsequent adjustment. When making multiple adjustments, you can 'creep' to an invalid solution if you don't start from a fresh support file. This means that the current *.sup, *.ipf, and *.gpf files are corrupted and will cause any new bundle adjustment attempt to fail.

We suggest that after measuring points, but before solving for an adjustment, you exit MST and copy the original support files back into the project's main data folder. Then get back into MST and perform the Solve.

1.13 Multi-Sensor Triangulation (MST) Overview and Options

The purpose of MST is to perform “aerotriangulation” or “bundle adjustment” (the terms are equivalent) to improve the registration between overlapping images and between images and ground truth (or the planet's surface area being mapped). This is achieved by estimating improved values for parameters such as the position and pointing of the camera platform during imaging. Selected parameters (often only a subset of the total list of parameters available) are adjusted so as to minimize the sum of weighted and squared errors at image-to-image match points and image-to-ground tie points. The amounts by which the parameters are changed are also weighted and included in the formula to be minimized, in order to prevent the software from changing them more than a realistic amount.

1.14 Adjustable Parameters

MST permits each image to have a long list of adjustable parameters which can range from 18 to as many as 50 depending on the sensor model. Most of these parameter “slots” are normally unused. A few may be devoted to internal camera parameters such as focal length and distortion coefficients, in case it is necessary to improve these in flight (a process referred to as “self-calibration”). The key parameters are those that describe the position and pointing of the spacecraft during the time the image was taken.

For a framing camera, the position and pointing data consist of three numbers: the three coordinates of the position and three “camera angles” that fully describe where the spacecraft was positioned how it was oriented at the instant the image was exposed. Initial estimates of these values are stored in the image support file (.sup), and MST can calculate adjustments to any or all of them.

For a pushbroom camera like HiRISE, each image line is actually a tiny (one line high) frame image taken at a slightly different time. Thus, in principle, there must be three position and three pointing parameters for every image line. Fortunately for us, the pointing and especially the position of a spacecraft are usually smooth (but not always) functions of time, so we do not need to do the impossible job of solving for all these parameters. MST uses a kind of “reference history” of the trajectory (position) and pointing (described in terms of the direction of flight and the vertical) for the image that is stored in the support file. Adjustments to these reference histories are kept very simple. The trajectory can only be adjusted by a constant or a linear function of time in each of the three axes in-track (IT), cross-track (CT) and Radial (to the planet, i.e., vertical). Thus, the first three MST parameters are the IT, CT, and Radial position biases that act to shift the position at all image lines equally. The next three are IT, CT, and Radial velocity biases, which let the positions vary linearly with time. If these parameters are used, the position biases describe what happens at the time halfway between the start and end of the image.

Orientation angles are adjusted similarly but with a little more variation possible. For each axis of rotation relative to the nominal pointing, not only an angular bias and an angular velocity bias but also an angular acceleration bias is permitted. If this acceleration term is turned on, the pointing correction can vary quadratically with time. In all, there are thus nine orientation parameters. The rotation angles used to describe the pointing adjustment are called Omega, Phi, and Kappa, and they represent sequential rotations around the spacecraft axes that are roughly along the IT, CT, and Radial directions. **Thus, Omega represents rolling the spacecraft from side to side, Phi represents pitch, and Kappa a “twist” around the axis of the camera.**

There is a considerable degree of similarity between the effects of some of these parameters. For example, the CT bias acts to move the spacecraft, and thus ground point locations throughout the image, from side to side. Rolling the spacecraft (Omega bias) has much the same effect. Similarly, IT position bias and Phi rotation have similar effects of moving the image along track. For narrow-angle cameras like HiRISE the two effects are almost indistinguishable, so we generally use only one type of parameters and leave the others “turned off” or “frozen” by un-checking the appropriate check box in MST. The Radial position adjustment and Kappa (twist) adjustment have unique effects, so these are generally both used.

1.15 Weighting

For those parameters that we adjust in MST, we can specify an accuracy level. The software will generally try not to change the parameters by more than this amount (or at most a few times it). Setting the accuracy too small can prevent the image from adjusting as needed, which leaves the errors in the adjusted images almost as big as before MST was run. Somewhat paradoxically, relaxing the accuracy (so the parameters can adjust very freely) can also lead to large residual errors. This happens because there is no unique solution (especially if equivalent adjustments such as the CT bias and Omega angle are both turned on) so the MST process does not actually converge to an improved solution. Fortunately, the solution is relatively insensitive to the exact accuracy values over some middle range where they are “reasonable”. Appropriate values vary from mission to mission, but generally not from image to image. In the following pages, typical accuracy levels for HiRISE images are shown based on documentation about the accuracy of input SPICE data for the MRO mission and on practical experience.

For **generic planetary stereo imagery or HiRISE**, we recommend that the following image parameters be allowed to adjust by the amount accuracy values) shown.

Parameter	Accuracy
IT pos. bias	100 m
CT pos. bias	100 m
Radial pos. bias	10 m
IT vel. bias	13 m/s
CT vel. bias	13 m/s
Radial vel. bias	1.3 m/s
Kappa bias	0.1 deg

Basis of our Weighting (Accuracy) Criteria:

$\text{Sigma_vel} * \text{image_time_in_seconds} \sim \text{sigma_bias}$

$\text{Vel_adjust} * \text{image_time_in_seconds} \sim \text{bias_adjust}$

Where ~ means roughly similar, not hugely larger or hugely less

1.16 Relative and Absolute Orientations

For some studies, investigators may only need to measure the relative heights and distances of features - without the need to tie the measurements to ground (such as to MOLA in the HiRISE case, or LOLA in the LROC NAC case) elevations and positions. In this case, we only need to perform a relative orientation in which one image is adjusted relative to the other by measuring image tie points. In general, a relative orientation is a straightforward process that can be done in one adjustment. The resulting stereo model is free of y-parallax, but elevation and positional measurements are relative to the held image, NOT TO THE planet surface.

In order to make ground-truth coordinate and elevation measurements, we need to perform an *absolute orientation* in which both images are allowed to adjust by measuring vertical and horizontal ground points. For **generic planetary stereo imagery or HiRISE**, we derive vertical (z-only) control and horizontal (xy or xyz) control from the MOLA DEM and MOLA Track points. Absolute orientation is an involved and multi-step process because we need to derive control from MOLA products. The resulting stereo model is free of y-parallax, with elevation and positional measurements tied to MOLA heights and position.

Depending on available control information, and your choice for relative or absolute orientation, you will update image parameters for either one or both images:

For a relative orientation: set up MST so that the nadir-most image is held (turn off all adjustable parameters).

For the second image, allow the image parameters to adjust by the amounts listed above.

For an absolute orientation, set up MST to the image parameters of both images to adjust, by the amounts listed above.

1.16.1 Relative Orientation Point Picking and Solve

Set up MST for a relative orientation (details above). Use either IPM or APM to measure a set of tie points. You will need at least 9 points. Distribute the points in a 3xN pattern (3 across and N along the length of the stereo pair.) Avoid measuring points in high contrast areas with deep shadows because the image correlator will match on shadow edges rather than ground. Run Solve to do an adjustment. If the image RMS is under 0.6 pixel, save the solution, otherwise correct bad image measurements.

For the new SOCET SET user, step-by-step instructions for measuring image points will be provided at a later date. Until then, please refer to the most up-to-date SOCET SET User's Manual.

1.16.2 Absolute Orientation Point Picking and Solve

For absolute orientation we manually gather ground control information from MOLA DEM and Track data while measuring image points in IPM. While in IPM, SOCET SET now uses the coordinates in the *.gpf file as truth -- not the location based on the stereo geometry, so when querying the DEM for an elevation value, it will find the DEM post closest to the ground point file coordinate. This is OK if the coordinates are accurate, but *when collecting control points on the fly, the coordinates accrue substantial error.* (The location of the ground point is initialized at the location you clicked 'add point', which could be far away from where you decided to sample the point. Also, when independently adjusting one image to the other, SOCET SET continues to update its location, which compounds the error when adding each point.)

A Solution: As will be shown in the hands on part, multiple steps are used to build up to a ground point file with a combination of tie points, z-only control points, and at least one xyz-control point. In addition to using IPM in MST, you will also need the Interactive Terrain Edit (ITE) tool to query the DEM for elevation values, and the Feature Extraction tool to query the Altimeter track points for xyz- and z- coordinates. We have also found it useful to save input/output files for MST at each step in "input_step#" and "results_step#" folders so that we can easily restart at a prior step if needed, and use previous control solutions to aid with stereo viewing...keeping in mind that we need to compute a solution from unadjusted support files

Note that in some cases, there is not adequate MOLA TRACK data for horizontal control. Either the MOLA tracks are too sparse, or the terrain is too flat to tie a feature to an xy location. When this happens, we simply align the stereo model with the DEM (i.e., stop after step 1 below).

1.17 Compute ground coordinates of tie-points.

In this step, set up MST for a relative orientation and use IPM to measure a set of tie points in as many flat areas as possible. Distribute the points in a 3xN pattern (3 across and N along the length of the stereo pair, ~9000 pixels apart in the flight direction. (Tip: ~9000 pixels from the current cursor location can be estimated by displaying the images at 1:16 minification. Take note of features at the bottom edge of the display – this will be the location of the next horizontal line of points. Move the cursor to that horizontal “line”, and measure 3 points along it.) Measure a minimum of 24 points.

The goal is to convert as many of these tie-points to z-only control in Step 1, so when possible avoid steep slopes areas. Also avoid high contrast areas with deep shadows. Do an adjustment to update the coordinate of each point in the gpf file. If the image RMS is under 0.6 pixel, save the solution, otherwise correct bad image measurements. Load the images to view the results of the new solution. The stereo model should now be y-parallax free.

1.18 Control to the DEM (for vertical alignment):

In this step, start with the adjusted *.gpf and support files from Step 0 and go back into IPM. Also bring up ITE and load the DEM. Visit each tie point, and for those in flat areas, change the point to z-only and use the Post Editor in ITE to grab the DEM post closest to the tie point. Use the elevation of the post as the height estimate for the z-only point. Set the accuracy value of the points from 5 to 20 meters depending on the slope/terrain, and the quality of the DEM.

When finished gathering z-only points, Save the files and exit IPM. Exit MST. Exit ITE and *do not save changes to the DEM* when prompted to do so. Overwrite the support files in the project’s data directory with the backed up (original) versions. Bring up MST, load the current atf file, and Solve. If the image RMS is under 0.7 pixel, save the solution and exit MST. Load the images to view the results of the new solution. Drawing the DEM as contours should now align much better with the images.

1.19 Control to the Altimeter Track Points (for horizontal)

Use the adjusted gpf and support files from Step 1 and load the stereo pair. Bring up ITE, load the MOLA DEM and display it as 50 m or 100 m contours. Also bring up Feature Extraction (FE), load the MOLA track feature database and draw the points. Evaluate the alignment of the MOLA data with the stereo pair. It is likely that an XY shift applied to the image pair will result in a closer alignment with the MOLA track points. Look for elevation trends in the MOLA track data and stereo pair, and try to identify at least one MOLA point that aligns with a distinct feature (e.g., crater, ridge crest, etc). (These points are difficult to locate with high confidence, and most times only one point can be located.) Once you locate a distinguished MOLA point, select the point in FE and display its attributes. Record the values in the long_East, aerod_lat and

topography fields, and convert the lat/lon from decimal degrees to degrees-minutes-seconds. (Note, lat_North is the *ocentric* latitude of the point; aerod_lat is the *ographic* latitude needed by SOCET SET. 'Save the image load point' at this location to help relocate this point when you are in IPM. Now close FE and start MST. Bring up IPM and add a the new point. Press 'move to load point' to get you back to the point location, and measure this point as an xyz point with accuracy values of 5 meters for x and y, and 1 m for z. Save the files and exit IPM. Exit MST. Overwrite the support files in the project's data directory with the backed up (original) versions. Bring up MST, load the current *.atf file, and Solve. If the image RMS is under 0.7 pixel, save the solution and exit MST. Load the images to view the results of the new solution. Drawing the DEM track points should now align better with the images. If not, try another location for the xyz point, or a different altimeter track point.

1.20 Refine Z-Control to the Altimeter Track Points:

Finally, use the adjusted gpf and support files from Step 2 and re-load the stereo pair. Bring up Feature Extraction, load the Altimeter track feature database and draw the track data. Also bring up IPM. For tie points near Altimeter tracks, convert them to z-only points with the height gotten from the altimeter Track point coordinate (Also, relocate the point closer to the Altimeter track if need.) For Z-only points near MOLA tracks, update the heights based on the MOLA point coordinates (and move the point closer to the Altimeter Track if needed.) Set the z-accuracy of the refined points to 1 m or 2 m depending on terrain and proximity to MOLA track. Save the files and exit IPM. Exit MST. Overwrite the support files in the project's data directory with the backed up (original) versions. Bring up MST, load the current atf file, and Solve. If the image RMS is under 0.7 pixel, save the solution and exit MST. Load the images to view the results of the new solution.

NOTE: You cannot select and query Altimeter Track points in FE while IPM is running. IPM takes control of the extraction cursor and does not relinquish it to FE. You need to exit IPM and FE, and bring FE back up in order to select and query points. This is time consuming, so when refining z-control elevation estimates, it suffices to visually place the extraction cursor on the Altimeter Track point (at 4X zoom, with the image brightness set to 0 (black)), and cut-and-paste the elevation value displayed in the main SOCET SET frame. Remember to reset your image brightness.

1.21 Epipolar (Pairwise) Rectify Controlled Images

Epipolar rectification is used to enhance or enable stereo visualization of a stereo image pair. This rectification process:

- a) rotates the images so the epipolar (e.g., x-parallax) direction is horizontal, and
- b) scales the images to a common resolution.

Generally, SOCET SET can handle epipolar rectification on-the-fly (also referred to as Pairwise Rectification in the SOCET SET user's manual). However, for line-scanner stereo images, on-the-fly epipolar rectification does not work as expected when generating a DEM. Therefore, we need to generate epipolar (pairwise) rectified images of the stereo pair and supply them to NGATE and Adaptive ATE (AATE). (This is a known issue with BAE.)

1.22 Generate DEM

For **generic planetary stereo imagery**, both NGATE and AATE are used to generate a default 1 m/post DEM. In stereo pairs with substantial relief, and when the stereo images are controlled to the altimeter tracks, we use the approximate DEM (interpolated from the altimeter tracks) as a seed file. This closer approximation to ground-truth greatly increases success of the matcher. In stereo pairs of flat terrain, seeding with the DEM is not necessary.

We first run NGATE using a strategy file, such as `ngate_HIRISE.strategy` for HiRISE case (a modified version of `ngate_desert.strategy` (provided by BAE) to allow for 3-pixels of y-parallax), and seed with the MOLA DEM using `RSET64`. This is followed by a single pass AATE run to smooth the NGATE results. To prepare for AATE, make a copy of the NGATE results (either at the command line or with ITE), edit the new *.dth file to be compatible with AATE, and replace `<SS_install>\internal_dbs\DTM_STRATEGY\adapt.strat` with `<SS_install>\internal_dbs\DTM_STRATEGY\adapt.strat.onepassAfterNGATE` prior to running AATE. AATE only accepts 'adapt.strat' as the strategy file, hence the work around. *Save a backup copy of the original adapt.strat file prior to replacing it.*

NOTE 1: When using the output of one ATE run as input to a subsequent run, you must manually make changes to ATE parameters by editing the DEM header (*.dth file) in order to preserve the previous DEM results. Using the GUIs to make changes will force you to save the DEM, and doing so will re-initialize the DEM heights.

NOTE 2: Manually establish the DEM Boundary (i.e., do not use the image footprints), and make sure each DEM Boundary point is on the ground. For stereo pairs of flat terrain, 4 corner points plus 2 points halfway

done in the flight direction will suffice. For stereo pairs of steep terrain, measure a DEM Boundary point at 'major' min/max elevations (i.e., at the rim of a large crater, at the crater bottom, etc.) Establish the boundary within the stereo coverage by ~50 pixels. To estimate this distance, bring up the Cursor Editor (under Preferences), and change the Cursor size to 17. Move to where you want to place a boundary point, set the image minification to 4:1, aligned the cursor with the edge of the stereo coverage, then sample/measure the point.

1.23 Edit DEM

Use ITE to display and edit DEMs. What follows is our training guide for ITE. It is self-contained and steps you through loading a project, loading images, stereo display options needed for editing, setting graphical display and cursor preferences, ITE options and tips, and a FAQ section.

1.24 Generate Orthorectified Images

For **generic planetary stereo imagery**, we generate an orthoimage of each image in stereo pair at the nominal image resolution (0.25 m) and at the resolution of the DEM (1 m). Using the default lower left (LL) and upper right (UR) boundaries of an image when running orthophoto generation will result in an image that does not have a 1:1 correspondence with the DEM. This may cause problems when working with DEMs and orthoimages in software that does no georeferencing (such as photoshop). To alleviate this potential problem, we calculate LL and UR corner coordinates to be used as input for orthophoto generation.

Note: Generation of 1 m orthoimages takes 1 to 2 hours. Generation of 0.25 m orthoimages can take up to 12 hours each.

1.25 Export DEMs and Orthoimages to ISIS3

To export DEMs or Orthoimages from SOCET SET to ISIS3, the DEM/Orthoimage is converted to a raw-format file (*.raw) along with an ISIS3 script (*.sh) to convert the raw file to an ISIS3 cube with all georeferencing information. SOCET SET and ISIS use different approaches for scaling radii when working in geographic coordinates, so the scripts produce two versions of an ISIS cube for each SOCET SET product. The first version has a prefix of "SS_" and contains the native SOCET SET pixels. The second version (called 'standard' below) has the name of the DEM/Orthoimage specified by the user, and has had some resampling done to scale the pixels as ISIS expects them. **The user also has the option to output a 'layout' version of the cube – mainly used by USGS to generate page layouts of the DEMs and Orthoimages in ARCMAP. By default, the layout cubes will not be generated.**

1.26 Using HiRISE Planetary Stereo imagery as an Example for Stereo Processing Workflow

Tutorial	Section	ISIS3 Workstation
ISIS Processing		Download Balanced Cubes from University of Arizona
ISIS Processing		Evaluate for jitter and image quality
ISIS Processing		Generate noproj'ed images and pushbroom keywords via hi4socet.pl
ISIS Processing		Extract MOLA DEM and MOLA Track data for project area via hidata4socet.pl
SocetSet Processing	2	Create SS project
SocetSet Processing	3	Transfer raw image files, pushbroom keyword files, MOLA DEM and MOLA Track data to SS Machine
SocetSet Processing	4,5	Import images via import_pushbroom
SocetSet Processing	6	Import MOLA DEM
SocetSet Processing	7	Import MOLA Tracks
SocetSet Processing	8,9	Control Images (Multi-Sensor Triangulation):
SocetSet Processing	10	Generate epipolar rectified images
SocetSet Processing	11	Generate DEM
SocetSet Processing	12	Edit DEM
SocetSet Processing	13	Generate Orthoimages with input from calcOrthoBdry
SocetSet Processing	14	Export DEM to raw data file and ISIS3 script via dem2isis3
ISIS Processing		Export Orthoimages to raw image file and ISIS3 script via ortho2isis3
ISIS Processing		Transfer raw DEM, raw Orthoimages and ISIS3 corresponding ISIS3 processing scripts to ISIS machine
ISIS Processing		Generate ISIS3 cubes of DEM via ISIS3 script *_dem2isis3.sh
ISIS Processing		Generate ISIS3 cubes of Orthoimages via ISIS3 script *_ortho2isis3.sh

1.27 Table of Abbreviations

AATE	Adaptive Automatic Terrain Extraction
ATE	Automatic Terrain Extraction
APM	Automatic Point Measurement
ATE	Automatic Terrain Extraction
DEM	Digital Elevation Model
DTM	Digital Terrain Model
FDB	Feature Database
FE	Feature Extraction
GSD	Ground Sample Distance
HiRISE	High Resolution Imaging Science Experiment
ISIS	Integrated Software for Imagers and Spectrometers
ITE	Interactive Terrain Edit
IPM	Interactive Point Measurement
MOLA	Mars Orbiter Laser Altimeter
MST	Multi-Sensor Triangulation
NGATE	Next Generation Automatic Terrain Extraction
PCGMWG	Planetary Cartography and Geologic Mapping Working Group
PEDR	Precision Experiment Data Records
SOCET SET	SOfCopy Exploitation Tool Set
SS	SOCET SET
TIN	Triangular Irregular Network

1.28 Disclaimers

Trademarks and Trade-names

Any use of trade, product, or firm names in this document is for descriptive purposes only and does not imply endorsement by the U.S. Government.

ISIS Warranty

Although ISIS has been used by the USGS, no warranty, expressed or implied, is made by the USGS as to the accuracy and functioning of such software and related material nor shall the fact of distribution constitute any such warranty, and no responsibility is assumed by the USGS in connection therewith.

Preliminary Content

Please note that some information provided in this document may be preliminary in nature. This information is provided with the understanding that it is not guaranteed to be complete, and conclusions drawn from such information are the responsibility of the user.

1.29 Additional Resources

SOCET_SET_for_HiRISE_June2009.ppt provided in TUTORIALS_JUNE2009.zip at <http://webgis.wr.usgs.gov/pigwad/tutorials/socetset/SocetSet4HiRISE.htm>. This is an updated version of the "SOCET SET for HiRISE" PowerPoint presentation from our first training session held in October, 2007. Updates reflect our current software and procedures, but supplements this tutorial by providing some background about HiRISE and why we do the processing we do. Also includes tips on using Difference-of-Gaussian images to produce DEMs in bland areas, and more.

1.30 Additional peer-reviewed papers on stereo mapping:

Heipke, C., Oberst, J., Albertz, J., Attwenger, M., Dorninger, P., Dorrer, E., Ewe, M., Gehrke, S., Gwinner, K., Hirschmüller, H., Kim, J.R., Kirk, R.L., Mayer, H., Muller, J.-P., Rengarajan, R., Rentsch, M., Schmidt, R., Scholten, F., Shan, J., Spiegel, M., Wählisch, M., Neukum, G., and the HRSC Co-Investigator Team, 2007, Evaluating planetary digital terrain models: The HRSC DTM Test, *Planet. Space Sci.*, 55, p. 2173–2191, doi:10.1016/j.pss.2007.07.006.

Kirk, R.L., Howington-Kraus, E., Redding, B.L., Becker, T.L., Lee, E.M., Stiles, B.W., Hensley, S., Hayes, A.G., Lopes, R.M.C., Lorenz, R.D., Mitchell, K.L., Radebaugh, J., Paganelli, F., Soderblom, L.A., Stofan, E.R., Wall, S.D., Wood, C.A., Elachi, C., and the Cassini RADAR Team, 2009, Three-Dimensional Views of Titan's Diverse Surface Features from Cassini RADAR Stereogrammetry, *Icarus*, in revision.

Kirk, R. L., Howington-Kraus, E., Soderblom, L. A., Giese, B., and Oberst, J., 2004, Comparison of USGS and DLR topographic models of Comet Borrelly and photometric applications, *Icarus*, 167, pp. 54–69, doi:10.1016/j.icarus.2003.07.009.

Kirk, R. L., Howington-Kraus, E., Redding, B., Galuszka, D., Hare, T. M., Archinal, B. A., Soderblom, L. A., and Barrett, J. M., 2003, High-resolution topomapping of candidate MER landing sites with Mars Orbiter Camera Narrow-Angle images, *J. Geophys. Res.*, 108 (E12), 8088, doi:10.1029/2003JE002131.

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Rosiek, M. R., Kirk, R. L., Archinal, B. A., Howington-Kraus, E., Hare, T., Galuszka, D., and Redding, B., 2005, Utility of Viking Orbiter Images and Products for Mars Mapping, *Photogrammetric Engineering & Remote Sensing*, 71 (10), 1187–1196.

Soderblom, L., Tomasko, M., Archinal, B., Becker, T., Bushroe, M., Cook, D., Doose, L., Galuszka, L., Hare, T., Howington-Kraus, A., Karkoschka, E., Kirk, R., Lunine, J., McFarlane, E., Redding, B., Rizk, B., Rosiek, M., See, C., and Smith, P., 2007, Topography and geomorphology of the Huygens landing site on Titan, *Planet. Space Sci.*, 55, 2015–2024, doi:10.1016/j.pss.2007.04.015.

Conference papers on topics not yet published in journals:

Kirk, R.L., and Howington-Kraus, E., 2008, Radargrammetry on three planets, *International Archives of Photogrammetry, Remote Sensing, and Spatial Information Sciences*, XXXVII, Part 4, "A Silk Road for Information from Imagery", Beijing, 3–11 July, 2008, pp. 973–980 (DVD-ROM).

Howington-Kraus, E., Kirk, R.L., Galuszka, D., and Redding, B., 2006, USGS Magellan stereomapping of Venus, *International Archives of Photogrammetry, Remote Sensing, and Spatial Information Sciences*, XXXVI, Part 4, "Geospatial Databases for Sustainable Development", Goa (CD-ROM).

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Abstracts on topics not published in conference papers:

Kirk, R. L., Duxbury, T. C., Hörz, F., Brownlee, D. E., Newburn, R. L., Tsou, P. and the Stardust Team, 2005, Topography of the 81P/Wild 2 Nucleus derived from Stardust Stereoimages, *Lunar Planet. Sci.*, XXXVI, Abstract #2244, Lunar and Planetary Institute, Houston (CD-ROM).

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