The Ames Stereo Pipeline:

NASA's Open Source Automated Stereogrammetry Software

A part of the NASA NeoGeography Toolkit

Version 2.1.0

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Credits

This open source version of the Ames Stereo Pipeline (ASP) was developed by the Intelligent Robotics Group (IRG), in the Intelligent Systems Division at the National Aeronautics and Space Administration (NASA) Ames Research Center in Moffett Field, CA. It builds on over ten years of IRG experience developing surface reconstruction tools for terrestrial robotic field tests and planetary exploration.

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Any opinions, findings, and conclusions or recommendations expressed in this documentation are those of the authors and do not necessarily reflect the views of the National Aeronautics and Space Administration.

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Chapter 1

Introduction

The NASA Ames Stereo Pipeline (ASP) is a suite of automated geodesy and stereogrammetry tools designed for processing planetary imagery captured from orbiting and landed robotic explorers on other planets. It was designed to process stereo imagery captured by NASA spacecraft and produce cartographic products including digital elevation models (DEMs), ortho-projected imagery, and 3D models. These data products are suitable for science analysis, mission planning, and public outreach.

1.1 Background

The Intelligent Robotics Group (IRG) at the NASA Ames Research Center has been developing 3D surface reconstruction and visualization capabilities for planetary exploration for more than a decade. First demonstrated during the Mars Pathfinder Mission, the IRG has delivered tools providing these capabilities to the science operations teams of the Mars Polar Lander (MPL) mission, the Mars Exploration Rover (MER) mission, the Mars Reconnaissance Orbiter (MRO) mission, and most recently the Lunar Reconnaissance Orbiter (LRO) mission. A critical component technology enabling this work is the Ames Stereo Pipeline (ASP). The Stereo Pipeline generates high quality, dense, texture-mapped 3D surface models from stereo image pairs.

Although initially developed for ground control and scientific visualization applications, the Stereo Pipeline has evolved in recent years to address orbital stereogrammetry and cartographic applications. In particular, long-range mission planning requires detailed knowledge of planetary topography, and high resolution topography is often derived from stereo pairs captured from orbit. Orbital mapping satellites are sent as precursors to planetary bodies in advance of landers and rovers. They return a wealth of imagery and other data that helps mission planners and scientists identify areas worthy of more detailed study. Topographic information often plays a central role in this planning and analysis process.

Our recent development of the Stereo Pipeline coincides with a period of time when NASA orbital mapping missions are returning orders of magnitude more data than ever before. Data volumes from the Mars and Lunar Reconnaissance Orbiter missions now measure in the tens of Terabytes. There is growing consensus that existing processing techniques, which are still extremely human intensive and expensive, are no longer adequate to address the data processing needs of NASA and the Planetary Science community. To pick an example of particular relevance, the High Resolution Imaging Science Experiment (HiRISE) instrument has captured a few thousand stereo pairs. Of these, only about a hundred stereo pairs have been processed to date; mostly on human-operated, high-end photogrammetric workstations. It is clear that much more value could be extracted from this valuable raw data if a more streamlined, efficient process could be developed.

The Stereo Pipeline was designed to address this very need. By applying recent advances in robotics and computer vision, we have created an *automated* process that is capable of generating high quality DEMs

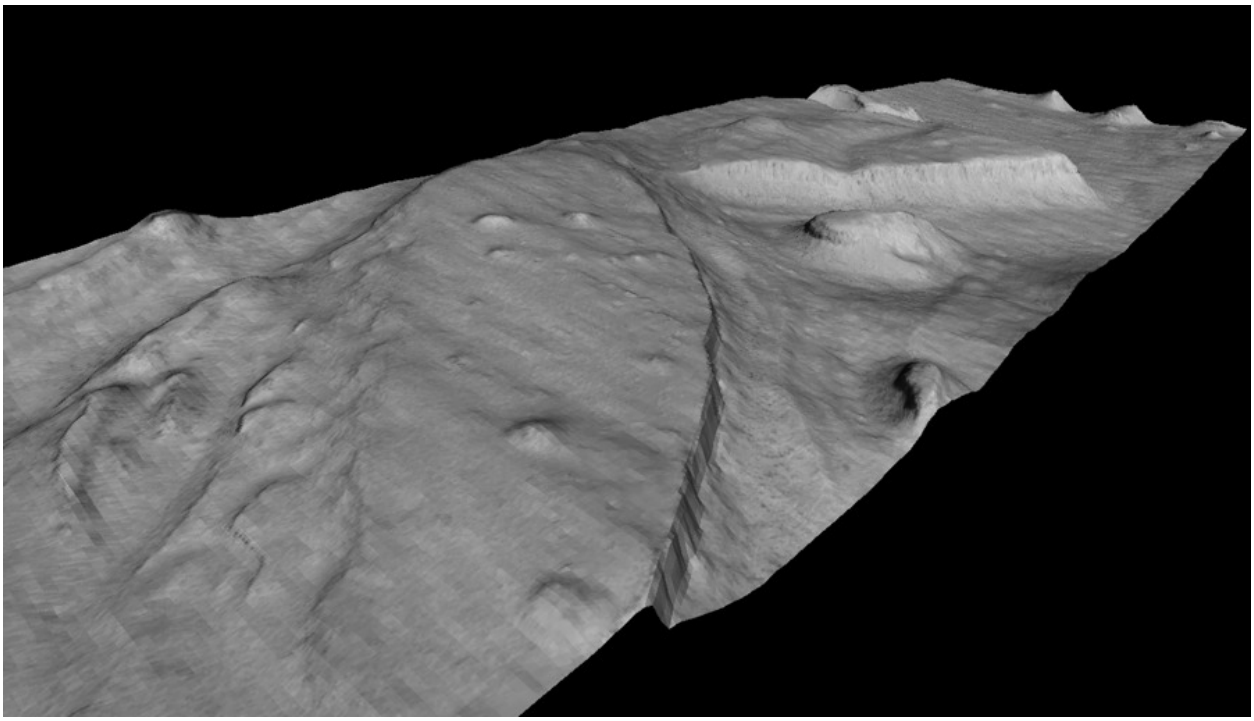


Figure 1.1: This 3D model was generated from a Mars Orbiter Camera (MOC) image pair M01/00115 and E02/01461 (34.66N, 141.29E). The complete stereo reconstruction process takes approximately thirty minutes on a 3.0 GHz workstation for input images of this size (1024 × 8064 pixels). This model, shown here without vertical exaggeration, is roughly 2 km wide in the cross-track dimension.

with minimal human intervention. Users of the Stereo Pipeline can expect to spend some time picking a handful of settings when they first start processing a new type of imagery, but once this is done the Stereo Pipeline can be used to process tens, hundreds, or even thousands of stereo pairs without further adjustment. With the release of this software, we hope to encourage the adoption of this tool chain at institutions that run and support these remote sensing missions. Over time, we hope to see this tool incorporated into ground data processing systems alongside other automated image processing pipelines. As this tool continues to mature, we believe that it will be capable of producing digital elevation models of exceptional quality without any human intervention.

1.2 Human vs. Computer: When to Choose Automation

When is it appropriate to choose automated stereo mapping over the use of a conventional, human-operated photogrammetric workstation? This is a philosophical question with an answer that is likely to evolve over the coming years as automated data processing technologies become more robust and widely adopted. For now, our opinion is that you should *always* rely on human-guided, manual data processing techniques for producing mission critical data products for missions where human lives or considerable capital resources are at risk. In particular, maps for landing site analysis and precision landing absolutely require the benefit of an expert human operator to eliminate obvious errors in the DEM; and also to guarantee that the proper procedures have been followed to correct satellite telemetry errors so that the data have the best possible geodetic control.

When it comes to using DEMs for scientific analysis, both techniques have their merits. Human-guided stereo reconstruction produces DEMs of unparalleled quality that benefit from the intuition and experience of an expert. The process of building and validating these DEMs is well established and accepted in the

scientific community.

However, only a limited number of DEMs can be processed to this level of quality. For the rest, automated stereo processing can be used to produce DEMs at a fraction of the cost. The results are not necessarily less accurate than those produced by the human operator, but they will not benefit from the same level of scrutiny and quality control. As such, users of these DEMs must be able to identify potential issues, and be on the lookout for errors that may result from the improper use of these tools.

We recommend that all users of the Stereo Pipeline take the time to thoroughly read this documentation and build an understanding of how stereo reconstruction and bundle adjustment can be best used together to produce high quality results. Please don't hesitate to contact us if you have any questions!

1.3 Software Foundations

1.3.1 NASA Vision Workbench

The Stereo Pipeline is built upon the Vision Workbench software which is a general purpose image processing and computer vision library also developed by the IRG. Some of the tools discussed in this document are actually Vision Workbench programs, but any distribution of the Stereo Pipeline requires the Vision Workbench. Unless you're compiling the Vision Workbench and Stereo Pipeline from source, the distinctions probably won't matter to you.

1.3.2 The USGS Integrated Software for Imagers and Spectrometers

This version of the Stereo Pipeline must be installed alongside a copy of United States Geological Survey (USGS) Integrated Software for Imagers and Spectrometers (ISIS) if you wish to process NASA satellite imagery. ISIS is widely used in the planetary science community for processing raw spacecraft imagery into high level data products of scientific interest such as map projected and mosaicked imagery [1, 10, 28]. We chose ISIS because (1) it is widely adopted by the planetary science community, (2) it contains the authoritative collection of geometric camera models for planetary remote sensing instruments, and (3) it is open source software that is easy to leverage.

By installing the Stereo Pipeline, you will be adding an advanced stereo image processing capability that can be used in your existing ISIS work flow. The Stereo Pipeline supports the ISIS "cube" (`.cub`) file format, and can make use of the ISIS camera models and ancillary information (i.e. SPICE kernels) for imagers on many NASA spacecraft. The use of this single standardized set of camera models ensures consistency between products generated in the Stereo Pipeline and those generated by ISIS. Also by leveraging ISIS camera models, the Stereo Pipeline can process stereo pairs captured by just about any NASA mission.

As an additional note, the Stereo Pipeline can also process arbitrary, non-ISIS images with accompanying camera information, but doing so requires a significant amount of extra work and setup. This advanced use of the software is not covered in this user's manual, however feel free to contact us if you are interested in learning more about adapting the pipeline to other stereo data sets.

1.4 Getting Help

All bugs, feature requests, and general discussion should be sent to the Ames Stereo Pipeline user mailing list:

stereo-pipeline@lists.nasa.gov

To subscribe to this list, send an empty email message with the subject 'subscribe' (without the quotes) to:

stereo-pipeline-request@lists.nasa.gov

To contact the lead developers and project manager directly, send mail to:

stereo-pipeline-owner@lists.nasa.gov

1.5 Typographical Conventions

Names of programs that are meant to be run on the command line are written in a constant-width font, like the `stereo` program, as are options to those programs.

An indented line of constant-width text can be typed into your terminal, these lines will either begin with a '`>`' to denote a regular shell, or with '`ISIS`' which denotes an ISIS-enabled shell (which means you have to set the `ISISROOT` environment variable and sourced the appropriate ISIS 3 Startup script, as detailed in the ISIS 3 instructions).

```
> ls

ISIS 3> pds2isis
```

Italicized constant-width text denotes an option or argument that a user will need to supply. For example, '`stereo E0201461.map.cub M0100115.map.cub out`' is specific, but '`stereo` *`left-image right-image`* `out`' indicates that *`left-image`* and *`right-image`* are not the names of specific files, but dummy parameters which need to be replaced with actual file names.

Square brackets denote optional options or values to a command, and items separated by a vertical bar are either aliases for each other, or different, specific options. Default arguments are prefixed by an equals sign within parentheses, and line continuation with a backslash:

```
point2dem [--help|-h] [-r moon|mars] [-s float(=0)] \
          [-o output-filename] pointcloud-PC.tif
```

The above indicates a run of the `point2dem` program. The only argument that it requires is a point cloud file, which is produced by the `stereo` program and ends in `-PC.tif`, although its prefix could be anything (hence the italics for that part). Everything else is in square brackets indicating that they are optional.

Both `--help` and `-h` are really the same thing (both will get you help). Similarly, the argument to the `-r` option must be either `moon` or `mars`. The `-s` option takes a floating point value as its argument, and has a default value of zero. The `-o` option takes a filename that will be used as the output DEM.

Although there are two lines of constant-width text, the backslash at the end of the first line indicates that the command continues on the second line. You can either type everything into one long line on your own terminal, or use the backslash character (or appropriate line continuation character) and a return to continue typing on a second line in your terminal.

1.6 Referencing the Ames Stereo Pipeline in your own work

Although no peer-reviewed paper or report yet exists which details the Ames Stereo Pipeline (see the warning below about this being **RESEARCH** software), if you do use this software in your work, we'd appreciate it if you referenced one or more of these abstracts:

Moratto, Z. M., M. J. Broxton, R. A. Beyer, M. Lundy, and K. Husmann. 2010. Ames Stereo Pipeline, NASA's Open Source Automated Stereogrammetry Software. *Lunar and Planetary Science Conference* **41**, abstract #2364. [ADS Abstract].

Broxton, M. J. and L. J. Edwards. 2008. The Ames Stereo Pipeline: Automated 3D Surface Reconstruction from Orbital Imagery. *Lunar and Planetary Science Conference* **39**, abstract #2419. [ADS Abstract].

1.7 Warnings to users of the Ames Stereo Pipeline

Ames Stereo Pipeline is a **RESEARCH** product. There are known bugs and incomplete features. We reserve the ability to change the API and command line options of the tools we provide. Some of the documentation is incomplete and some of it may be out of date or incorrect. Although we hope you will find this release helpful, you use it at your own risk. Please check each release's **NEWS** file to see a summary of our recent changes.

While we are confident that the algorithms used by this software are robust, they have not been systematically tested or rigorously compared to other methods in the peer-reviewed literature. We have a number of efforts underway to carefully compare Stereo Pipeline-generated data products to those produced using established processes, and we will publish those results as they become available. In the meantime, **we strongly recommend that you consult us first before publishing any results based on the cartographic products produced by this software**. You have been warned!

Part I

Getting Started

Chapter 2

Installation

2.1 Binary Installation

This is the recommended method. Only the Stereo Pipeline binaries are required. ISIS is required only for users who wish to process NASA non-terrestrial imagery. A full ISIS installation is no longer required for operation of Stereo Pipeline programs (only the ISIS data directory is needed), but is required for certain preprocessing steps before Stereo Pipeline programs are run for planetary data. If you only want to process terrestrial Digital Globe imagery, skip to section 2.1.2.

Stereo Pipeline Tarball.
The main Stereo Pipeline page is http://irg.arc.nasa.gov/ngt/stereo. Download the *Binary* option that matches the platform you wish to use. The recommend, but optional, ISIS version is listed next to the name; choose the newest version you have available.

USGS ISIS.
The Stereo Pipeline optionally depends on ISIS version 3 from the USGS. For processing planetary data, processing steps with ISIS programs are needed prior to running Stereo Pipeline. However, this processing could be done on a completely separate machine. Stereo Pipeline itself uses ISIS internally, but the Stereo Pipeline binaries now have a self-contained version of ISIS (meaning that Stereo Pipeline itself doesn't depend on a particular version of ISIS installed on your computer). So while the Stereo Pipeline binary programs don't depend on a local ISIS installation, they will need access to an ISIS data directory (if working with planetary data).

If you are working with planetary missions, you will need to install ISIS so that you can perform preprocessing. Their installation guide is at http://isis.astrogeology.usgs.gov/documents/InstallGuide. You must use their binaries as-is; if you need to recompile, you must follow the *Source Installation* guide for the Stereo Pipeline in Section 2.2. Note also that the USGS provides only the current version of ISIS and the previous version (denoted with a '`_OLD`' suffix) via their `rsync` service. If the current version is newer than the version of ISIS that the Stereo Pipeline is compiled against, be assured that we're working on rolling out a new version. However, since Stereo Pipeline has its own self-contained version of ISIS, as long as there aren't major differences, you should be able to use a slightly newer version of ISIS to preprocess your data, and then still get good results with the Stereo Pipeline binaries. If not, you should be able to sync the previous version of ISIS which should work with Stereo Pipeline. To do so, view the listing of modules that is provided via the '`rsync isisdist.astrogeology.usgs.gov::`' command. You should see several modules listed with the '`_OLD`' suffix. Select the one that is appropriate for your system, and `rsync` according to the instructions.

The Stereo Pipeline should be able to work with data from newer versions of ISIS than it was built against as long as the ISIS cube format hasn't changed. Running the Stereo Pipeline executables only requires that you have downloaded the ISIS secondary data and have appropriately set the `ISIS3DATA` environment variable. This is normally performed for the user by ISIS's startup script, `$ISISROOT/scripts/isis3Startup.sh`.

2.1.1 Quick Start for ISIS users

Fetch Stereo Pipeline
Download the Stereo Pipeline from http://irg.arc.nasa.gov/ngt/stereo.

Fetch ISIS Binaries
As detailed at http://isis.astrogeology.usgs.gov/documents/InstallGuide.

Fetch ISIS Data
As detailed at http://isis.astrogeology.usgs.gov/documents/InstallGuide.

Untar Stereo Pipeline
`tar xzvf StereoPipeline-`*`VERSION-ARCH-OS`*`.tar.gz`

Add Stereo Pipeline to Path (optional)
bash: `export PATH="`*`/path/to/StereoPipeline`*`/bin:${PATH}"`
csh: `setenv PATH "`*`/path/to/StereoPipeline`*`/bin:${PATH}"`

Set Up ISIS
bash:
```
export ISISROOT=/path/to/isisroot
source $ISISROOT/scripts/isis3Startup.sh
```
csh:
```
setenv ISISROOT /path/to/isisroot
source $ISISROOT/scripts/isis3Startup.csh
```

Try It Out!
See the next chapter (Chapter 3) for an example.

2.1.2 Quick Start for Digital Globe users

Fetch Stereo Pipeline
Download the Stereo Pipeline from http://irg.arc.nasa.gov/ngt/stereo.

Untar Stereo Pipeline
`tar xvfz StereoPipeline-`*`VERSION-ARCH-OS`*`.tar.gz`

Try It Out!
This documentation hasn't been finished yet. However your imagery needs to be converted to the GeoTIFF format before ASP can read it. ASP doesn't have native support for NITF that uses an underlying JPEG2000 compression.

Once converted, the command line arguments to `stereo` look like the following:
`stereo` *`left-image right-image left-xml right-xml output-prefix`*

The settings discussed in the next chapter (Chapter 3) apply to Digital Globe sessions as well. However the example requires ISIS to be installed inorder to run. This may or may not be worth your time to install.

2.1.3 Common Traps

Here are some errors you might see, and what it could mean. Treat these as templates for problems. In practice, the error messages might be slightly different.

```
**I/O ERROR** Unable to open [$ISIS3DATA/Some/Path/Here].
Stereo step 0: Preprocessing failed
```

You need to set up your ISIS environment or manually set the correct location for `ISIS3DATA`.

```
point2mesh E0201461-M0100115-PC.tif E0201461-M0100115-L.tif
[...]
99%  Vertices:   [************************************************************] Complete!
       > size: 82212 vertices
Drawing Triangle Strips
Attaching Texture Data
zsh: bus error  point2mesh E0201461-M0100115-PC.tif E0201461-M0100115-L.tif
```

The source of this problem is an old version of OpenSceneGraph in your library path. Check your `LD_LIBRARY_PATH` (for Linux), `DYLD_LIBRARY_PATH` (for OSX), or your `DYLD_FALLBACK_LIBRARY_PATH` (for OSX) to see if you have an old version listed, and remove it from the path if that is the case. It is not necessary to remove the old versions from your computer, you just need to remove the reference to them from your library path.

2.2 Source Installation

This method is for advanced users with moderate build system experience. Some dependencies such as ISIS and its dependencies *(like SuperLU, Qwt, CSpice)* use their own custom build systems. Due to the complex nature of the dependent software, we can't help you with questions about those libraries.

In order to compile and build your own version of Stereo Pipeline you will need the source code. The binary distribution that we provide does not provide this. The source code for Stereo Pipeline is available from Github at https://github.com/NeoGeographyToolkit/StereoPipeline.

2.2.1 Dependency List

This is a list of the prime dependencies of Stereo Pipeline. Some libraries (like ISIS and Vision Workbench (VW)) have dependencies of their own which are not covered here.

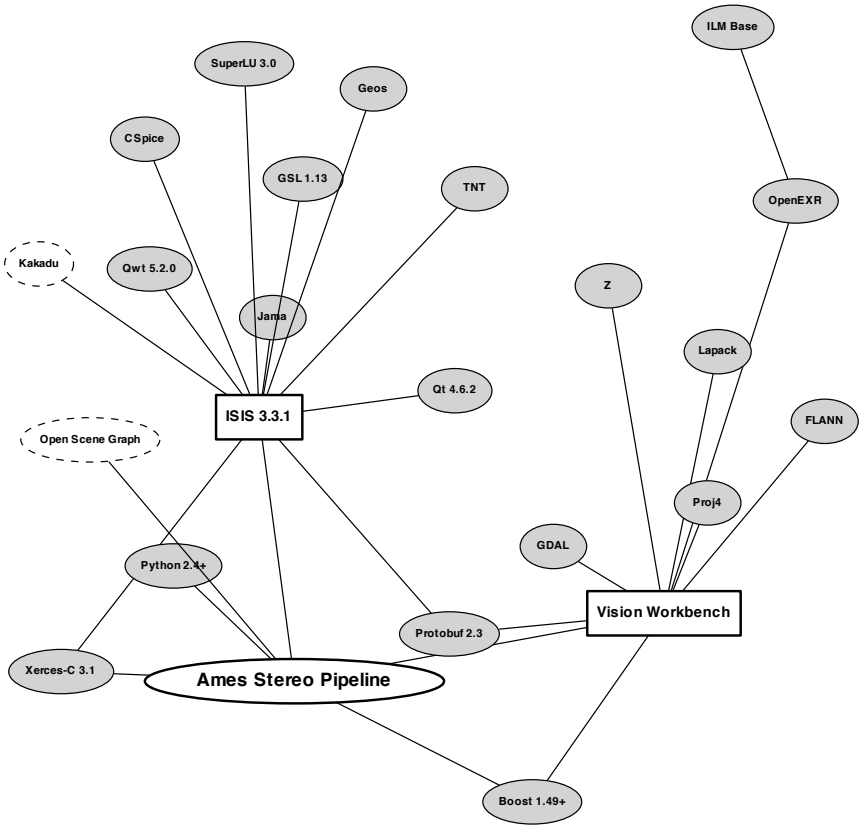


Figure 2.1: Graph outlining some dependencies. Not all of ISIS's are shown.

Boost (Required) http://www.boost.org/
Version 1.46 or greater is required. Along with the base library set, the Stereo Pipeline specifically requires: Program Options, Filesystem, Thread, and Graph.

GDAL (Recommended) http://www.gdal.org
GDAL handles most of the File IO for Ames Stereo Pipeline. It also provides support for the ingestion

of proj4 strings from the user. This is required if you wish to support the BigTIFF format and write files larger that 4GB.

ISIS (Recommended) http://isis.astrogeology.usgs.gov/documents/InstallGuide
The USGS Integrated Software for Imagers and Spectrometers (ISIS) library. This library handles the camera models and image formats used for instruments. ISIS is usually downloaded and used as a binary distribution. Compilation of ISIS from source can be challenging, and their support forums may provide assistance: https://isis.astrogeology.usgs.gov/IsisSupport/. Cleaning and modification of their source code may be required if you would like to use a newer version of ISIS's dependencies than may be available on your system.

ISIS is a complex suite of software to build from source, it is not recommended that users try to build ISIS themselves. Even though ISIS provides pre-compiled libraries, not all of the headers are included.

LAPACK (Required)
There are many sources for LAPACK. For OSX, you can use the vecLib framework. For Linux, you can use the netlib LAPACK/CLAPACK distributions, or Intel's MKL, or any of a number of others. The math is unfortunately not a hotspot in the code, though, so using a faster LAPACK implementation will not change much. Therefore, you should probably just use the LAPACK your package manager (RPM for Red Hat Linux, Yast for SuSE, etc.) has available.

OpenSceneGraph (Optional) http://www.openscenegraph.org/
OpenSceneGraph is required to run the `point2mesh` tool (See Section A.4). This library provides a convenient way of building OpenGL graphics through the method of scene graphs. It also provides a file format and utilities for display these scene graphs. The output file of `point2mesh` is an OpenSceneGraph binary scene graph format.

Python 2.4+ (Required) http://www.python.org
Some applications of Stereo Pipeline are python scripts. Python provides a friendly enviroment that hopefully encourages users to attempt modifications of their own.

Vision Workbench (Required) http://ti.arc.nasa.gov/visionworkbench/
Vision Workbench forms much of the core processing code of the Stereo Pipeline. Vision Workbench contains almost all of the image processing algorithms, such as image filters, image arithmetic, stereo correlation, and triangulation. This means that Stereo Pipeline is just a collection of applications that implement Vision Workbench in the context of ISIS.

2.2.2 Build System

The build system is built on GNU autotools. In-depth information on autotools is available from http://sources.redhat.com/autobook/. The basics, however, are simple. To compile the source code, first run `./configure` from the top-level directory. This will search for the dependencies and enable the modules you requested. There are a number of options that can be passed to `configure`; many of these options can also be placed into a `config.options` file (in the form of `VARIABLE="VALUE"`) in the same directory as `configure`. Table 2.2 lists the supported options.

Variable Name	Configure option	Default	Function
PREFIX	--prefix	/usr/local	Set the install prefix (ex: binaries will go in $PREFIX/bin)
HAVE_PKG_XXX	--with-xxx	auto	Set to "no" to disable package XXX, or a path to only search that path
PKG_PATHS	--with-pkg-paths	many	Prepend to default list of search paths
ENABLE_PKG_PATHS_DEFAULT	--enable-pkg-paths-default	yes	Append built-in list of search paths
ENABLE_OPTIMIZE	--enable-optimize	3	Level of compiler optimization?
ENABLE_DEBUG	--enable-debug	no	How much debug information?
ENABLE_CCACHE	--enable-ccache	no	Use `ccache` if available
ENABLE_RPATH	--enable-rpath	no	Set RPATH on built binaries and libraries
ENABLE_ARCH_LIBS	--enable-arch-libs	no	Pass in 64 or 32 to look for libraries by default in `lib64` or `lib32`
ENABLE_PROFILE	--enable-profile	no	Use function profiling?
PKG_XXX_CPPFLAGS			Append value to CPPFLAGS for package XXX
PKG_XXX_LDFLAGS			Prepend value to LDFLAGS for package XXX
PKG_XXX_LIBS			Override the required libraries for package XXX
PKG_XXX_MORE_LIBS			Append to required libraries for package XXX
ENABLE_EXCEPTIONS	--enable-exceptions	yes	Use C++ exceptions? Disable at own risk.
ENABLE_MULTI_ARCH	--enable-multi-arch	no	OSX Only: Build *Fat* binary with space-separated list of arches
ENABLE_AS_NEEDED	--enable-as-needed	no	Pass –as-needed to GNU linker. Use at your own risk.

Table 2.2: Supported configure options

2.3 Settings Optimization

Finally the last thing to be done for Stereo Pipeline is to setup up Vision Workbench's render settings. This step is optional, but for best performance some thought should be applied here.

Vision Workbench is a multithreaded image processing library used by Stero Pipeline. The settings by which Vision Workbench processes is configurable by having a `.vwrc` file hidden in your home directory. Below is an example.

```
# This is an example VW log configuration file. Save
# this file to ~/.vwrc to adjust the VW log
# settings, even if the program is already running.
#
# The following integers are associated with the
# log levels throughout the Vision Workbench.  Use
# these in the log rules below.
#
#    ErrorMessage = 0
#    WarningMessage = 10
#    InfoMessage = 20
#    DebugMessage = 30
#    VerboseDebugMessage = 40
#    EveryMessage = 100
#
# You can create a new log file or adjust the settings
# for the console log:
#
#   logfile <filename>
#       - or -
#   logfile console
#
# Once you have created a logfile (or selected the
# console), you can add log rules using the following
# syntax. (Note that you can use wildcard characters
# '*' to catch all log_levels for a given log_namespace,
# or vice versa.)
#
# <log_level> <log_namespace>
#
# Example: For the console log, turn on InfoMessage
# logging for the thread sub-system and log every
# message from the cache sub-system.

[general]
default_num_threads = 16
write_pool_size = 40
system_cache_size = 1024000000 # ~ 1 GB

[logfile console]
20 = thread
* = cache
# Below turns off all progress bars to the console.
0 = *.progress
```

There are a lot of possible options that can be implemented in the above example. Let's cover the most important options and the concerns the user should have when selecting a value.

default_num_threads (default=2)

This sets the maximium number of threads that can be used for rendering. When stereo's `subpixel_rfne` is running you'll probably notice 10 threads are running when you have `default_num_threads` set to 8. This is not an error, you are seeing 8 threads being used for rendering, 1 thread for holding `main()`'s execution, and finally 1 optional thread acting as the interface to the file driver.

It is usually best to set this parameter equal to the number of processors on your system. Be sure to include the number of logical processors in your arithmetic if your system supports hyper-threading.

Adding more threads for rasterization increases the memory demands of Stereo Pipeline. If your system is memory limited, it might be best to lower the `default_num_threads` option. Remember that 32 bit systems can only allocate 4 GB of memory per process. Despite Stereo Pipeline being a multithreaded application, it is still a single process.

write_pool_size (default=21)

The `write_pool_size` option represents the max waiting pool size of tiles waiting to be written to disk. Most file formats do not allow tiles to be written arbitrarily out of order. Most however will let rows of tiles to be written out of order, while tiles inside a row must be written in order. Because of the previous constraint, after a tile is rasterized it might spend some time waiting in the 'write pool' before it can be written to disk. If the 'write pool' fills up, only the next tile in order can be rasterized. That makes Stereo Pipeline perform like it is only using a single processor.

Increasing the `write_pool_size` makes Stereo Pipeline more able to use all processing cores in the system. Having this value too large can mean excessive use of memory. For 32 bit systems again, they can run out of memory if this value is too high for the same reason as described for `default_num_threads`.

system_cache_size (default=805306368)

Accessing a file from the hard drive can be very slow. It is especially bad if an application needs to make multiple passes over an input file. To increase performance, Vision Workbench will usually leave an input file stored in memory for quick access. This file storage is known as the 'system cache' and its max size is dictated by `system_cache_size`. The default value is 768 MB.

Setting this value too high can cause your application to crash. It is usually recommend to keep this value around 1/4 of the maximum available memory on the system. For 32 bit systems, this means don't set this value any greater than 1 GB. The units of this property is in bytes.

0 = *.progress

This line is not assigning a value to progress, it is however setting the logging level of progress bars. In the above example, this statement is made under the `[logfile console]` state. This means that only progress bars of type `ErrorMessage` will ever be printed to the console. If you wanted progress bars up to type `InfoMessage`, then the line in log file should be changed to:

```
[logfile console]
20 = *.progress
```

Chapter 3

Tutorial: Processing Mars Orbiter Camera Imagery

3.1 Quick Start

The Stereo Pipeline package contains command-line programs that convert a stereo pair in ISIS *cube* format into a 3D "point cloud" image: *stereo-output*-PC.tif. This is an intermediate format that can be passed along to one of several programs that convert a point cloud into a mesh for 3D viewing or a gridded digital elevation model for GIS purposes.

There are a number of ways to fine-tune parameters and analyze the results, but ultimately this software suite takes images and builds models in a mostly automatic way. To create a point cloud file, you simply pass two image files to the stereo command:

```
ISIS 3> stereo image_file1 image_file2 stereo-output
```

You can then make a mesh or a DEM file with the following commands. The *stereo-output*-PC.tif and *stereo-output*-L.tif files are created by the stereo program above:

```
ISIS 3> point2mesh stereo-output-PC.tif stereo-output-L.tif

ISIS 3> point2dem stereo-output-PC.tif stereo-output-L.tif
```

3.2 Preparing the Data

The data set that is used in the tutorial and examples below is a pair of Mars Orbital Camera (MOC) [17, 16] images whose Planetary Data System (PDS) Product IDs are M01/00115 and E02/01461. This data can be downloaded from the PDS directly, or they can be found in the data/MOC/ directory of your Stereo Pipeline distribution.

3.2.1 Loading and Calibrating Images using ISIS

These raw PDS images (M0100115.imq and E0201461.imq) need to be imported into the ISIS environment and radiometrically calibrated. You will need to be in an ISIS environment (have set the ISISROOT environment variable and sourced the appropriate ISIS 3 Startup script, as detailed in the ISIS 3 instructions; we will denote this state with the 'ISIS 3>' prompt). Then you can use the mocproc program, like so:

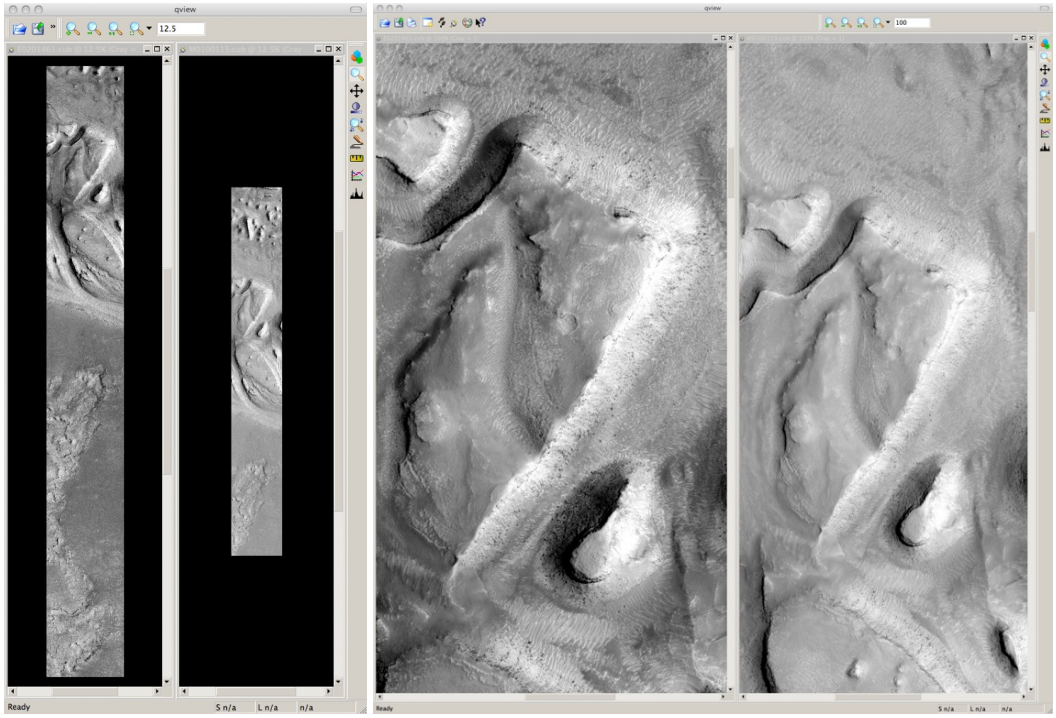


Figure 3.1: This figure shows `E0201461.cub` and `M0100115.cub` open in ISIS's qview program. The view on the left shows their full extents at the same zoom level, showing how they have different ground scales. The view on the right shows both images zoomed in on the same feature.

```
ISIS 3> mocproc from= M0100115.imq to= M0100115.cub Mapping= NO
ISIS 3> mocproc from= E0201461.imq to= E0201461.cub Mapping= NO
```

There are also `Ingestion` and `Calibration` parameters whose defaults are '`YES`' which will bring the image into the ISIS format and perform radiometric calibration. By setting the `Mapping` parameter to '`NO`' the resultant file will be an ISIS cube file that is calibrated, but not map-projected. Note that while we have not explicitly run `spiceinit`, the Ingestion portion of `mocproc` quietly ran `spiceinit` for you (you'll find the record of it in the ISIS Session Log, usually written out to a file named `print.prt`). Refer to Figure 3.1 to see the results at this stage of processing.

3.2.2 Aligning Images

The images also need to be rectified (or aligned). There are many ways to do this (see using `alignment-method` in `stereo`'s `stereo.default` file in section 3.3.1). The most straightforward process is to align the images by map projecting them in ISIS. This example continues with the files from above, `E0201461.cub` and `M010015.cub`.

This section describes the theory behind doing each of these steps, but we also provide the `cam2map4stereo.py` program (page 84) which performs these steps automatically for you.

The ISIS `cam2map` program will map-project these images:

```
ISIS 3> cam2map from=M0100115.cub to=M0100115.map.cub
ISIS 3> cam2map from=E0201461.cub to=E0201461.map.cub map=M0100115.map.cub matchmap=true
```

Notice the order in which the images were run through `cam2map`. The first projection with `M0100115.cub` produced a map-projected image centered on the center of that image. The projection of `E0201461.cub` used the `map=` parameter to indicate that `cam2map` should use the same map projection parameters as those of `M0100115.map.cub` (including center of projection, map extents, map scale, etc.) in creating the

projected image. By map projecting the image with the worse resolution first, and then matching to that, we ensure two things: (1) that the second image is summed or scaled down instead of being magnified up, and (2) that we are minimizing the file sizes to make processing in the Stereo Pipeline more efficient.

Technically, the same end result could be achieved by using the `mocproc` program alone, and using its `map= M0100115.map.cub` option for the run of `mocproc` on `E0201461.cub` (it behaves identically to `cam2map`). However, this would not allow for determining which of the two images had the worse resolution and extracting their minimum intersecting bounding box (see below). Furthermore, if you choose to conduct bundle adjustment (see Chapter 5, page 39) as a pre-processing step, you would do so between `mocproc` (as run above) and `cam2map`.

The above procedure is in the case of two images which cover similar real estate on the ground. If you have a pair of images where one image has a footprint on the ground that is much larger than the other, only the area that is common to both (the intersection of their areas) should be kept to perform correlation (since non-overlapping regions don't contribute to the stereo solution). If the image with the larger footprint size also happens to be the image with the better resolution (i.e. the image run through `cam2map` second with the `map=` parameter), then the above `cam2map` procedure with `matchmap=true` will take care of it just fine. Otherwise you'll need to figure out the latitude and longitude boundaries of the intersection boundary (with the ISIS `camrange` program). Then use that smaller boundary as the arguments to the `MINLAT`, `MAXLAT`, `MINLON`, and `MAXLON` parameters of the first run of `cam2map`. So in the above example, after `mocproc` with `Mapping= NO` you'd do this:

```
ISIS 3> camrange fr= M0100115.cub
        [ ... lots of camrange output omitted ... ]
Group = UniversalGroundRange
  LatitudeType       = Planetocentric
  LongitudeDirection = PositiveEast
  LongitudeDomain    = 360
  MinimumLatitude    = 34.079818835324
  MaximumLatitude    = 34.436797628116
  MinimumLongitude   = 141.50666207418
  MaximumLongitude   = 141.62534719278
End_Group
        [ ... more output of camrange omitted ... ]
```

```
ISIS 3> camrange fr= E0201461.cub
        [ ... lots of camrange output omitted ... ]
Group = UniversalGroundRange
  LatitudeType       = Planetocentric
  LongitudeDirection = PositiveEast
  LongitudeDomain    = 360
  MinimumLatitude    = 34.103893080982
  MaximumLatitude    = 34.547719435156
  MinimumLongitude   = 141.48853937384
  MaximumLongitude   = 141.62919740048
End_Group
        [ ... more output of camrange omitted ... ]
```

Now compare the boundaries of the two above and determine the intersection to use as the boundaries for `cam2map`:

```
ISIS 3> cam2map from=M0100115.cub to=M0100115.map.cub DEFAULTRANGE= CAMERA \
                MINLAT= 34.10 MAXLAT= 34.44 MINLON= 141.50 MAXLON= 141.63
ISIS 3> cam2map from=E0201461.cub to=E0201461.map.cub map=M0100115.map.cub matchmap=true
```

You only have to do the boundaries explicitly for the first run of `cam2map`, because the second one uses the `map=` parameter to mimic the map projection of the first. These two images aren't radically different in areal coverage, so this isn't really necessary for these images, its just an example.

Again, unless you are doing something complicated, using the `cam2map4stereo.py` program (page 84) will take care of all these steps for you.

3.3 Running the Stereo Pipeline

Once the data has been prepared for processing, we invoke the the `stereo` program (page 77). The `stereo` program can generate a number of output files, and you may find it helpful to create a directory to store the results of stereo processing, as illustrated below.

```
ISIS 3> ls
E0201461.cub   E0201461.map.cub   M0100115.cub   M0100115.map.cub
ISIS 3> mkdir results
```

3.3.1 Setting Options in the `stereo.default` File

The `stereo` program requires a `stereo.default` file that contains settings that affect the stereo reconstruction process. Its contents can be altered for your needs; details are found in appendix B on page 85. You may find it useful to save multiple versions of the `stereo.default` file for various processing needs. If you do this, be sure to specify a configuration file by invoking `stereo` with the `-s` option. If this option is not given, the `stereo` program will search for a file named `stereo.default` in the current working directory. The extension of this file is unimportant. Feel free to use any name that best suits your project.

There is a `stereo.map` file included with the example data set for MOC that is different from the example `stereo.default.example` file distributed with the Stereo Pipeline. The `stereo.map` included with the example data has a smaller correlation window (smaller values for the `corr-search` variables) that is more suited to that particular MOC stereo image pair.

Alternatively, it is possible to not `corr-search` in the stereo settings file. If no such options are specified, `stereo` will attempt to guess the correct search range. The guess is printed along with the rest of the program output. If this technique does not produce satisfactory results, then it can at least be used as a starting point for picking a better search range by hand.

For this example use the `stereo.default` that is included with the example data set. It has these key properties:

```
alignment-method none
corr-search -35 -280 -15 -265
```

The first says, *'Don't do try to automatically align my images!'* since we have map-projected the images. The other line defines the range that should be searched by scanning a template from the left image over the right image. The values above are tuned to the range of offsets that are found in this particular set of map projected images. The order of the arguments are horizontal minimum index, vertical minimum index, horizontal maximum index, and finally vertical maximum index.

Given that we map projected the images using the same settings, you may be wondering why there would still be an offset. The reason is twofold: (1) the camera position may be slightly off, resulting in slight mis-alignment between stereo images; or (2) ISIS doesn't have a perfect surface to project onto during map projection, so small terrain features still produce changes in perspective. (In fact, these are precisely the features we are hoping to detect!)

> Given the uncertainties due to (1) and (2) above, it can be tricky to select a good search range for the `stereo.default` file. One way is to let `stereo` perform one round of auto search range search. Look at the results using the `disparitydebug` program. The output images will clearly show good data or bad data depending on whether the search range is correct. If the edges of these images look degraded, then the search range may need to be expanded by hand.
>
> The worst case scenario is to determine search range manually by opening both images in `qview` and comparing the coordinates of points that you can match visually. Subtract line,sample locations in the first image from the coordinates of the same feature in the second image, this will yield offsets that must be in the search range. Make several of these offset measurements and use them to define a line,sample bounding box, then expand this by 50% and use it for `corr-search`. This will produce good results in most images.

3.3.2 Performing Stereo Correlation

Here is how the `stereo` program is invoked:

```
ISIS 3> stereo E0201461.map.cub M0100115.map.cub \
          -s stereo.map                          \
          results/E0201461-M0100115
```

That last option (`results/E0201461-M0100115`) is a prefix that is used when generating names for `stereo` output files. In this case the first part is `results/`, which causes the program to generate results in that directory with filenames that start with `E0201461-M0100115`. If instead that last text was `E0201461-M0100115` it would have created a collection of files that start with `E0201461-M0100115` in the *same* directory as the input files.

All the settings given via the `stereo.default` file can be over-ridden from the command line. Just add a double hyphen (`--`) in front the option's name and then fill out the option just as you would in the configuration file. For options in the `stereo.default` file that take multiple numbers, they must be separated by spaces (like '`corr-kernel 25 25`') on the command line. Below is an example of overriding the search range and subpixel mode from the command line.

```
ISIS 3> stereo E0201461.map.cub M0100115.map.cub  \
          -s stereo.map --corr-search -70 -4 40 4 \
          --subpixel-mode 0                       \
          results/E0201461-M0100115
```

Figure 3.2: These are the four viewable `.tif` files created by the `stereo` program. On the left are the two aligned, pre-processed images: (`E0201461-M0100115-L.tif` and `E0201461-M0100115-R.tif`). The next two are mask images (`E0201461-M0100115-lMask.tif` and `E0201461-M0100115-rMask.tif`), which indicate which pixels in the aligned images are good to use in stereo correlation. The image on the right is the "Good Pixel map", (`E0201461-M0100115-GoodPixelMap.tif`), which indicates (in gray) which were successfully matched with the correlator, and (in red) those that were not matched.

3.3.3 Diagnosing Problems

Once invoked, `stereo` proceeds through several stages that are detailed on page 78. Intermediate and final output files are generated as it goes. See Appendix C, page 91 for a comprehensive listing. Many of these files are useful for diagnosing and debugging problems. For example, as Figure 3.2 shows, a quick look at some of the TIFF files in the `results/` directory provides some insight into the process.

Perhaps the most important file for assessing the quality of your results is the good pixel image, (`E0201461-M0100115-GoodPixelMap.tif`). If this file shows mostly good, gray pixels in the overlap area (the area that is white in both the `E0201461-M0100115-lMask.tif` and `E0201461-M0100115-rMask.tif` files), then your results are just fine. If the good pixel image shows lots of failed data, signified by red pixels in the overlap area, then you need to go back and tune your `stereo.default` file until your results improve. This might be a good time to make a copy of `stereo.default` as you tune the parameters to improve the results.

You should also know that whenever the `stereo` executable is run, it makes a copy of the configuration file used in *output-prefix*-stereo.default. Opening that output file will show when the command was run, what the flags were from the command line, and then a copy of the `stereo.default`. This will hopefully help debug and log what was performed so that others in the future can recreate your work.

Another handy debugging tool is the `disparitydebug` program, which allows you to generate viewable versions of the intermediate results from the stereo correlation algorithm. `disparitydebug` converts information in the disparity image files into two TIFF images that contain horizontal and vertical components of the disparity (i.e. matching offsets for each pixel in the horizontal and vertical directions). There are actually four flavors of disparity map: the `-D.tif`, the `-RD.tif`, the `-F-corrected.tif`, and `-F.tif`. You can run `disparitydebug` on any of them. Each shows the disparity map at the different stages of processing.

```
ISIS 3> cd results
ISIS 3> disparitydebug E0201461-M0100115-F.tif
```

If the output H and V files from `disparitydebug` look okay, then the point cloud image is most likely ready for post-processing. You can proceed to make a mesh or a DEM by processing `E0201461-M0100115-PC.tif` using the `point2mesh` or `point2dem` tools, respectively.

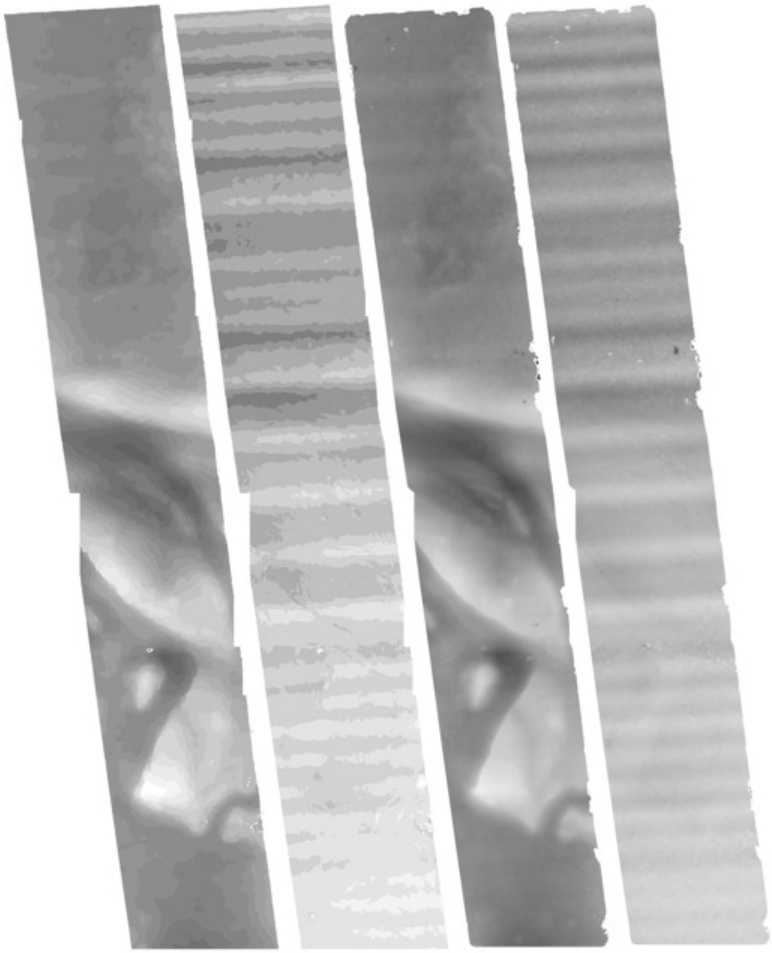


Figure 3.3: Disparity images produced using the `disparitydebug` tool. The two images on the left are the `E0201461-M0100115-D-H.tif` and `E0201461-M0100115-D-V.tif` files, which are normalized horizontal and vertical disparity components produced by the disparity map initialization phase. The two images on the right are `E0201461-M0100115-F-H.tif` and `E0201461-M0100115-F-V.tif`, which are the final filtered, sub-pixel-refined disparity maps that are fed into the Triangulation phase to build the point cloud image. Since these MOC images were acquired by rolling the spacecraft across-track, most of the disparity that represents topography is present in the horizontal disparity map. The vertical disparity map shows disparity due to "wash-boarding," which is not from topography but from spacecraft movement. Note however that the horizontal and vertical disparity images are normalized independently. Although both have the same range of gray values from white to black, they represent significantly different absolute ranges of disparity.

3.4 Visualizing the Results

When `stereo` finishes, it will have produced a point cloud image. At this point, many kinds of data products can be built from the `E0201461-M0100115-PC.tif` point cloud file.

3.4.1 Building a 3D Model

If you wish to see the data in an interactive 3D browser, then you can generate a 3D object file using the `point2mesh` command (page 81). The resulting file is stored in Open Scene Graph binary format [8]. It can be viewed with `osgviewer` (the Open Scene Graph Viewer program, distributed with the binary version of the Stereo Pipeline). The `point2mesh` program takes the point cloud file and the left normalized image as inputs:

```
ISIS 3> point2mesh E0201461-M0100115-PC.tif E0201461-M0100115-L.tif -l
```

When the `osgviewer` program starts, you may want to toggle the lighting with the 'L' key, toggle texturing with the 'T' key, and toggle wireframe mode with the 'W'. Press '?' to see a variety of other interactive options.

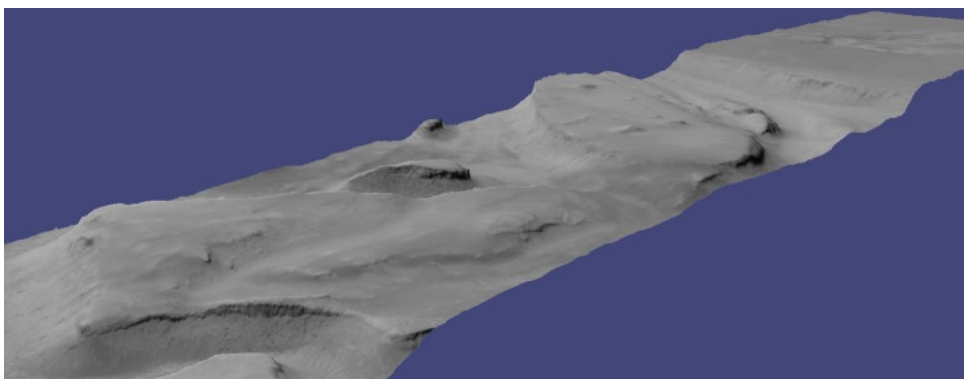


Figure 3.4: The `E0201461-M0100115.ive` file displayed in the OSG Viewer.

3.4.2 Building a Digital Elevation Model

The `point2dem` program (page 79) creates a DEM from the point cloud file.

```
ISIS 3> point2dem E0201461-M0100115-PC.tif
```

The resulting TIFF file is map projected and will contain georeferencing information stored as GeoTIFF tags. You can specify a coordinate system (e.g., mercator, sinusoidal) and a reference spheroid (i.e., calculated for the Moon or Mars).

```
ISIS 3> point2dem -r mars E0201461-M0100115-PC.tif
```

This product is suitable for scientific use, and can be imported into a variety of GIS platforms. However, the resulting file, `E0201461-M0100115-DEM.tif`, will have 32-bit floating point pixels, and will not render well in typical image viewers.

The `point2dem` program can also be used to orthoproject raw satellite imagery onto the DEM. To do this, invoke `point2dem` just as before, but add the `--orthoimage` option and specify the use of the left image file as the texture file to use for the projection:

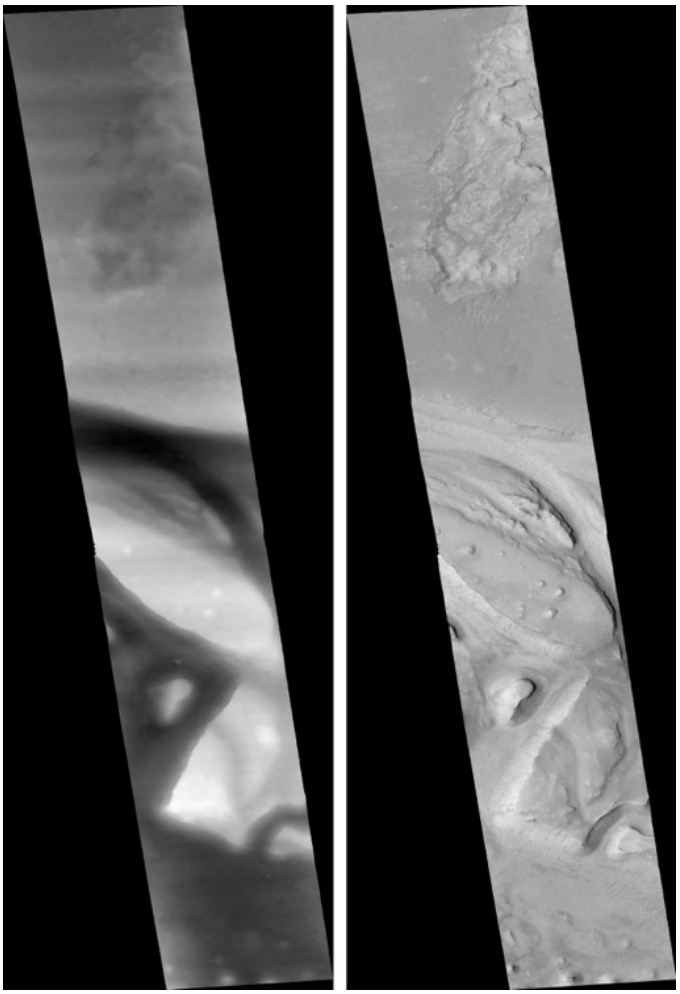


Figure 3.5: The image on the left is a normalized DEM (generated using the `-n` option), which shows low terrain values as black and high terrain values as white. The image on the right is the left input image projected onto the DEM (created using the `--orthoimage` option to `point2dem`).

```
ISIS 3> point2dem -r mars --orthoimage E0201461-M0100115-L.tif \
    E0201461-M0100115-PC.tif
```

The `point2dem` program is also able to accept output projection options the same way as the popular tools in GDAL. Well known EPSG, IAU2000 projections, and custom Proj4 strings can applied with the target spatial reference set flag, `--t_srs`. If the target spatial reference flag is applied with any of the reference spheroid options, the reference spheroid option will overwrite the datum defined in the target spatial reference set. The following examples produce the same output.

```
ISIS 3> point2dem --t_srs IAU2000:49900 E0201461-M0100115-PC.tif
ISIS 3> point2dem --t_srs "+proj=longlat +a=3396190 +b=3376200"
    E0201461-M0100115-PC.tif
```

The `point2dem` program can be used in many different ways. Be sure to take your time to explore all of the options.

3.4.3 Generating Color Hillshade Maps

Once you have generated a DEM file, you can use the Vision Workbench's `colormap` and `hillshade` tools to create colorized and/or shaded relief images.

To create a colorized version of the DEM, you need only specify the DEM file to use. The colormap is applied to the full range of the DEM, which is computed automatically. Alternatively you can specific your own min and max range for the color map.

```
ISIS 3> colormap E0201461-M0100115-DEM.tif -o hrad-colorized.tif
```

To create a hillshade of the DEM, specify the DEM file to use. You can control the azimuth and elevation of the light source using the `-a` and `-e` options.

```
ISIS 3> hillshade E0201461-M0100115-DEM.tif -o hrad-shaded.tif -e 25
```

To create a colorized version of the shaded relief file, specify the DEM and the shaded relief file that should be used:

```
ISIS 3> colormap E0201461-M0100115-DEM.tif -s hrad-shaded.tif -o hrad-color-shaded.tif
```

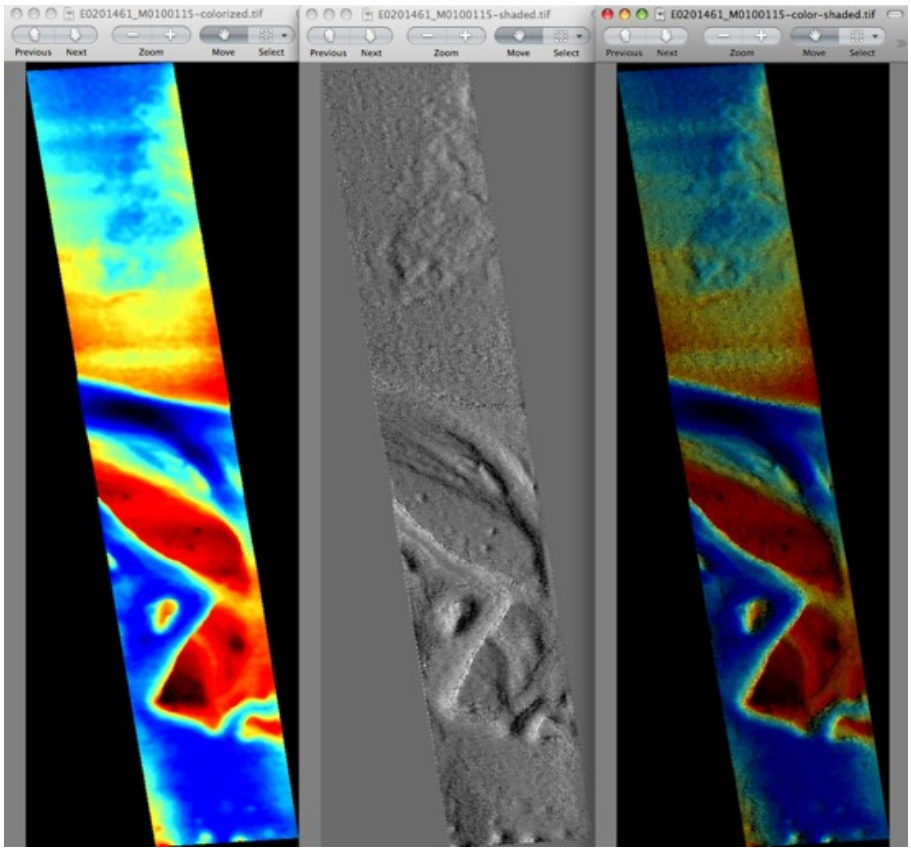


Figure 3.6: The colorized DEM, the shaded relief image, and the colorized hillshade.

3.4.4 Building Overlays for Moon and Mars mode in Google Earth

The final program in the Stereo Pipeline package that this tutorial will address is `image2qtree`. This tool was designed to create tiled, multi-resolution overlays for Google Earth. In addition to generating image tiles, it produces a metadata tree in KML format that can be loaded from your local hard drive or streamed from a remote server over the Internet.

The `image2qtree` program can only be used on 8-bit image files with georeferencing information (e.g. grayscale or RGB geotiff images). In this example, it can be used to process `E0201461-M0100115-DEM-normalized.tif`, `E0201461-M0100115-DRG.tif` `hrad-shaded.tif`, `hrad-colorized.tif`, and `hrad-shaded-colorized.tif`

```
ISIS 3> image2qtree hrad-shaded-colorized.tif -m kml --draw-order 100
```

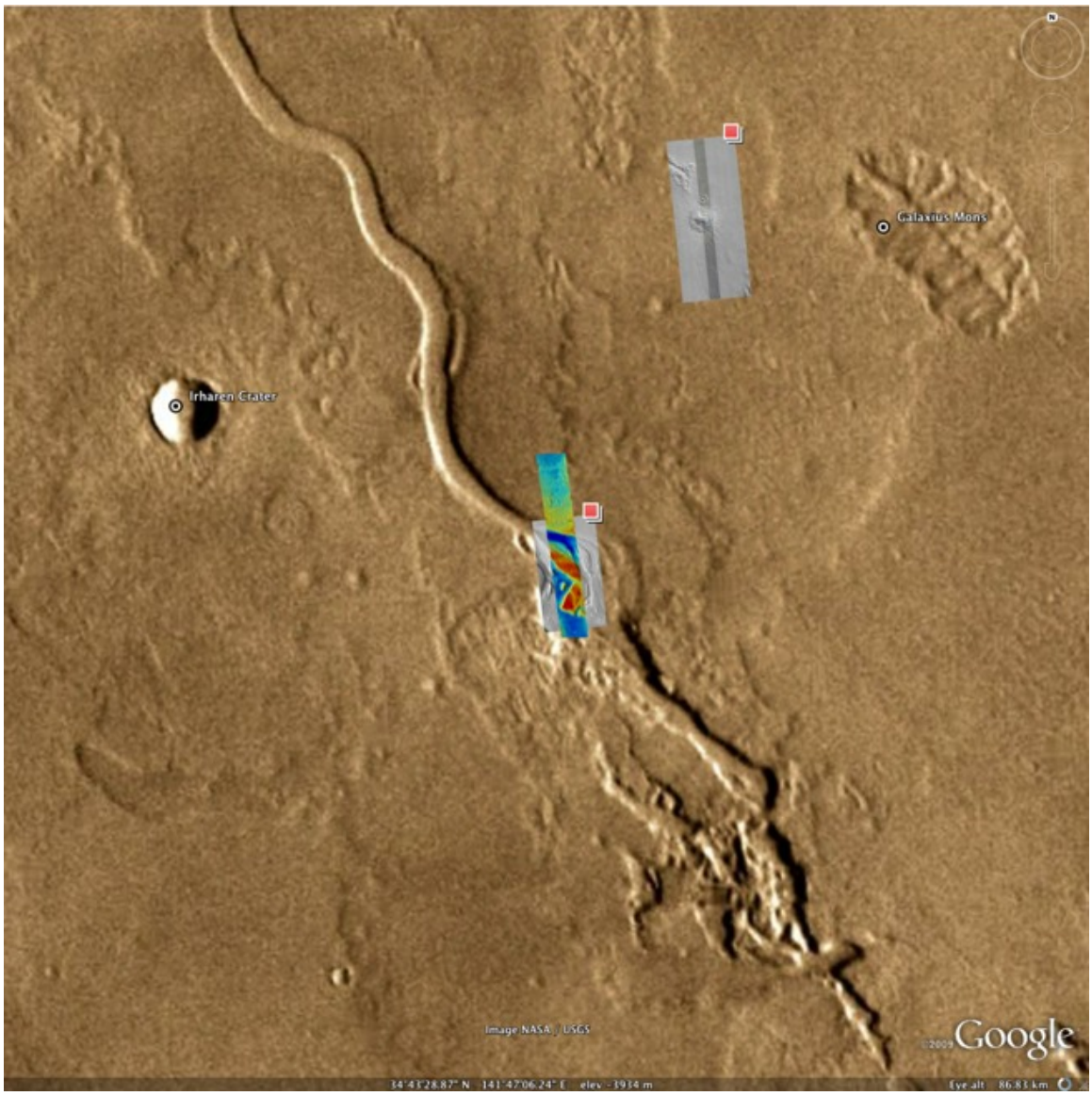


Figure 3.7: The colorized hillshade DEM as a KML overlay.

Part II

The Stereo Pipeline in Depth

Chapter 4

Correlation

In this chapter we will dive much deeper into understanding the core algorithms in the Stereo Pipeline. We start with an overview of the five stages of stereo reconstruction. Then we move into an in-depth discussion and exposition of the various correlation algorithms.

The goal of this chapter is to build an intuition for the stereo correlation process. This will help users to identify unusual results in their DEMs and hopefully eliminate them by tuning various parameters in the `stereo.default` file. For scientists and engineers who are using DEMs produced with the Stereo Pipeline, this chapter may help to answer the question, "What is the Stereo Pipeline doing to the raw data to produce this DEM?"

A related question that is commonly asked is, "How accurate is a DEM produced by the Stereo Pipeline?" This chapter does not yet address matters of accuracy and error, however we have several efforts underway to quantify the accuracy of Stereo Pipeline-derived DEMs, and will be publishing more information about that shortly. Stay tuned.

The entire stereo correlation process, from raw input images to a point cloud or DEM, can be viewed as a multistage pipeline as depicted in Figure 4.1, and detailed in the following sections.

4.1 Pre-processing

The first optional (but recommended) step in the process is least squares Bundle Adjustment, which is described in detail in Chapter 5.

Next, the left and right images are roughly aligned using one of three methods: (1) a homography transform of the right image based on automated tie-point measurements, (2) a 3D rotation that achieves epipolar rectification *(only implemented for Pinhole sessions for missions like MER or K10)* or (3) map projection of both the left and right images using the ISIS `cam2map` command or through `gdal_translate` for Digital Globe and GeoEye images. The first two options can be applied automatically by the stereo pipeline when the `alignment-method` variable in the `stereo.default` file is set to `HOMOGRAPHY` or `EPIPOLAR`.

The latter option, running `cam2map`, `cam2map4stereo.py`, or `gdal_translate` must be carried out by the user prior to invoking the `stereo` command. Map projecting the images using ISIS eliminates any unusual distortion in the image due to the unusual camera acquisition modes (e.g. pitching "ROTO" maneuvers during image acquisition for MOC, or highly elliptical orbits and changing line exposure times for the High Resolution Stereo Camera, HRSC). It also eliminates some of the perspective differences in the image pair that are due to large terrain features by taking the existing low-res terrain model into account (e.g. the Mars Orbiter Laser Altimeter, MOLA; Lunar Orbiter Laser Altimeter, LOLA; National Elevation Dataset, NED; or Unified Lunar Coordinate Network, ULCN, 2005 models).

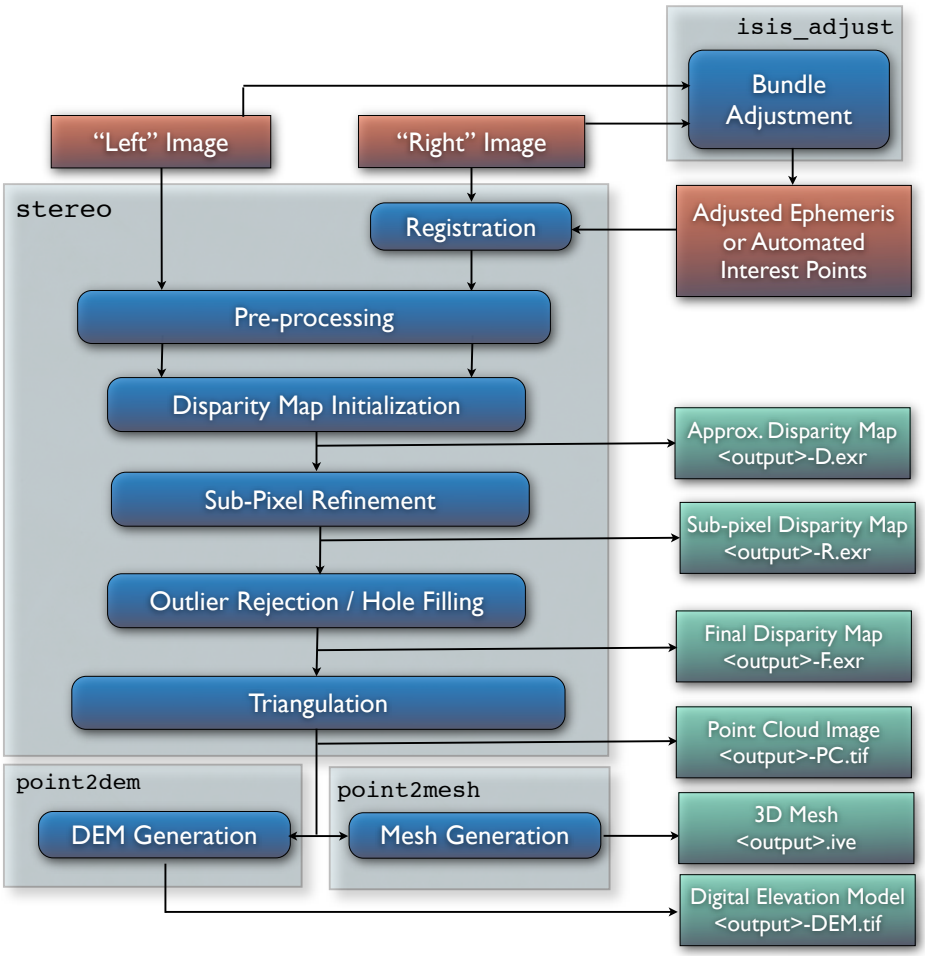


Figure 4.1: Flow of data through the Stereo Pipeline.

In essence, map projecting the images results in a pair of very closely matched images that are as close to ideal as possible given existing information. This leaves only small perspective differences in the images, which are exactly the features that the stereo correlation process is designed to detect.

For this reason, we recommend map projection for pre-alignment of most stereo pairs. Its only cost is longer triangulation times as more math must be applied to work back through the transforms applied to the images. In either case, the pre-alignment step is essential for performance because it ensures that the disparity search space is bounded to a known area. In both cases, the effects of pre-alignment are taken into account later in the process during Triangulation, so you do not need to worry that pre-alignment will compromise the geometric integrity of your DEM.

In some cases the pre-processing step may also normalize the pixel values in the left and right images to bring them into the same dynamic range. Various options in the `stereo.default` file affect whether or how normalization is carried out, including `individual-normalize` and `force-use-entire-range`. Although the defaults work in most cases, the use of these normalization steps can vary from data set to data set, so we recommend you refer to the examples in Chapter 6 to see if these are necessary in your use case.

Finally, pre-processing can perform some filtering of the input images (as determined by `prefilter-mode`) to reduce noise and extract edges in the images. When active, these filters apply a kernel with a sigma of `prefilter-kernel-width` pixels that can improve results for noisy images (`prefilter-mode` must be chosen carefully in conjunction with `cost-mode`, see Appendix B). The pre-processing modes that

extract image edges are useful for stereo pairs that do not have the same lighting conditions, contrast, and absolute brightness [23]. We recommend that you use the defaults for these parameters to start with, and then experiment only if your results are sub-optimal.

4.2 Disparity Map Initialization

Correlation is the process at the heart of the Stereo Pipeline. It is a collection of algorithms that compute correspondences between pixels in the left image and pixels in the right image. The map of these correspondences is called a *disparity map*. You can think of a disparity map as an image whose pixel locations correspond to the pixel (u, v) in the left image, and whose pixel values contain the horizontal and vertical offsets (d_u, d_v) to the matching pixel in the right image, which is $(u + d_u, v + d_v)$.

The correlation process attempts to find a match for every pixel in the left image. The only pixels skipped are those marked invalid in the mask images. For large images (e.g. from HiRISE, Lunar Reconnaissance Orbiter Camera, LROC, or WorldView), this is very expensive computationally, so the correlation process is split into two stages. The disparity map initialization step computes approximate correspondences using a pyramid-based search that is highly optimized for speed, but trades resolution for speed. The results of disparity map initialization are integer-valued disparity estimates. The sub-pixel refinement step takes these integer estimates as initial conditions for an iterative optimization and refines them using the algorithm discussed in the next section.

We employ several optimizations to accelerate disparity map initialization: (1) a box filter-like accumulator that reduces duplicate operations during correlation [25]; (2) a coarse-to-fine pyramid based approach where disparities are estimated using low resolution images, and then successively refined at higher resolutions; and (3) partitioning of the disparity search space into rectangular sub-regions with similar values of disparity determined in the previous lower resolution level of the pyramid [25].

Naive correlation itself is carried out by moving a small, rectangular template window from the from left image over the specified search region of the right image, as in Figure 4.2. The "best" match is determined by applying a cost function that compares the two windows. The location at which the window evaluates to the lowest cost compared to all the other search locations is reported as the disparity value. The `cost-mode` variable allows you to choose one of three cost functions, though we recommend normalized cross correlation [18], since it is most robust to slight lighting and contrast variations between a pair of images. Try the others if you need more speed at the cost of quality.

Our implementation of pyramid correlation is a little unique in that it is actually split into two levels of pyramid searching. There is a *`output_prefix`*`-D_sub.tif` disparity image that is computed from the greatly reduced input images `*-L_sub.tif` and *`output_prefix`*`-R_sub.tif`. Those "sub" images have their size chosen so that their area is around 2.25 mega pixels, a size that is easily viewed on the screen unlike the raw source imagery. The low resolution disparity image then defines the per thread search range of the higher resolution disparity, *`output_prefix`*`-D.tif`.

This solution is imperfect but comes from our model of multithreaded processing. ASP processes individual tiles of the output disparity in parallel. The smaller the tiles, the easier it is to distribute evenly among the CPU cores. The size of the tile unfortunately limits the max number of pyramid levels we can process. We've struck a balance where every 1024 by 1024 pixel area is processed individually in a tile. This practice allows only 5 levels of pyramid processing. With the addition of the second tier of pyramid searching with *`output_prefix`*`-D_sub.tif`, we are allowed to process beyond that limitation.

Finally, this might go with out saying, but any colossal failure in the low resolution disparity image will be detrimental to the performance of the higher resolution disparity. In the event that the low resolution disparity is completely unhelpful, it can be skipped by adding `corr-seed-mode 0` in the `stereo.default`

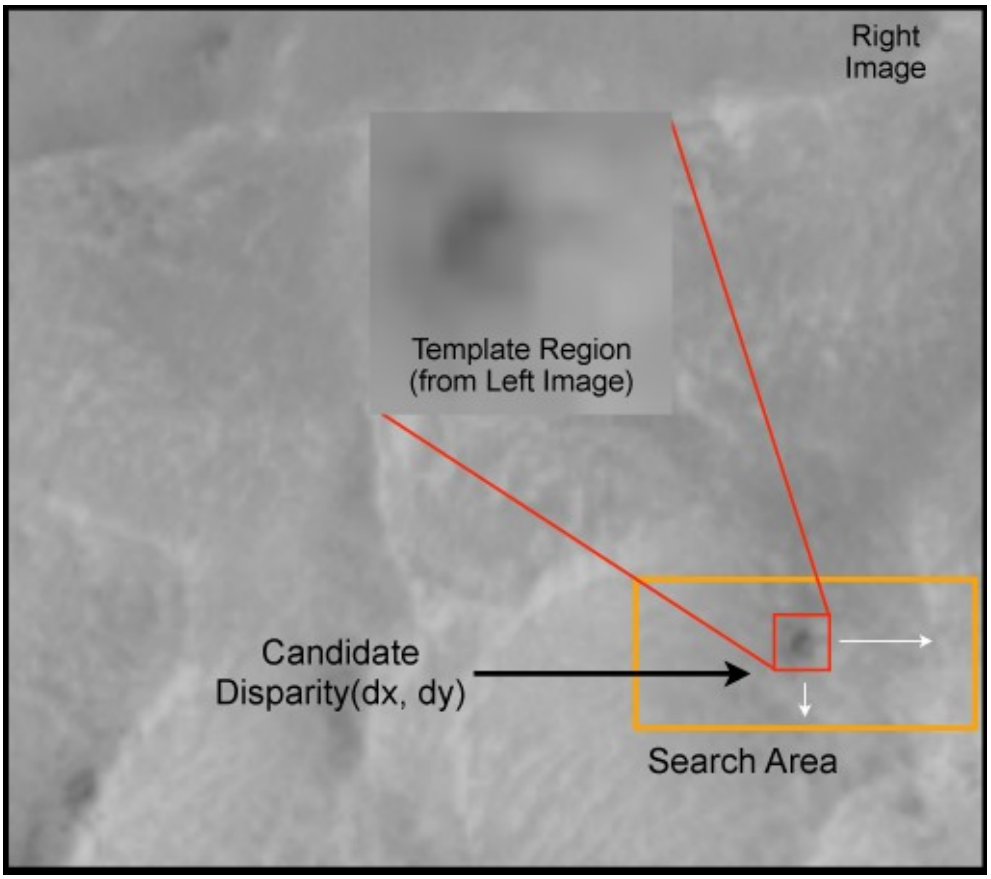


Figure 4.2: The correlation algorithm in disparity map initialization uses a sliding template window from the left image to find the best match in the right image. The size of the template window can be adjusted using the `H_KERN` and `V_KERN` parameters in the `stereo.default` file, and the search range can be adjusted using the {`H`,`V`}`_CORR_`{`MIN`/`MAX`} parameters.

file. This should only be considered in cases where the texture in an image is completely lost when subsampled. An example would be satellite imagery of fresh snow in the arctic.

4.2.1 Debugging Disparity Map Initialization

Never will all pixels be successfully matched during stereo matching. Though a good chunk of the image should be correctly processed. If you see large areas where matching failed, this could be due to a variety of reasons:

- In regions where the images do not overlap, there should be no valid matches in the disparity map.
- Match quality may be poor in regions of the images that have different lighting conditions, contrast, or specular properties of the surface.
- Areas that have image content with very little texture or extremely low contrast may have an insufficient signal to noise ratio, and will be rejected by the correlator.
- Areas that are highly distorted due to different image perspective, such as crater and canyon walls, may exhibit poor matching performance. This could also be due to failure of the preprocessing step in aligning the images. The correlator can not match images that are rotated differently from each other or have different scale/resolution.

Bad matches, often called "blunders" or "artifacts" are also common, and can happen for many of the same reasons listed above. The Stereo Pipeline does its best to automatically detect and eliminate these blunders, but the effectiveness of these outlier rejection strategies does vary depending on the quality of the input imagery.

When tuning up your `stereo.default` file, you will find that it is very helpful to look at the raw output of the disparity map initialization step. This can be done using the `disparitydebug` tool, which converts the *`output_prefix`*`-D.tif` file into a pair of normal images that contain the horizontal and vertical components of disparity. You can open these in a standard image viewing application and see immediately which pixels were matched successfully, and which were not. Stereo matching blunders are usually also obvious when inspecting these images. With a good intuition for the effects of various `stereo.default` parameters and a good intuition for reading the output of `disparitydebug`, it is possible to quickly identify and address most problems.

4.3 Sub-pixel Refinement

Once disparity map initialization is complete, every pixel in the disparity map will either have an estimated disparity value, or it will be marked as invalid. All valid pixels are then adjusted in the sub-pixel refinement stage based on the `subpixel-mode` setting.

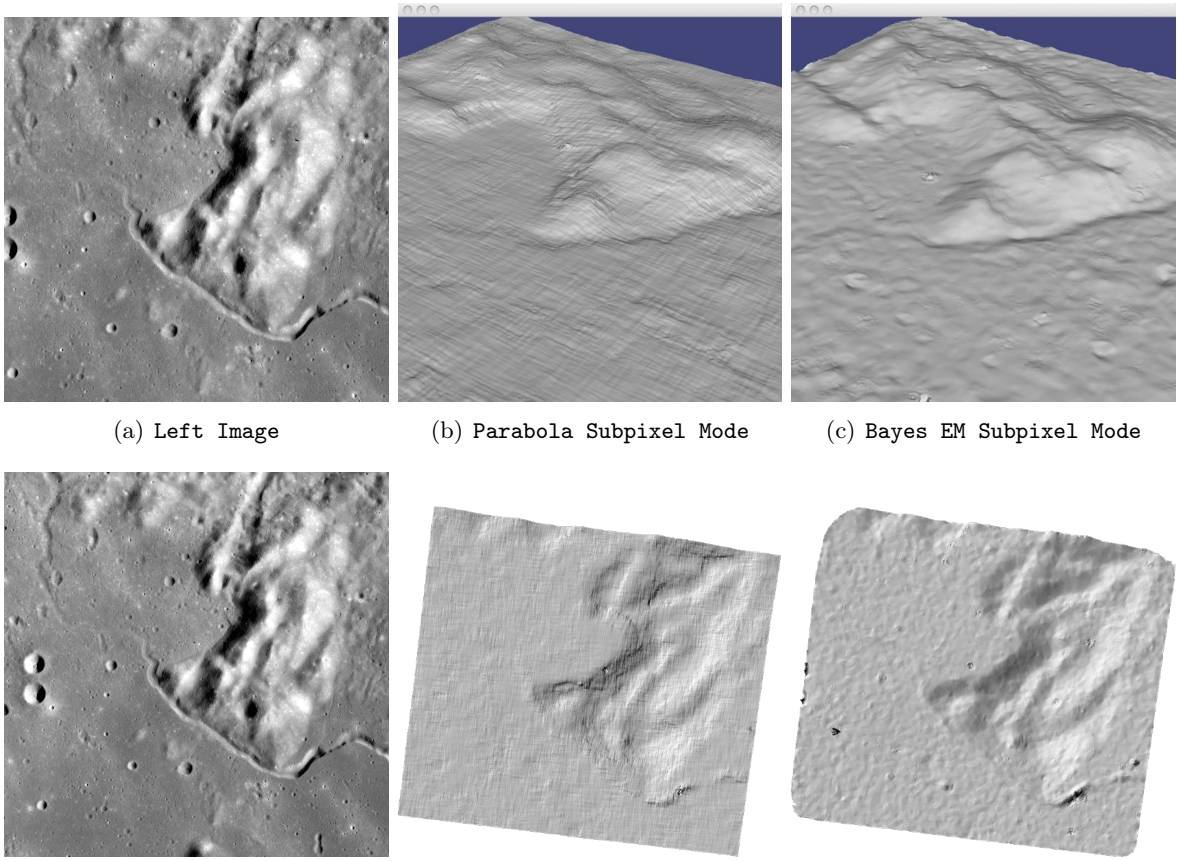
The first mode is parabola-fitting sub-pixel refinement (`subpixel-mode 1`). This technique fits a 2D parabola to points on the correlation cost surface in an 8-connected neighborhood around the cost value that was the "best" as measured during disparity map initialization. The parabola's minimum can then be computed analytically and taken as as the new sub-pixel disparity value.

This method is easy to implement and extremely fast to compute, but it exhibits a problem known as pixel-locking: the sub-pixel disparities tend toward their integer estimates and can create noticeable "stair steps" on surfaces that should be smooth [24, 26]. See e.g. Figure 4.3(b). Furthermore, the parabola subpixel mode is not capable of refining a disparity estimate by more than one pixel, so although it produces smooth disparity maps, these results are not much more accurate than the results that come out of the disparity map initialization in the first place. However, the speed of this method makes it very useful as a "draft" mode for quickly generating a DEM for visualization (i.e. non-scientific) purposes. It is also beneficial in the event that a user will simply downsample their DEM after generation in Stereo Pipeline.

For high quality results, we recommend `subpixel-mode 2`: the Bayes EM weighted affine adaptive window correlator. This advanced method produces extremely high quality stereo matches that exhibit a high degree of immunity to image noise. For example Apollo Metric Camera images are affected by two types of noise inherent to the scanning process: (1) the presence of film grain and (2) dust and lint particles present on the film or scanner. The former gives rise to noise in the DEM values that wash out real features, and the latter causes incorrect matches or hard to detect blemishes in the DEM. Attenuating the effect of these scanning artifacts while simultaneously refining the integer disparity map to sub-pixel accuracy has become a critical goal of our system, and is necessary for processing real-world data sets such as the Apollo Metric Camera data.

The Bayes EM subpixel correlator also features a deformable template window from the left image that can be rotated, scaled, and translated as it zeros in on the correct match in the right image. This adaptive window is essential for computing accurate matches on crater or canyon walls, and on other areas with significant perspective distortion due to foreshortening.

This affine-adaptive behavior is based on the Lucas-Kanade template tracking algorithm, a classic algorithm in the field of computer vision [3]. We have extended this technique; developing a Bayesian model that treats the Lucas-Kanade parameters as random variables in an Expectation Maximization (EM) framework. This statistical model also includes a Gaussian mixture component to model image noise that is the basis



(a) `Left Image` (b) `Parabola Subpixel Mode` (c) `Bayes EM Subpixel Mode`

(d) `Right Image` (e) `Parabola Hillshade` (f) `Bayes EM Hillshade`

Figure 4.3: Left: Input images. Center: results using the parabola draft subpixel mode (`subpixel-mode = 1`). Right: results using the Bayes EM high quality subpixel mode (`subpixel-mode = 2`).

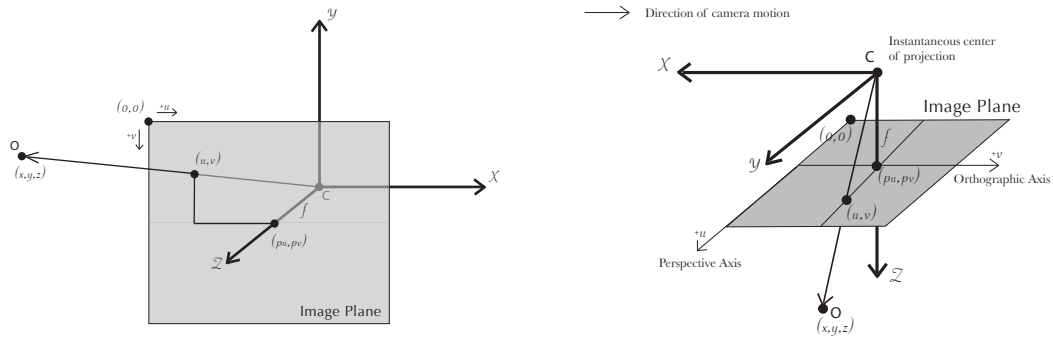
for the robustness of our algorithm. We will not go into depth on our approach here, but we encourage interested readers to read our papers on the topic [22, 5].

However we do note that, like the computations in the disparity map initialization stage, we adopt a multi-scale approach for sub-pixel refinement. At each level of the pyramid, the algorithm is initialized with the disparity determined in the previous lower resolution level of the pyramid, thereby allowing the subpixel algorithm to shift the results of the disparity initialization stage by many pixels if a better match can be found using the affine, noise-adapted window. Hence, this sub-pixel algorithm is able to significantly improve upon the results to yield a high quality, high resolution result.

4.4 Triangulation

When running an ISIS session, the Stereo Pipeline uses geometric camera models available in ISIS [2]. These highly accurate models are customized for each instrument that ISIS supports. Each ISIS "cube" file contains all of the information that is required by the Stereo Pipeline to find and use the appropriate camera model for that observation.

Other sessions such as DG (*Digital Globe*) or Pinhole, require that their camera model be provided as additional arguments to the `stereo` command. Those camera models come in the form of an XML document for DG and as `*.pinhole, *.tsai, *.cahv, *.cahvor` for Pinhole sessions. Those files must be the third and forth arguments or immediately follow after the 2 input images for `stereo`.



(a) `Framing Camera Model` (b) `Pushbroom Camera Model`

Figure 4.4: Most remote sensing cameras fall into two generic categories based on their basic geometry. Framing cameras (left) capture an instantaneous two-dimensional image. Linescan cameras (right) capture images one scan line at a time, building up an image over the course of several seconds as the satellite moves through the sky.

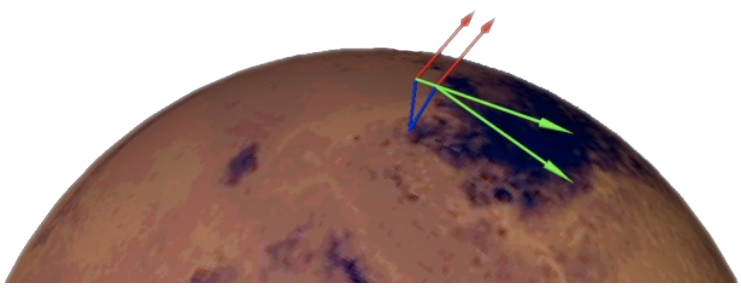


Figure 4.5: Once a disparity map has been generated and refined, it can be used in combination with the geometric camera models to compute the locations of 3D points on the surface of Mars. This figure shows the position (at the origins of the red, green, and blue vectors) and orientation of the Mars Global Surveyor at two points in time where it captured images in a stereo pair.

ISIS camera models account for all aspects of camera geometry, including both intrinsic (i.e. focal length, pixel size, and lens distortion) and extrinsic (e.g. camera position and orientation) camera parameters. Taken together, these parameters are sufficient to "forward project" a 3D point in the world onto the image plane of the sensor. It is also possible to "back project" from the camera's center of projection through a pixel corresponding to the original 3D point.

Notice, however, that forward and back projection are not symmetric operations. One camera is sufficient to "image" a 3D point onto a pixel located on the image plane, but the reverse is not true. Given only a single camera and a pixel location $x = (u, v)$ that is the image of an unknown 3D point $P = (x, y, z)$, it is only possible to determine that P lies somewhere along a ray that emanates from the camera's center of projection through the pixel location x on the image plane (see Figure 4.4).

Alas, once images are captured, the route from image pixel back to 3D points in the real world is through back projection, so we must bring more information to bear on the problem of uniquely reconstructing our 3D point. In order to determine P using back projection, we need *two* cameras that both contain pixel locations x_1 and x_2 where P was imaged. Now, we have two rays that converge on a point in 3D space (see Figure 4.5). The location where they meet must be the original location of P.

In practice, the two rays rarely intersect perfectly because any slight error in the camera position or pointing information will effect the rays' positions as well. Instead, we take the *closest point of intersection* of the two rays as the location of point P.

Additionally, the actual distance between the rays at this point is an interesting and important error metric that measures how self-consistent our two camera models are for this point. You will learn in the next chapter that this information, when computed and averaged over all reconstructed 3D points, can be a valuable statistic for determining whether to carry out bundle adjustment. Distance between the two rays at their closest intersection is recorded in the fourth channel of the point cloud file, `output-prefix-PC.tif`. This information can be brought to the same perspective as the output DEM by using the *--error* argument on the `point2dem` command.

This error in the triangulation, the distance between two rays, *is not the true accuracy of the DEM*. It is only another indirect measure of quality. A DEM with high triangulation error is always bad and should have its images bundle adjusted. A DEM with low triangulation error is at least self consistent but could still be bad. A map of the triangulation error should only be interpreted as a relative measurement. Where small areas are found with high triangulation error came from correlation mistakes and large areas of error came from camera model inadequacies.

Chapter 5

Bundle Adjustment

Satellite position and orientation errors have a direct effect on the accuracy of digital elevation models produced by the Stereo Pipeline. If they're not corrected, these uncertainties will result in systematic errors in the overall position and slope of the DEM. Severe distortions can occur as well, resulting in twisted or "taco shaped" DEMs, though in most cases these effects are quite subtle and hard to detect. In the worse case, such as with old mission data like Voyager or Apollo, these gross camera misalignments can prohibit Stereo Pipeline's internal interest point matcher and block auto search range detection.

USGS's ISIS software contains a suite of tools for correcting camera position and orientation errors for their cameras using a process called *bundle adjustment*. Bundle adjustment is the process of simultaneously adjusting the properties of many cameras and the 3D locations of the objects they see in order to minimize the error between the estimated, back-projected pixel location of the 3D objects and their actual measured location in the captured images.

That complex process can be boiled down to this simple idea: bundle adjustment ensures that observations in multiple different images of a single ground feature are self-consistent. If they are not consistent, then the position and orientation of the cameras as well as the 3D position of the feature must be adjusted until they are. This optimization is carried out along with thousands (or more) of similar constraints involving many different features observed in other images. Bundle adjustment is very powerful and versatile: it can operate on just two overlapping images, or on thousands. It is also a dangerous tool. Careful consideration is required to insure and verify that the solution does represent reality.

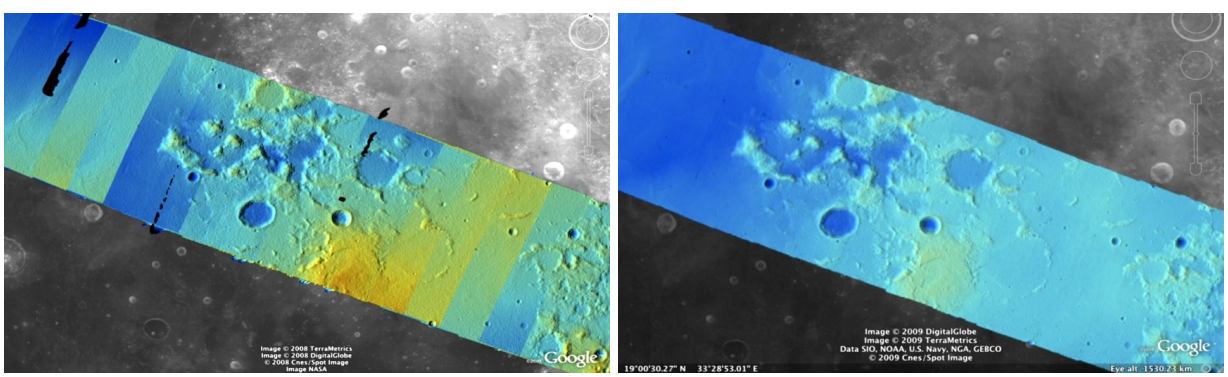


Figure 5.1: Bundle adjustment is illustrated here using a color-mapped, hill-shaded DEM mosaic from Apollo 15, Orbit 33, imagery. (a) Prior to bundle adjustment, large discontinuities can exist between overlapping DEMs made from different images. (b) After bundle adjustment, DEM alignment errors are minimized, and no longer visible.

Bundle adjustment can also take advantage of ground control points (GCPs), which are 3D locations of features that are known apriori (often by measuring them by hand in another existing DEM). GCPs can improve the internal consistency of your DEM or align your DEM to an existing data product. Finally, even though bundle adjustment calculates the locations of the 3D objects it views, only the final properties of the cameras are recorded for use by the Ames Stereo Pipeline. Those properties can be loaded into the `stereo` program which uses its own method for triangulating 3D feature locations.

When using the Stereo Pipeline, bundle adjustment is an optional step between the capture of images and the creation of DEMs. The bundle adjustment process described below should be completed prior to running the `stereo` command.

Although bundle adjustment is not a required step for generating DEMs, it is *highly recommended* for users who plan to create DEMs for scientific analysis and publication. Incorporating bundle adjustment into the stereo work flow not only results in DEMs that are more internally consistent, it is also the correct way to co-register your DEMs with other existing data sets and geodetic control networks.

At the moment however, Bundle Adjustment does not automatically work against outside DEMs from sources such as laser altimeters. Hand picked GCPs are the only way for ASP to register to those types of sources.

5.0.1 A deeper understanding

In bundle adjustment the position and orientation of each camera station are determined jointly with the 3D position of a set of image tie-points points chosen in the overlapping regions between images. Tie points, like they sound, tie individual camera images together. Their physical manifestation would be a rock or small crater than can be observed across multiple images.

Tie-points can be automatically extracted using Vision Workbench's Interest Point module, ISIS's `autoseed` and `pointreg`, or through a number of outside methods such as the famous SURF[4]. We'll be discussing the method of gathering these measurements using ISIS's toolchain. Creating a collection of tie points, *called a control network*, is a three step process. First, a general geographic layout of the points must be decided upon. This is traditionally just a grid layout that has some spacing that allows for about a 20-30 measurements to be made per image. This decided upon grid shows up in slightly different projected locations each image due to their slight misalignments. The second step is have an automatic registration algorithm try to find the same feature in all images using the prior grid as a starting location. The third step is to manually verify all measurements visually, checking to insure that each measurement is looking at the same feature.

Bundle Adjustment in ISIS is performed with the `jigsaw` executable. It generally follows the method described in [27] and determines the best camera parameters that minimize the projection error given by $\epsilon = \sum_k \sum_j (I_k - I(C_j, X_k))^2$ where I_k are the tie points on the image plane, C_j are the camera parameters, and X_k are the 3D positions associated with features I_k. $I(C_j, X_k)$ is an image formation model (i.e. forward projection) for a given camera and 3D point. To recap, it projects the 3D point, X_k, into the camera with parameters C_j. This produces a predicted image location for the 3D point that is compared against the observed location, I_k. It then reduces this error with the Levenberg-Marquardt algorithm (LMA). Speed is improved by using sparse methods as described in Hartley and Zisserman [13], Konolige [14], and Chen et al. [7].

Even though the arithmetic for bundle adjustment sounds clever, there are faults with the base implementation. Imagine a case where all cameras and 3D points were collapsed into a single point. If you evaluate the above cost function, you'll find that the error is indeed zero. This is not the correct solution if the images were taken from orbit. Another example is if a translation was applied equally to all 3D points and camera locations. This again would not affect the cost function. This fault comes from bundle adjust-

ment's inability to control the scale and translation of the solution. It will correct the geometric shape of the problem, yet it cannot guarantee that the solution will have correct scale and translation.

ISIS attempts to fix this problem by adding two additional cost functions to bundle adjustment. First of which is $\epsilon = \sum_j (C_j^{initial} - C_j)^2$. This constrains camera parameters to stay relatively close to their initial values. Second, a small handful of 3D ground control points can be chosen by hand and added to the error metric as $\epsilon = \sum_k (X_k^{gcp} - X_k)^2$ to constrain these points to known locations in the planetary coordinate frame. A physical example of a ground control point could be the location of a lander that has a well known location. GCP could also be hand picked points against a highly regarded and prior existing map such as the THEMIS Global Mosaic or the LRO-WAC Global Mosaic.

Like other iterative optimization methods, there are several conditions that will cause bundle adjustment to terminate. When updates to parameters become insignificantly small or when the error, ϵ, becomes insignificantly small, then the algorithm has converged and the result is most likely as good as it will get. However, the algorithm will also terminate when the number of iterations becomes too large, in which case bundle adjustment may or may not have finished refining the parameters of the cameras.

5.1 Performing bundle adjustment with USGS's ISIS

Ames Stereo Pipeline at one point provided its own bundle adjustment utilities but at this point it is of our opinion that they not be used for general use. USGS's ISIS bundle adjustment software has improved and gets more regular service than we could hope to provide.

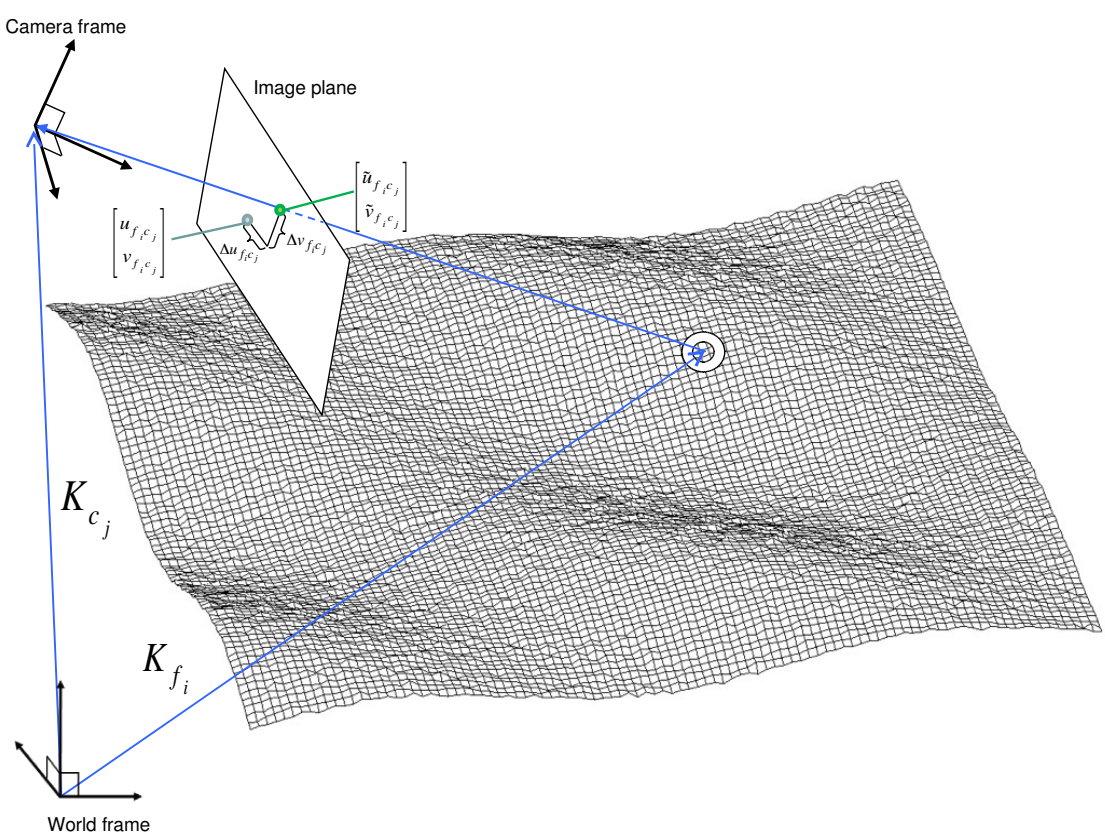


Figure 5.2: A feature observation in bundle adjustment, from Moore et al. [19]

This tutorial for ISIS's bundle adjustment tools is taken from [20] and [21]. These tools are not a product of NASA nor the authors of Stereo Pipeline. They were created by USGS and their documentation is available at [6].

5.1.1 Processing Mars Orbital Camera Imagery

What follows is an example of bundle adjustment using two MOC images of Hrad Vallis. We use images E02/01461 and M01/00115, the same as used in Chapter 3. These images are available from NASA's PDS (the ISIS `mocproc` program will operate on either the IMQ or IMG format files, we use the `.imq` below in the example). For reference, the following ISIS commands are how to convert the MOC images to ISIS cubes.

```
ISIS 3> mocproc from= e0201461.imq to= e0201461.cub mapping=no
ISIS 3> mocproc from= m0100115.imq to= m0100115.cub mapping=no
```

Note that the resulting images are not map projected. Bundle adjustment requires the ability to project arbitrary 3D points into the camera frame. The process of map projecting an image dissociates the camera model from the image. Map projecting can be perceived as the generation of a new infinitely large camera sensor that may be parallel to the surface, a conic shape, or something more complex. That makes it extremely hard to project a random point into the camera's original model. The math would follow the transformation from projection into the camera frame, then projected back down to surface that ISIS uses, then finally up into the infinitely large sensor. `Jigsaw` does not support this and thus does not operate on map projected imagery.

Before we can dive into creating our tie-point measurements we must finish prepping these images. The following commands will add a vector layer to the cube file that describes its outline on the globe. It will also create a data file that describes the overlapping sections between files.

```
ISIS 3> footprintinit from= e0201461.cub
ISIS 3> footprintinit from= m0100115.cub
ISIS 3> echo *cub |  xargs -n1 echo > cube.lis
ISIS 3> findimageoverlaps from=cube.lis overlaplist=overlap.lis
```

At this point, we are ready to start generating our measurements. This is a three step process that requires defining a geographic pattern for the layout of the points on the groups, an automatic registration pass, and finally a manual clean up of all measurements. Creating the ground pattern of measurements is performed with `autoseed`. It requires a settings file that defines the spacing in meters between measurements. For this example, write the following text into a *autoseed.def* file.

```
Group = PolygonSeederAlgorithm
      Name = Grid
      MinimumThickness = 0.01
      MinimumArea = 1
      XSpacing = 1000
      YSpacing = 2000
End_Group
```

The minimum thickness defines the minimum ratio between the sides of the region that can have points applied to it. A choice of 1 would define a square and anything less defines thinner and thinner rectangles.

The minimum area argument defines the minimum square meters that must be in an overlap region. The last two are the spacing in meters between control points. Those values were specifically chosen for this pair so that about 30 measurements would be produced from `autoseed`. Having more control points just makes for more work later on in this process. Run `autoseed` with the following instruction.

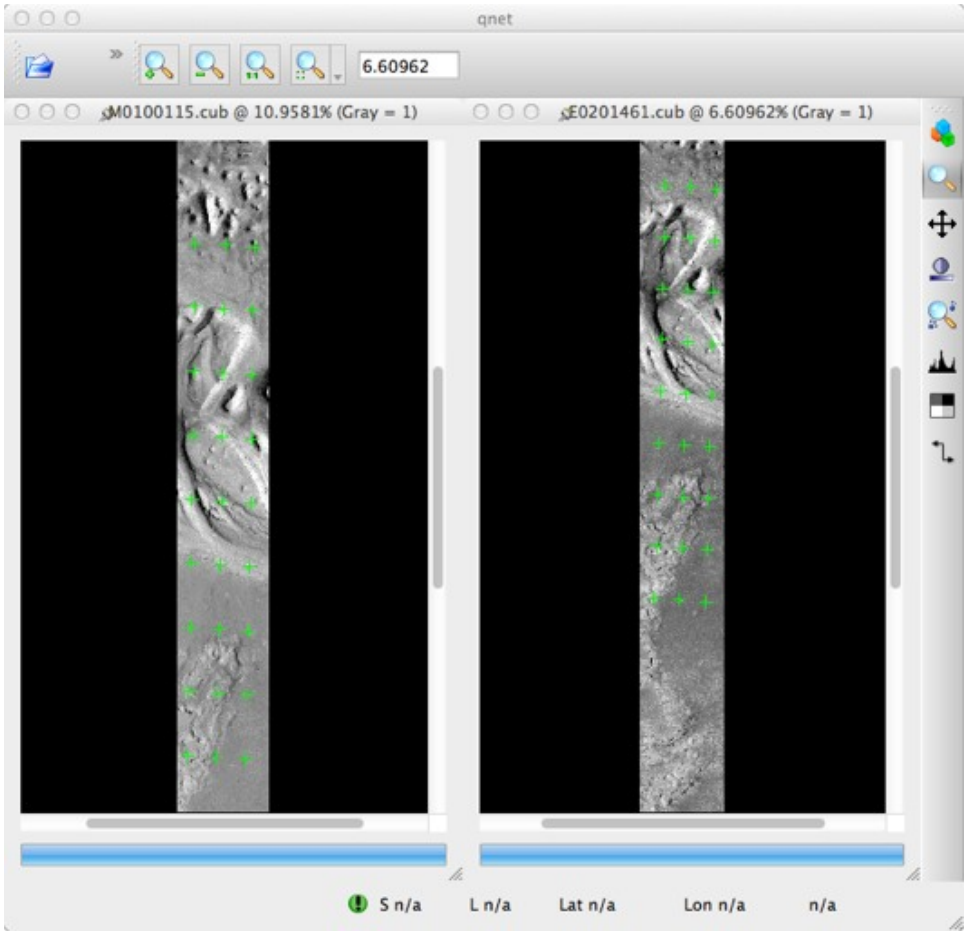


Figure 5.3: A visualization of the features layed out by `autoseed` in `qnet`. Note that the marks do not cover the same features between images. This is due to the poor initial spice data for MOC imagery.

```
ISIS 3> autoseed fromlist=cube.lis overlaplist=overlap.lis    \
          onet=control.net deffile=autoseed.def networkid=moc \
          pointid=???? description=hrad_vallis
```

The next step is to perform auto registration of these features between the two images using `pointreg`. This program also requires a settings file that describes how to do the automatic search. Copy the text box below into a *autoRegTemplate.def* file.

```
Object = AutoRegistration
 Group = Algorithm
   Name         = MaximumCorrelation
   Tolerance    = 0.7
 EndGroup

 Group = PatternChip
```

```
    Samples = 21
    Lines   = 21
    MinimumZScore = 1.5
    ValidPercent = 80
  EndGroup

  Group = SearchChip
    Samples = 75
    Lines   = 1000
  EndGroup
EndObject
```

The search chip defines the search range for which `pointreg` will look for matching imagery. The pattern chip is simply the kernel size of the matching template. The search range is specific for this image pair. The control network result after `autoseed` had a large vertical offset in the ball park of 500 px. The large misalignment dictated the need for the large search in the lines direction. Use `qnet` to get an idea for what the pixel shifts look like in your stereo pair to help you decide on a search range. In this example, only one measurement failed to match automatically. Here are the arguments to use in this example of `pointreg`.

```
ISIS 3> pointreg fromlist=cube.lis cnet=control.net            \
           onet=control_pointreg.net deffile=autoRegTemplate.def
```

The third step is to manually edit the control and verify the measurements in `qnet`. Type `qnet` in the terminal and then open *cube.lis* and lastly *control_pointreg.net*. From the Control Network Navigator window, click on the first point listed as *0001*. That opens a third window called the Qnet Tool. That window will allow you to play a flip animation that shows alignment of the feature between the two images. Correcting a measurement is performed by left clicking in the right image, then clicking *Save Measure*, and finally finishing by clicking *Save Point*.

In this tutorial, measurement *0025* ended up being incorrect. Your number may vary if you used different settings than the above or if MOC spice data has improved since this writing. When finished, go back to the main Qnet window. Save the final control network as *control_qnet.net* by clicking on *File*, and then *Save As*.

Once the control network is finished, it is finally time to start bundle adjustment. Here's what the call to `jigsaw` looks like:

```
ISIS 3> jigsaw fromlist=cube.lis update=yes twist=no radius=yes \
           cnet=control_qnet.net onet=control_ba.net
```

The update option defines that we would like to update the camera pointing, if our bundle adjustment converges. The *twist=no* says to not solve for the camera rotation about the camera bore. That property is usually very well known as it is critical for integrating an image with a line-scan camera. The *radius=yes* means that the radius of the 3D features can be solved for. Using no will force the points to use height values from another source, usually LOLA or MOLA.

The above command will spew out a bunch of diagnostic information from every iteration of the optimization algorithm. The most important feature to look at is the *sigma0* value. It represents the mean of pixel errors in the control network. In our run, the initial error was 1065 px and the final solution had an error of 1.1 px.

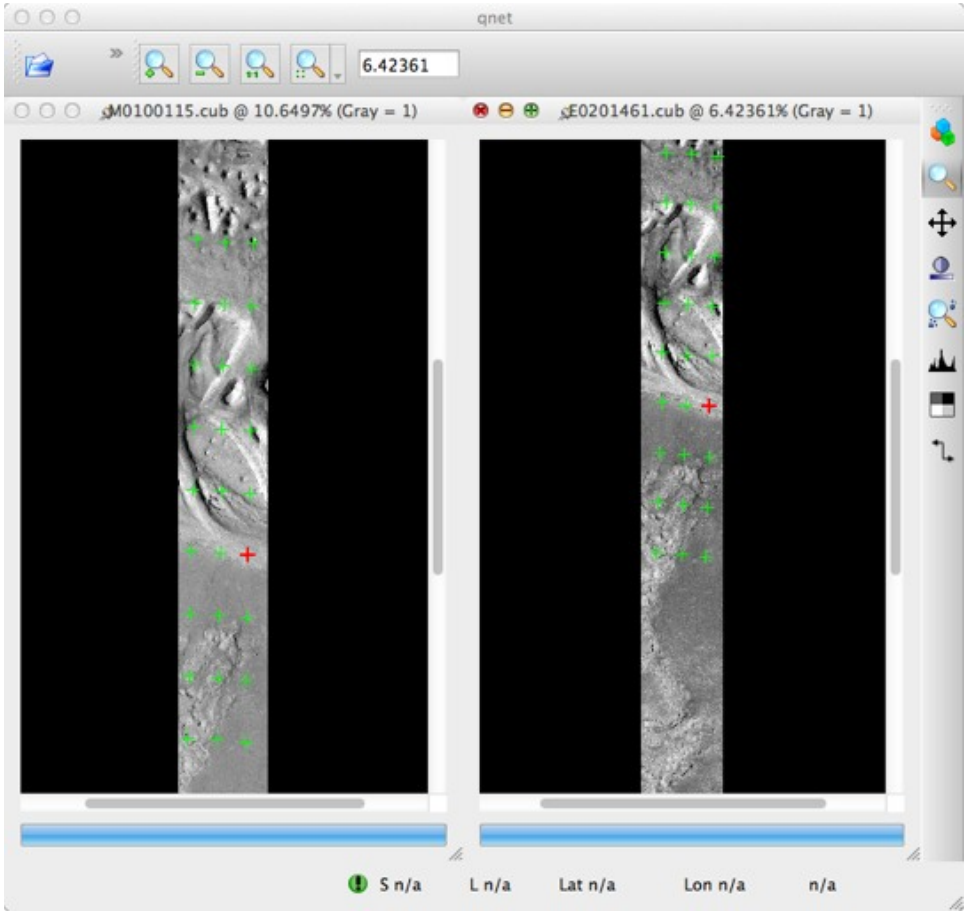


Figure 5.4: A visualization of the features after manual editing in `qnet`. Note that the marks now appear in the same location between images.

Producing a DEM using the newly created camera corrections is the same as covered in the Tutorial on page 17. When using `jigsaw`, it modifies a copy of the spice data that is stored internally to the cube file. Thus when we want to create a DEM using the correct camera geometry, no extra information needs to be given to `stereo` since it is already contained in the file. In the event a mistake has been made, `spiceinit` will overwrite the spice data inside a cube file and provide the original uncorrected camera pointings.

```
ISIS 3> stereo E0201461.cub M0100115.cub bundled/bundled
```

Chapter 6

Data Processing Examples

This chapter showcases a variety of results that are possible when processing different data sets with the Stereo Pipeline. It is also a shortened guide that shows the commands used to process specific mission data. There is no definitive method yet for making elevation models as each stereo pair is unique. We hope that the following sections serve as a cookbook for strategies that will get you started in processing your own data. We recommend that you second check your results against another source.

6.1 Guidelines for Selecting Stereo Pairs

When choosing image pairs to process, images that are taken with similar viewing angles, lighting conditions, and significant surface coverage overlap are best suited for creating terrain models. Depending on the characteristics of the mission data set and the individual images, the degree of acceptable variation will differ. Significant differences between image characteristics increases the likelihood of stereo matching error and artifacts, and these errors will propagate through to the resulting data products.

Although images do not need to be map projected before running the `stereo` program, we recommend that you do run `cam2map` (or `cam2map4stereo.py`) beforehand, especially for image pairs that contain large topographic variation (and therefore large disparity differences across the scene, e.g. Valles Marineris). Map projection is especially necessary when processing HiRISE images. This removes the large disparity differences between HiRISE images and leaves only the small detail for the Stereo Pipeline to compute. Remember that ISIS can work backwards through a map-projection when applying the camera model, so the geometric integrity of your images will not be sacrificed if you map project first.

Excessively noisy images will not correlate well, so images should be photometrically calibrated in whatever fashion suits your purposes. If there are photometric problems with the images, those photometric defects can be misinterpreted as topography.

Remember, in order for `stereo` to process stereo pairs in ISIS cube format, the images must have had SPICE data associated by running ISIS's `spiceinit` program run on them first.

6.1.1 Combatting long run times

The factor that predominantly determines running time in the Stereo Pipeline is the size of the search space considered by the correlation algorithm. These are set in the `stereo.default` file using the `corr-search` parameter. If you comment that parameter out (either by putting a '`#`' at the beginning of their line or deleting them from your `stereo.default` file), the Stereo Pipeline will try to automatically determine the search range for you, but this does not always work perfectly. A spurious bad match can lead the pipeline

to select a search range that is far too large, and performance will suffer as a result. If you know (or can estimate) the range of horizontal and vertical offsets you expect to see between the two images, then you may want to try setting the search range yourself in your `stereo.default` using the aforementioned parameters.

More generally, here are three strategies that tend to keep the search range small and run-times low:

1. You can crop your stereo pair (using the ISIS `crop` command) to a small region of interest within a large stereo pair. ISIS and the Stereo Pipeline will keep track of these crop parameters automatically and take them into account when applying the camera model during triangulation. You may want to work with a cropped pair when you first start working with a new data set. Run times will be much lower (minutes instead of days), and you can quickly tune parameters in the `stereo.default` file before scaling up to the full image.

2. The ISIS `reduce` command can be used to subsample the image pair. In this case, you are trading resolution for speed, so this probably only makes sense for debugging or "previewing" 3D terrain. That said, subsampling will tend to increase the signal to noise ratio, so it may also be helpful for pulling 3D terrain out of noisy, low quality images.

   These options of croping or reducing the resolution of the source imagery are only easily achieved with ISIS sessions. Pinhole and Digital Globe sessions will be required to manually edit their camera models in the event that you have edited the source imagery. This is a unique problem for each camera model and thus will not be discussed here.

3. You can map project the images (using the ISIS `cam2map` command or the `cam2map4stereo.py` program provided with the Stereo Pipeline). If you project both images into the same map projection and same pixel scale, then they will be aligned modulo uncertainty in spacecraft telemetry (typically 10-100's of meters of error when the image is projected onto the ground). By default `cam2map` will also project the image onto the local elevation model (MOLA or LOLA), which removes the stereo disparity in the images that is due to coarse topography. The resulting image pair has only small position offsets and fine 3D detail left to discover, so the search range can be kept very small and run times can be improved. Again, ISIS and the Stereo Pipeline will keep track of how these map projections affect the camera model, and take them into account when building up the 3D mesh via triangulation. If you use `cam2map`, be sure that your `stereo.default`'s `alignment-method` is set to NONE. Note also that the `--lat` and `--lon` arguments to `cam2map4stereo.py` can be used to crop your stereo images, and the `--resolution` argument can be used to subsample them.

If you are working with very large images, we highly recommend cropping or subsampling and working with smaller sized images while you fine-tune the parameters in the `stereo.default` file, and once you get satisfactory results to apply those parameters to the full images.

6.2 Mars Reconnaissance Orbiter HiRISE

HiRISE is one of the most challenging cameras to use when making 3D models because HiRISE exposures can be several gigabytes each. Working with this data requires patience as it will take time.

One important fact to know about HiRISE is that it is composed of multiple linear CCDs that are arranged side by side with some vertical offsets. These offsets mean that the CCDs will view some of the same terrain but at a slightly different time and a slightly different angle. Mosaicking the CCDs together to a single image is not a simple process and involves living with some imperfections.

One cannot simply use the HiRISE RDR products, as they do not have the required geometric stability. Instead, the HiRISE EDR products must be assembled using ISIS `noproj`. The USGS distributes a script in use by the HiRISE team that works forward from the team-produced 'balance' cubes, which provides a de-jittered, noproj'ed mosaic of a single observation, which is perfectly suitable for use by the Stereo Pipeline (this script was originally engineered to provide input for SOCET SET). However, the 'balance' cubes are not available to the general public, and so we include a program (`hiedr2mosaic.py`, written in Python) that will take PDS available HiRISE EDR products and walk through the processing steps required to provide good input images for `stereo`.

The program takes all the red CCDs and projects them using the ISIS `noproj` command into the perspective of the RED5 CCD. From there, `hijitreg` is performed to work out the relative offsets between CCDs. Finally the CCDs are mosaicked together using the average offset listed from `hijitreg` using the `handmos` command. Below is an outline of the processing.

```
hi2isis          # Import HiRISE IMG to Isis
hical            # Calibrate
histitch         # Assemble whole-CCD images from the channels
spiceinit
spicefit         # For good measure
noproj           # Project all images into perspective of RED5
hijitreg         # Work out alignment between CCDs
handmos          # Mosaic to single file
```

To use our script, first go to the directory where you have downloaded the HiRISE's RED EDR `IMG` files. You can run the `hiedr2mosaic.py` program without any arguments to view a short help statement, with the `-h` option to view a longer help statement, or just run the program on the EDR files like so:

```
hiedr2mosaic.py *.IMG
```

If you have more than one observation's worth of EDRs in that directory, then limit the program to just one observation's EDRs at a time, e.g. `hiedr2mosaic.py PSP_001513_1655*IMG`. If you run into problems, try using the `-k` option to retain all of the intermediary image files to help track down the issue. The `hiedr2mosaic.py` program will create a single mosaic file with the extension `.mos_hijitreged.norm.cub`. Be warned that the operations carried out by `hiedr2mosaic.py` can take many hours to complete on the very large HiRISE images.

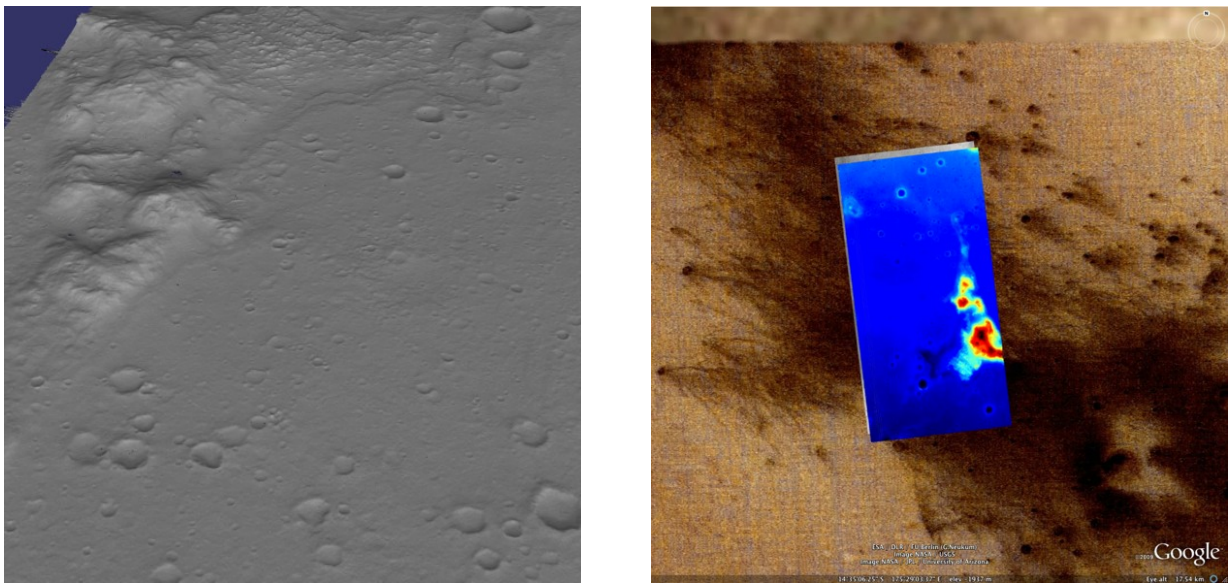
Finally we recommend map projecting the product and normalizing both images in the stereo pair using the same dynamic range. Notice that we map project the second image using the same map settings and crop of the first image. This means the images will share the same origin and the `stereo.default` search range can be centered around zero.

```
ISIS 3> cam2map4stereo.py first.mos_hijitreged.norm.cub second.mos_hijitreged.norm.cub
ISIS 3> bandnorm f=first.map.cub t=first.norm.cub
ISIS 3> bandnorm f=second.map.cub t=second.norm.cub
ISIS 3> ls first.norm.cub second.norm.cub > fromlist
ISIS 3> ls first.norm.cub > holdlist
ISIS 3> equalizer fromlist=fromlist holdlist=holdlist
ISIS 3> mkdir result
ISIS 3> stereo first.norm.equ.cub second.norm.equ.cub result/output
```

In the future, the HiRISE team will be producing de-jittered, noproj'ed imagery in the `extras/` directory of their PDS volume. When this happens, most of the above commands will no longer be required, as you will be able to just run `cam2map4stereo.py` on their provided imagery.

6.2.1 Columbia Hills

HiRISE observations PSP_001513_1655 and PSP_001777_1650 are on the floor of Gusev Crater and cover the area where the MER Spirit landed and has roved, including the Columbia Hills.



(a) `3D Rendering` (b) `KML Screenshot`

Figure 6.1: Example output using HiRISE images PSP_001513_1655 and PSP_001777_1650 of the Columbia Hills.

Commands

Download all 20 of the RED EDR `.IMG` files for each observation.

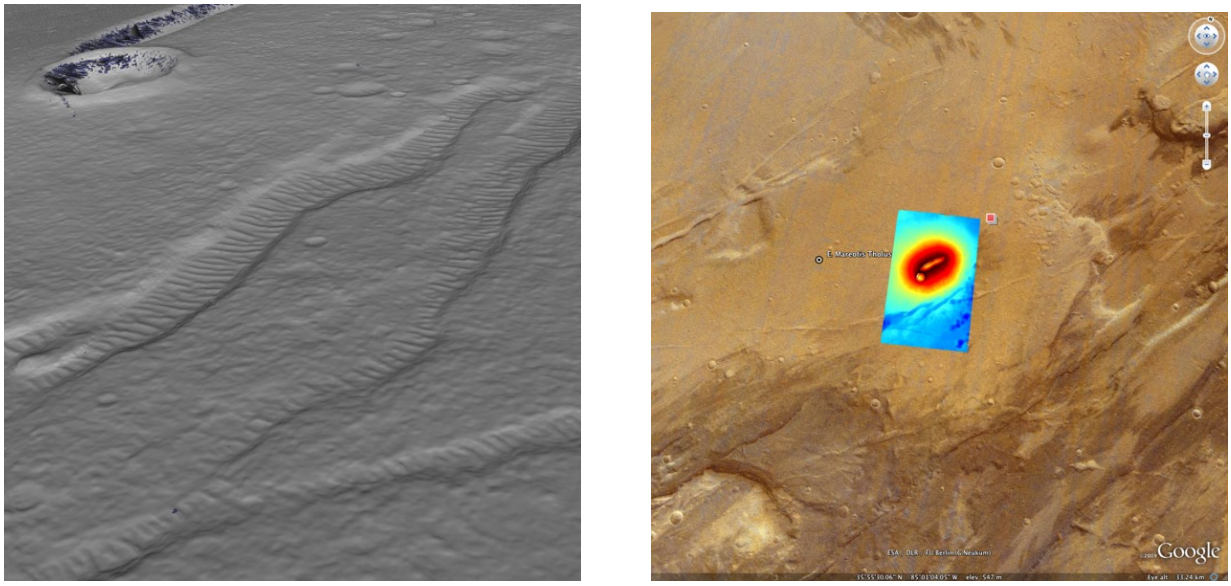
```
ISIS 3> hiedr2mosaic.py PSP_001513_1655_RED*.IMG
ISIS 3> hiedr2mosaic.py PSP_001777_1650_RED*.IMG
ISIS 3> cam2map4stereo.py PSP_001777_1650_RED.mos_hijitreged.norm.cub \
                          PSP_001513_1655_RED.mos_hijitreged.norm.cub
ISIS 3> bandnorm from=PSP_001513_1655_RED.map.cub \
                 to=PSP_001513_1655_RED.map.norm.cub
ISIS 3> bandnorm from=PSP_001777_1650_RED.map.cub \
                 to=PSP_001777_1650_RED.map.norm.cub
ISIS 3> rm *RED.map.cub
ISIS 3> mkdir result
ISIS 3> stereo PSP_001513_1655.map.norm.cub \
               PSP_001777_1650.map.norm.cub result/output
```

stereo.default

The stereo.default example file should apply well to HiRISE. Just set `alignment-method` to `homography`. The `corr-kernel` value can usually be safely reduced to 21 pixels to resolve finer detail and faster processing for images with good contrast.

6.2.2 East Mareotis Tholus

HiRISE observations PSP_001760_2160 and PSP_001364_2160 cover East Mareotis Tholus, a small volcano in Tempe Terra.



(a) `3D Rendering` (b) `KML Screenshot`

Figure 6.2: Example output using HiRISE images PSP_001364_2160 and PSP_001760_2160 of East Mareotis Tholus.

Commands

Download all 20 of the RED EDR `.IMG` files for each observation.

```
ISIS 3> hiedr2mosaic.py PSP_001364_2160_RED*.IMG
ISIS 3> hiedr2mosaic.py PSP_001760_2160_RED*.IMG
ISIS 3> cam2map4stereo.py PSP_001364_2160_RED.mos_hijitreged.norm.cub \
                          PSP_001760_2160_RED.mos_hijitreged.norm.cub
ISIS 3> bandnorm from=PSP_001364_2160_RED.map.cub \
                 to=PSP_001364_2160_RED.map.norm.cub
ISIS 3> bandnorm from=PSP_001760_2160_RED.map.cub \
                 to=PSP_001760_2160_RED.map.norm.cub
ISIS 3> ls *.map.norm.cub > fromlist
ISIS 3> ls *1760*.map.norm.cub > holdlist
ISIS 3> equalizer fromlist=fromlist holdlist=holdlist
ISIS 3> rm *RED.map.norm.cub *RED.map.cub
ISIS 3> mkdir result
ISIS 3> stereo PSP_001364_2160.map.norm.equ.cub \
               PSP_001760_2160.map.norm.equ.cub result/output
```

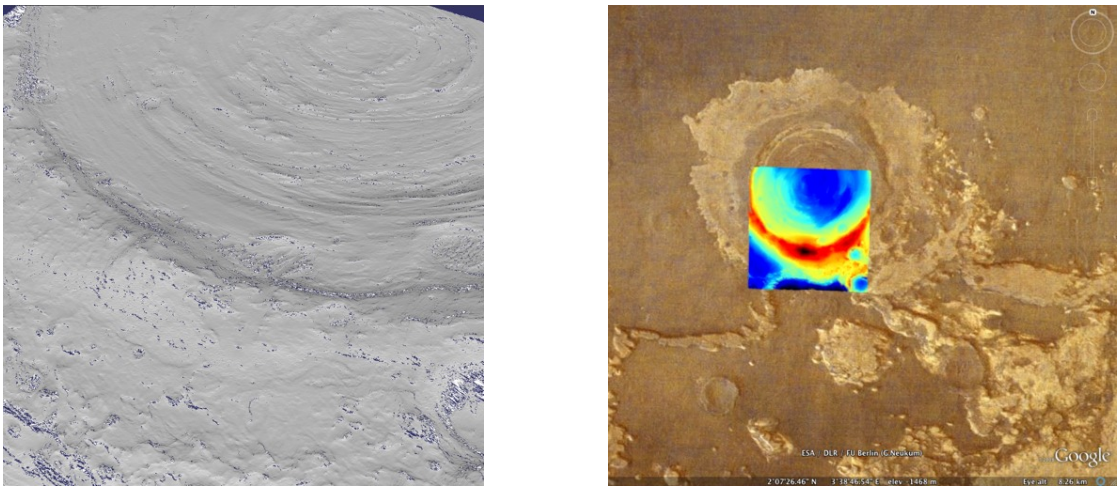
stereo.default

The stereo.default example file should apply well to HiRISE. Just set `alignment-method` to `homography`. The `corr-kernel` parameter can usually be safely reduced to 21 pixels to resolve finer detail and faster

processing for images with good contrast.

6.2.3 North Terra Meridiani Crop

HiRISE observations PSP_001981_1825 and PSP_002258_1825 show a small crater filled by layered material.



(a) 3D Rendering (b) KML Screenshot

Figure 6.3: Example output using cropped HiRISE data of North Terra Meridiani.

Commands

Notice here that we have applied a crop to select a subset of these HiRISE images that we are interested in. Cropping is often an efficient way to go because it greatly reduces the amount of computation necessary to get results in a limited area. As always, Download all 20 of the RED EDR `.IMG` files for each observation.

```
ISIS 3> hiedr2mosaic.py PSP_001981_1825_RED*.IMG
ISIS 3> hiedr2mosaic.py PSP_002258_1825_RED*.IMG
ISIS 3> cam2map from=PSP_001981_1825_RED.mos_hijitreged.norm.cub \
                 to=PSP_001981_1825_REDmosaic.map.cub
ISIS 3> cam2map from=PSP_002258_1825_RED.mos_hijitreged.norm.cub \
                map=PSP_001981_1825_REDmosaic.map.cub \
                 to=PSP_002258_1825_REDmosaic.map.cub matchmap=true
ISIS 3> bandnorm from=PSP_001981_1825_REDmosaic.map.cub \
                  to=PSP_001981_1825_REDmosaic.map.norm.cub
ISIS 3> bandnorm from=PSP_002258_1825_REDmosaic.map.cub \
                  to=PSP_002258_1825_REDmosaic.map.norm.cub
ISIS 3> ls *.map.norm.cub > fromlist
ISIS 3> ls *1981*.map.norm.cub > holdlist
ISIS 3> equalizer fromlist=fromlist holdlist=holdlist
ISIS 3> crop from=PSP_001981_1825_REDmosaic.map.norm.equ.cub \
              to=PSP_001981_1825.crop.cub sample=7497 line=41318 nsamp=10000 nline=10000
ISIS 3> crop from=PSP_002258_1825_REDmosaic.map.norm.equ.cub \
              to=PSP_002258_1825.crop.cub sample=7982 line=41310 nsamp=10000 nline=10000
ISIS 3> rm *REDmosaic*.cub
ISIS 3> mkdir result
ISIS 3> stereo PSP_001981_1825.crop.cub PSP_002258_1825.crop.cub result/output
```

stereo.default

The stereo.default example file should apply well to HiRISE. Just set `alignment-method` to `homography`. The `corr-kernel` value can usually be safely reduced to 21 pixels to resolve finer detail and faster processing for images with good contrast.

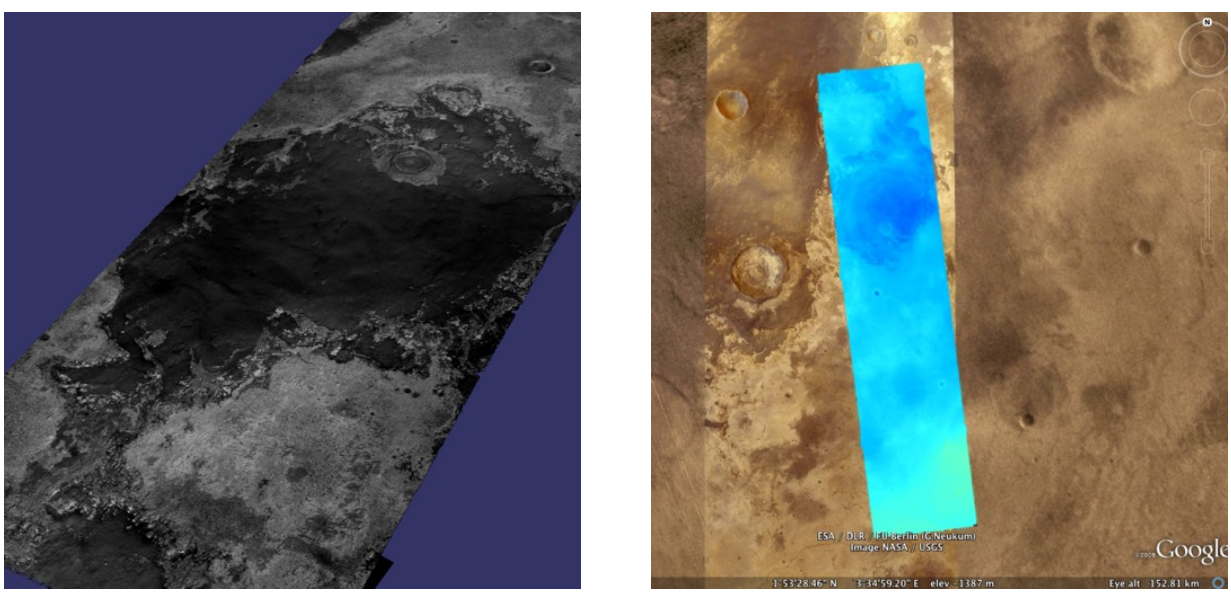
6.3 Mars Reconnaissance Orbiter CTX

Context Camera (CTX) is a moderate camera to work with. Processing times for CTX can be pretty long when using Bayes EM subpixel refinement. Otherwise the disparity between images is relatively small, allowing efficient computation and a reasonable processing time.

6.3.1 North Terra Meridiani

In this example, we use map projected images. Map projecting the images is the most reliable way to align the images for correlation. However when possible, use non-map-projected images with the `alignment-method homography` option. This greatly reduces the time spent in triangulation. For all cases using linescan cameras, triangulation of map-projected images is 10x slower than non-map-projected images.

This example is distributed in the `examples/CTX` directory.



(a) `3D Rendering` (b) `KML Screenshot`

Figure 6.4: Example output possible with the CTX imager aboard MRO.

Commands

Download the CTX images P02_001981_1823_XI_02N356W.IMG and P03_002258_1817_XI_01N356W.IMG from the PDS.

```
ISIS 3> mroctx2isis from=P02_001981_1823_XI_02N356W.IMG to=P02_001981_1823.cub
ISIS 3> mroctx2isis from=P03_002258_1817_XI_01N356W.IMG to=P03_002258_1817.cub
ISIS 3> spiceinit from=P02_001981_1823.cub
ISIS 3> spiceinit from=P03_002258_1817.cub
ISIS 3> ctxcal from=P02_001981_1823.cub to=P02_001981_1823.cal.cub
ISIS 3> ctxcal from=P03_002258_1817.cub to=P03_002258_1817.cal.cub
  you can also optionally run ctxevenodd on the cal.cub files, if needed
ISIS 3> cam2map4stereo.py P02_001981_1823.cal.cub P03_002258_1817.cal.cub
ISIS 3> mkdir result
ISIS 3> stereo P02_001981_1823.map.cub P03_002258_1817.map.cub results/out
```

stereo.default

The stereo.default example file works generally well with all CTX pairs. Just set `alignment-method` to `homography`.

6.4 Mars Global Surveyor MOC-NA

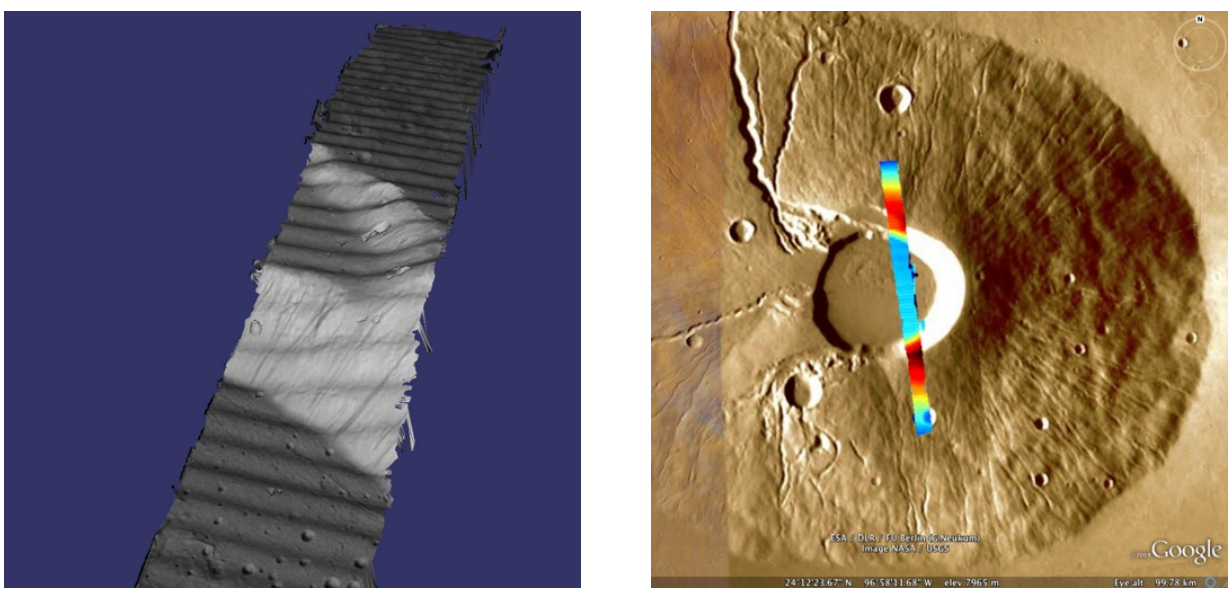
In the Stereo Pipeline Tutorial in Chapter 3, we showed you how to process a narrow angle MOC stereo pair that covered a portion of Hrad Vallis. In this section we will show you more examples, some of which exhibit a problem common to stereo pairs from linescan imagers: "spacecraft jitter" is caused by oscillations of the spacecraft due to the movement of other spacecraft hardware. All spacecraft wobble around to some degree but some are particularly susceptible.

Jitter causes wave-like distortions along the track of the satellite orbit in DEMs produced from linescan camera images. This effect can be very subtle or quite pronounced, so it is important to check your data products carefully for any sign of this type of artifact. The following examples will show the typical distortions created by this problem.

Note that the science teams of HiRISE and Lunar Reconnaissance Orbiter Camera (LROC) are actively working on detecting and correctly modeling jitter in their respective SPICE data. If they succeed in this, the distortions will still be present in the raw imagery, but the jitter will no longer produce ripple artifacts in the DEMs produced using ours or other stereo reconstruction software.

6.4.1 Ceraunius Tholus

Ceraunius Tholus is a volcano in northern Tharsis on Mars. It can be found at 23.96 N and 262.60 E. This DEM crosses the volcano's caldera.



(a) `3D Rendering` (b) `KML Screenshot`

Figure 6.5: Example output for MOC-NA of Ceraunius Tholus. Notice the presence of severe washboarding artifacts due to spacecraft "jitter."

Commands

Download the M08/06047 and R07/01361 images from the PDS.

```
ISIS 3> moc2isis f=M0806047.img t=M0806047.cub
```

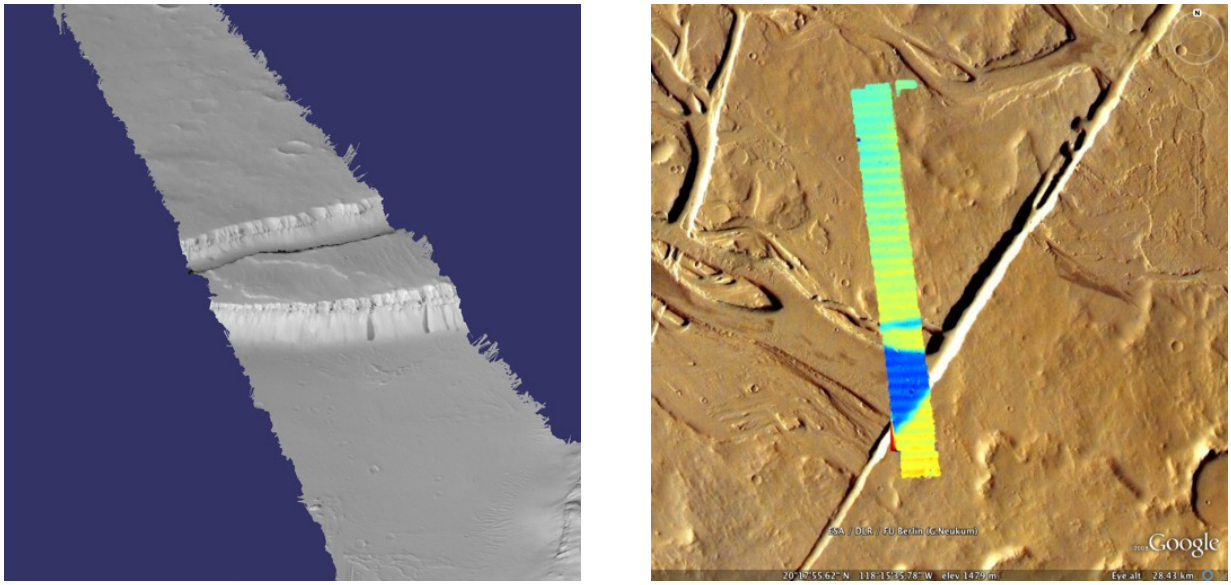
```
ISIS 3> moc2isis f=R0701361.img t=R0701361.cub
ISIS 3> spiceinit from=M0806047.cub
ISIS 3> spiceinit from=R0701361.cub
ISIS 3> cam2map4stereo.py M0806047.cub R0701361.cub
ISIS 3> mkdir result
ISIS 3> stereo M0806047.map.cub R0701361.map.cub result/output
```

stereo.default

The stereo.default example file works generally well with all MOC-NA pairs. Just set `alignment-method` to `homography`.

6.4.2 North Tharsis

These images cover troughs and terraces in northern Tharsis. This DEM is located at 20.20 N and 118.18 W on Mars.



(a) `3D Rendering` (b) `KML Screenshot`

Figure 6.6: Example output for MOC-NA of North Tharsis.

Commands

Download the M08/03097.img and S07/01420 images from the PDS.

```
ISIS 3> moc2isis f=M0803097.img t=M0803097.cub
ISIS 3> moc2isis f=S0701420.img t=S0701420.cub
ISIS 3> cam2map4stereo.py M0803097.cub S0701420.cub
ISIS 3> mkdir result
ISIS 3> stereo M0803097.map.cub S0701420.map.cub result/output
```

stereo.default

The stereo.default example file works generally well with all MOC-NA pairs. Just set `alignment-method` to `homography`.

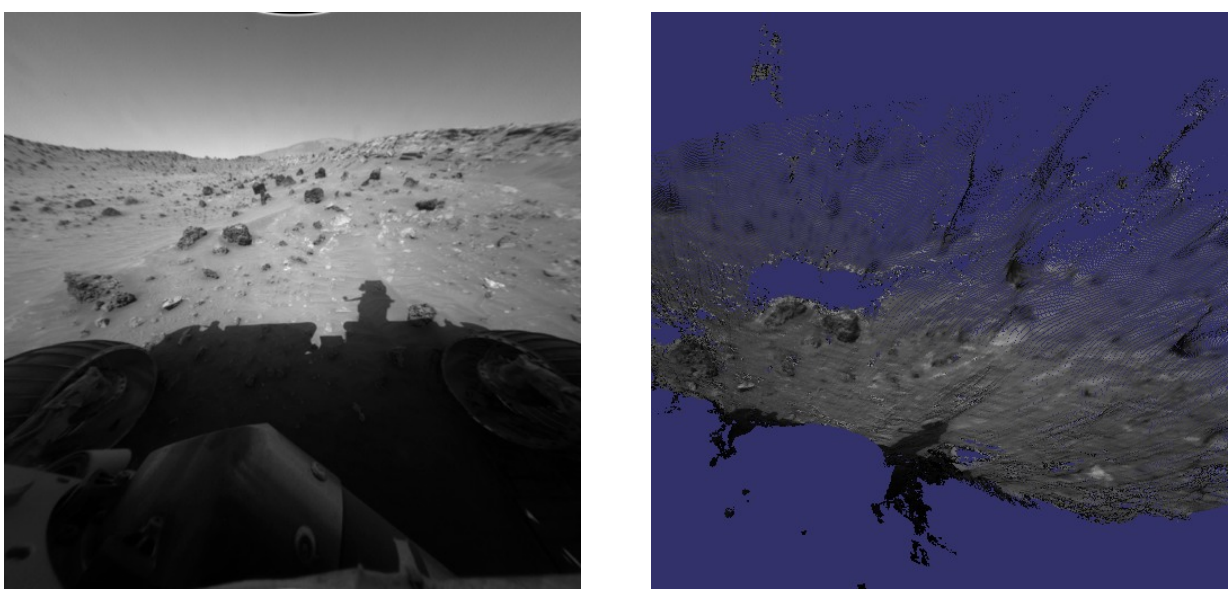
6.5 Mars Exploration Rovers MER

The MER rovers have several cameras on board and they all seem to have a stereo pair. With ASP you are able to process the PANCAM, NAVCAM, and HAZCAM camera imagery. ISIS has no telemetry or camera instrinsic supports for these images. That however is not a problem as their raw imagery contains the cameras' information in JPL's CAHV, CAHVOR, and CHAVORE formats.

These cameras are all variations of a simple pinhole camera model so they are processed with ASP in the `PINHOLE` session instead of the usual `ISIS`. ASP only supports creating of point clouds. *The *-PC.tif is a raw point cloud with the first 3 channels being XYZ in the rover site's coordinate frame.* We don't support the creation of DEMs from these images and that is left as an excercise for the user.

6.5.1 PANCAM, NAVCAM, HAZCAM

All of these cameras are processed the same way. I'll be showing 3D processing of the front hazard cams. The only new things in the pipeline is the new executable `mer2camera` along with the use of `alignment-method epipolar`. This example is also provided in the MER data example directory.



(a) `Rectified Input` (b) `Output Point Cloud`

Figure 6.7: Example output possible with the front hazard cameras.

Commands

Download 2f194370083effap00p1214l0m1.img and 2f194370083effap00p1214r0m1.img from the PDS.

```
ISIS 3> gdal_translate -scale -ot byte 2f194370083effap00p1214l0m1.img \
                                       2f194370083effap00p1214l0m1.tif
ISIS 3> gdal_translate -scale -ot byte 2f194370083effap00p1214r0m1.img \
                                       2f194370083effap00p1214r0m1.tif
ISIS 3> mer2camera 2f194370083effap00p1214l0m1.img
ISIS 3> mer2camera 2f194370083effap00p1214r0m1.img
ISIS 3> stereo 2f194370083effap00p1214l0m1.tif 2f194370083effap00p1214r0m1.tif \
               2f194370083effap00p1214l0m1.cahvore 2f194370083effap00p1214r0m1.cahvore \
               fh01/fh01
```

stereo.default

The default stereo settings will work but change the following options:

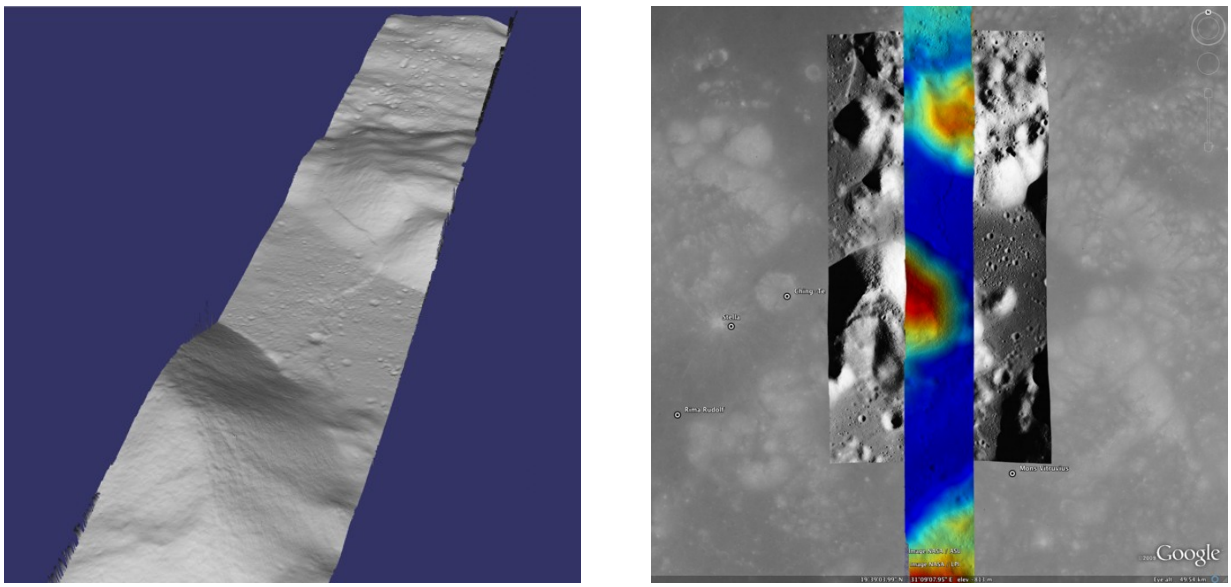
```
additional settings for MER
    alignment-method EPIPOLAR
    force-use-entire-range

    # This deletes points that are too far away
    # from the camera to truly triangulate.
    universe-center Camera
    near-universe-radius 0.7
    far-universe-radius 80.0
```

6.6 Lunar Reconaissance Orbiter LROC NAC

6.6.1 Lee-Lincoln Scarp

This stereo pair covers the Taurus-Littrow valley on the Moon where, on December 11, 1972, the astronauts of Apollo 17 landed. However, this stereo pair does not contain the landing site. It is slightly west; focusing on the Lee-Lincoln scarp that is on North Massif. The scarp is an 80 m high feature that is the only visible sign of a deep fault.



(a) 3D Rendering (b) KML Screenshot

Figure 6.8: Example output possible with a LROC NA stereo pair, using only a single CCD from each observation.

Commands

Download the EDRs for the left CCDs for observations M104318871 and M104318871. Alternatively you can search by original IDs of 2DB8 and 4C86 in the PDS.

```
ISIS 3> lronac2isis from=M104318871LE.img to=M104318871LE.cub
ISIS 3> lronac2isis from=M104311715LE.img to=M104311715LE.cub
ISIS 3> spiceinit M104318871LE.cub
ISIS 3> spiceinit M104311715LE.cub
ISIS 3> lronaccal from=M104318871LE.cub to=M104318871LE.cal.cub
ISIS 3> lronaccal from=M104311715LE.cub to=M104311715LE.cal.cub
ISIS 3> cam2map4stereo.py M104318871LE.cal.cub M104311715LE.cal.cub
ISIS 3> stereo M104318871LE.map.cub M104311715LE.map.cub result/output
```

stereo.default

The stereo.default example file works generally well with LRO-NAC pairs. The recommended route for processing LRO-NAC imagery is by map projecting them. Map-projecting with higher resolution data such

as LRO-WAC Global DTM also helps processing greatly. When map projecting, be sure to remember to set `alignment-method NONE`.

6.7 Apollo 15 Metric Camera Images

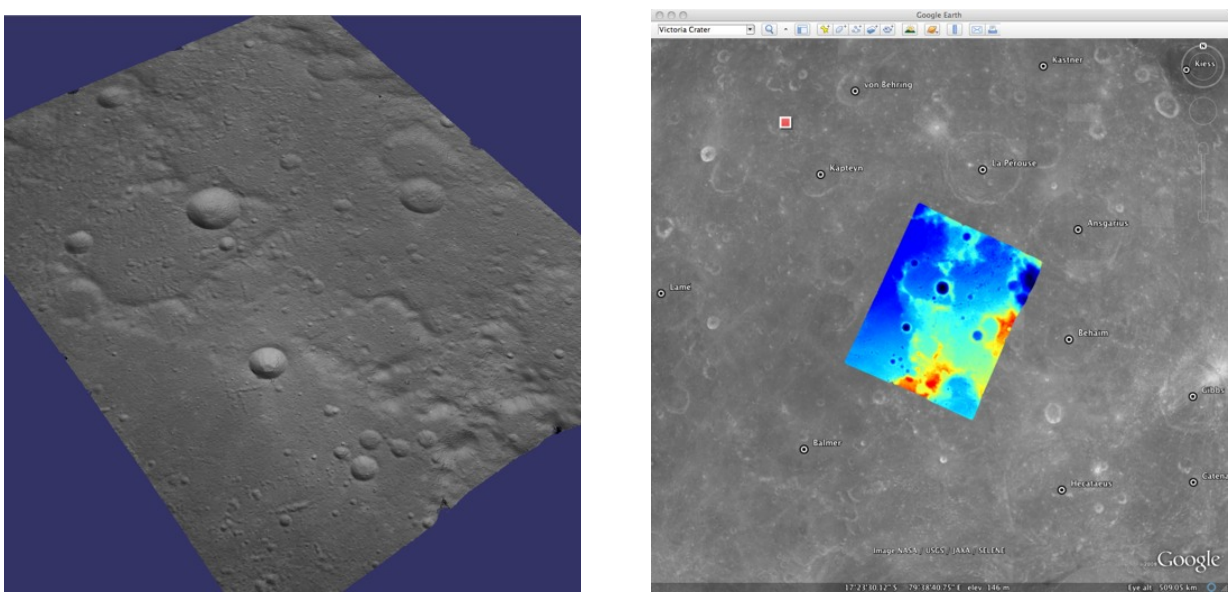
Apollo Metric images were all taken at regular intervals, which means that the same `stereo.default` can be used for all sequential pairs of images. Apollo Metric images are ideal for stereo processing. They produce consistent, excellent results.

The scans performed by ASU are sufficiently detailed to exhibit film grain at the highest resolution. The amount of noise at the full resolution is not helpful for the correlator, so we recommend subsampling the images by a factor of 4.

Currently the tools to ingest Apollo TIFFs into ISIS are not available, but these images should soon be released into the PDS for general public usage.

6.7.1 Ansgarius C

Ansgarius C is a small crater on the west edge of the farside of the Moon near the equator. It is east of Kapteyn A and B.



(a) `3D Rendering` (b) `KML Screenshot`

Figure 6.9: Example output possible with Apollo Metric frames AS15-M-2380 and AS15-M-2381.

Commands

Process Apollo TIFF files into ISIS.

```
ISIS 3> reduce from=AS15-M-2380.cub to=sub4-AS15-M-2380.cub sscale=4 lscale=4
ISIS 3> reduce from=AS15-M-2381.cub to=sub4-AS15-M-2381.cub sscale=4 lscale=4
ISIS 3> spiceinit from=sub4-AS15-M-2380.cub
ISIS 3> spiceinit from=sub4-AS15-M-2381.cub
ISIS 3> mkdir result
ISIS 3> stereo sub4-AS15-M-2380.cub sub4-AS15-M-2381.cub result/output
```

stereo.default

The stereo.default example file works generally well with all Apollo pairs. Just set `alignment-method` to `homography`.

6.8 Cassini ISS NAC

This is a proof of concept showing the strength of building the Stereo Pipeline on top of ISIS. Support for processing ISS NAC stereo pairs was not a goal during our design of the software, but the fact that a camera model exists in ISIS means that it too can be processed by the Stereo Pipeline.

Identifying stereo pairs from spacecraft that do not orbit their target is a challenge. We have found that one usually has to settle with images that are not ideal: different lighting, little perspective change, and little or no stereo parallax. So far we have had little success with Cassini's data, but nonetheless we provide this example as a potential starting point.

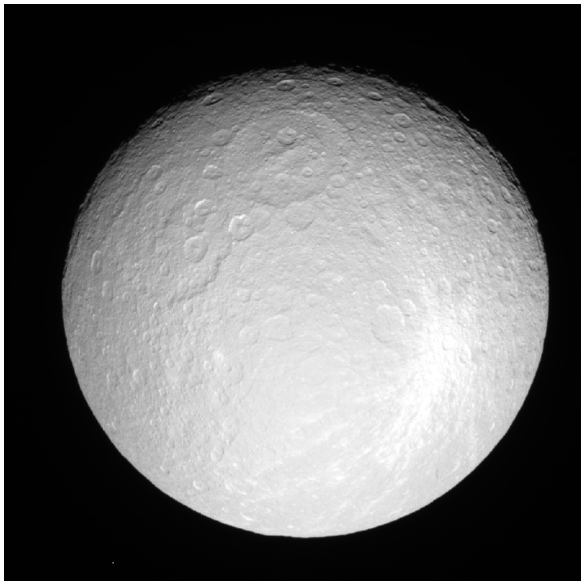
6.8.1 Rhea

Rhea is the second largest moon of Saturn and is roughly a third the size of our own Moon. This example shows, at the top right of both images, a giant impact basin named Tirawa that is 220 miles across. The bright white area south of Tirawa is ejecta from a new crater. The lack of texture in this area poses a challenge for our correlator. The results are just barely useful: the Tirawa impact can barely be made out in the 3D data while the new crater and ejecta become only noise.

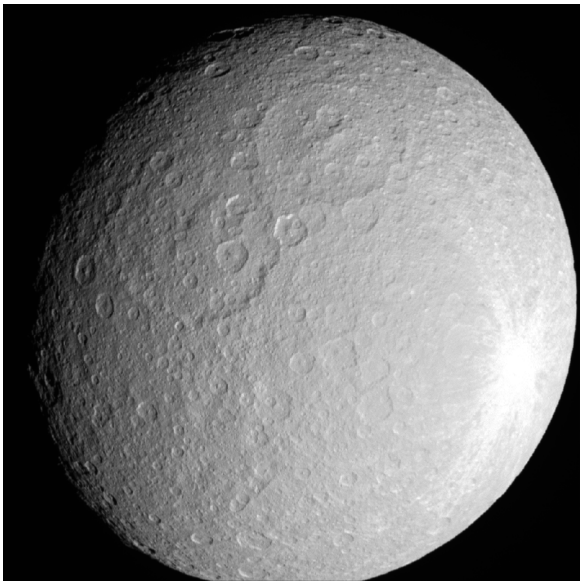
Commands

Download the N1511700120_1.IMG and W1567133629_1.IMG images and their label (.LBL) files from the PDS.

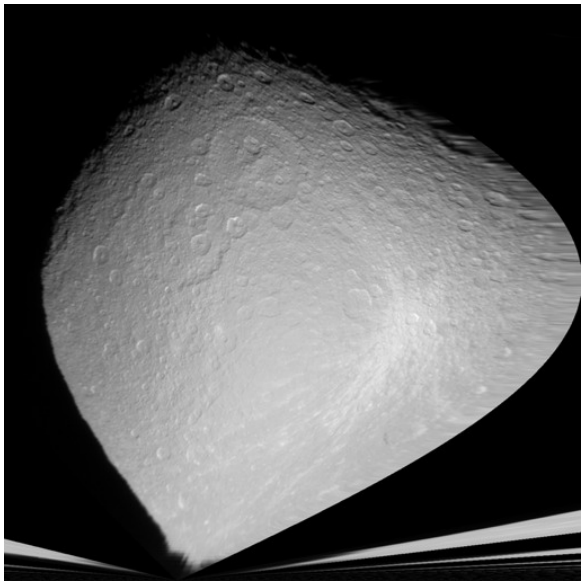
```
ISIS 3> ciss2isis f=N1511700120_1.LBL t=N1511700120_1.cub
ISIS 3> ciss2isis f=W1567133629_1.LBL t=W1567133629_1.cub
ISIS 3> cisscal from=N1511700120_1.cub to=N1511700120_1.lev1.cub
ISIS 3> cisscal from=W1567133629_1.cub to=W1567133629_1.lev1.cub
ISIS 3> fillgap from=W1567133629_1.lev1.cub to=W1567133629_1.fill.cub %Only one image
                                                                      %exhibits the problem
ISIS 3> cubenorm from=N1511700120_1.lev1.cub to=N1511700120_1.norm.cub
ISIS 3> cubenorm from=W1567133629_1.fill.cub to=W1567133629_1.norm.cub
ISIS 3> spiceinit fr= N1511700120_1.norm.cub
ISIS 3> spiceinit fr= W1567133629_1.norm.cub
ISIS 3> cam2map from=N1511700120_1.norm.cub to=N1511700120_1.map.cub
ISIS 3> cam2map from=W1567133629_1.norm.cub map=N1511700120_1.map.cub \
ISIS 3>          to=W1567133629_1.map.cub matchmap=true
ISIS 3> ls *.map.cub > fromlist
ISIS 3> ls N*.map.cub > holdlist
ISIS 3> equalizer fromlist=fromlist holdlist=holdlist
ISIS 3> mkdir result
ISIS 3> stereo N1511700120_1.map.equ.cub W1567133629_1.map.equ.cub result/rhea
```



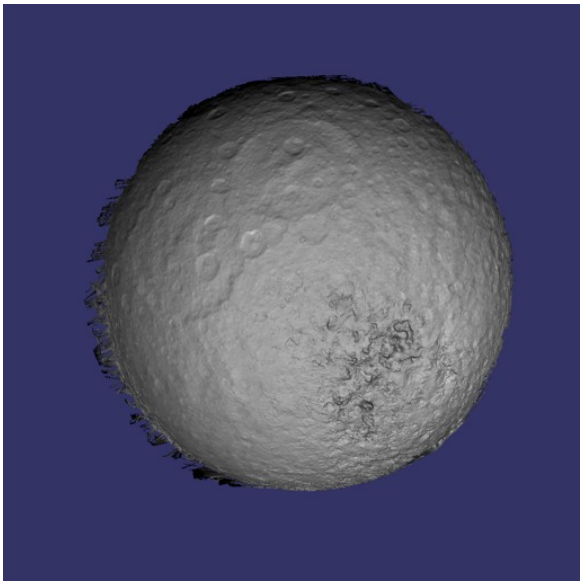
(a) `Original Left Image`



(b) `Original Right Image`



(c) `Map Projected Left`



(d) `3D Rendering`

Figure 6.10: Example output of what is possible with Cassini's ISS NAC

stereo.default

stereo.default for Cassini ISS

```
### PREPROCESSING
alignment-method None
force-use-entire-range
individually-normalize

### CORRELATION
prefilter-mode 2
prefilter-kernel-width 1.5

cost-mode 2

corr-kernel 25 25
corr-search -55 -2 -5 10

subpixel-mode 3
subpixel-kernel 21 21

### FILTERING
rm-half-kernel 5 5
rm-min-matches 60 # Units = percent
rm-threshold 3
rm-cleanup-passes 1
```

6.9 Digital Globe Imagery

Digital Globe provides imagery from the Quick Bird and the three World View satellites. These are the hardest images to process with Ames Stereo Pipeline because they are exceedingly large, much larger than HiRISE imagery. There is also a wide range of terrain challenges and atmospheric effects that can confuse ASP. Trees are particularly difficult for us since their texture is nearly nadir and perpendicular to our line of sight. It is important to know that the driving force behind our support for Digital Globe imagery is to create models of ice and bare rock. That is the type of imagery that we have tested with and have focused on. If we can make models of wooded or urban areas, that is a bonus, but we can't provide any advice for how to perform or improve the results if you choose to use ASP in that way.

ASP can only process Level 1B imagery and can not process Digital Globe's aerial imagery. We can pull a camera model from the RPC coefficients or from their linear camera model described in the provided XML files. We won't be discussing the RPC method in this section, however you can learn more about it in the later example where we discuss processing GeoEye imagery which comes only with RPC coefficients. Our implementation of the linear camera model only models the geometry of the imaging hardware itself and velocity aberration. We do not currently model refraction due to light bending in Earth's atmosphere. It is our understanding that this could represent misplacement of points up to a meter for some imagery. However this is still smaller error than the error from measurement of the spacecraft's position and orientation. We do not provide facilities for correcting spacecraft attitude either. So you will have to perform some manual shifting of the data to get it into the correct location. These errors are fortunately much less than found with extra-terrestrial missions largely due to the availability of GPS and high bandwidth comms with the satellite.

In the next 2 sections we will show how to process unmodified and map projected variants of World View 1 imagery. This steps will be the same for Digital Globe's other satellites. The imagery we are using are from the free stereo pair example of Lucknow, India available from Digital Globe's website [12]. These images represent a non-ideal problem for us since this is an urban location, but at least you should be able to download this imagery yourself and follow along.

6.9.1 Processing Raw

After you have downloaded the example stereo imagery of India, you will find a directory titled `052783824050_01_P001_`
It contains a lot of files and many of them contain redundant information just displayed in different forms. We are interested only in the TIF or NTF imagery and the similarly named XML file. In this example product from Digital Globe, we received our ideal format of a TIFF file. NTF files can sometimes use JPEG2000 for the underlining encoding. We supply a decoder from OpenJPEG in ASP, unfortunately it is quite slow and might mean extremely long preprocessing times.

Further investigation of the files downloaded will show that there are in fact 4 files. This is because Digital Globe breaks down a single observation into multiple files for what we assume are size reasons. These files have a pattern string of "_R[N]C1-", where N increments for every subframe of the full observation. ASP currently doesn't know how to ingest an entire frame, so instead we can only process pairs of subframes.

Since we are ingesting these images raw, it is strongly recommend that you use a homography alignment to reduce the search range. Processing with the `stereo` command is as simple as feeding the imagery as the second and third argument. The XML data is fed as the camera model argument and thus are used as the fourth and fifth argument. The completed command and a rendering in QGIS are shown below.

Commands

```
> stereo 12FEB12053305-P1BS_R2C1-052783824050_01_P001.TIF \
```

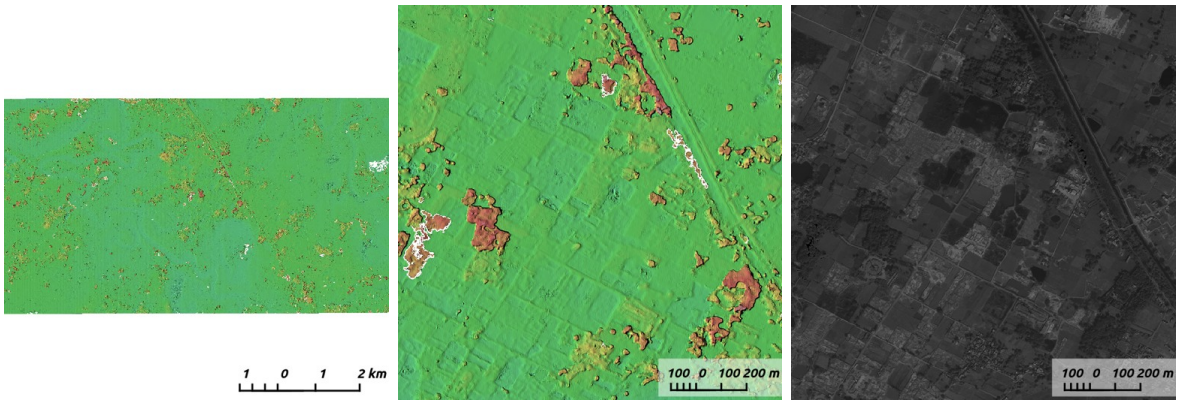


Figure 6.11: Example colorized height map and ortho image output.

```
12FEB12053341-P1BS_R2C1-052783824050_01_P001.TIF \
12FEB12053305-P1BS_R2C1-052783824050_01_P001.XML \
12FEB12053341-P1BS_R2C1-052783824050_01_P001.XML dg/dg
```

stereo.default

The stereo.default example file works generally well with all Digital Globe pairs. As well as they can anyways. Just set `alignment-method` to `homography`.

6.9.2 Processing Map Projected Imagery

Eventually you will run into Digital Globe imagery that has too much parallax to be processed in a reasonable time. (That wasn't the case for Lucknow, India because it is so flat.) We can speed up the result by processing map projected versions of the imagery. The catch is, you are not allowed to use any map projection software you like (such as GDAL). We need to have complete control of the process since ASP will have to work backwards through this math and interpolations in order to make the final elevation model. So we have provided a new utility called `rpc_mapproject` whose commands closely resemble `point2dem`. The purpose of this tool is to use the simplified RPC model to map project the imagery unto a low resolution and hole-less digital elevation model. Later, ASP will then work backwards through the RPC model and then forward through the linear camera model to calculate the final result.

The hardest part of this whole process is getting your input low resolution 3D model. In this example we will use a void filled variant of NASA SRTM data. Other choices might be GMTED2010 or USGS's NED data. However, you must be careful that the DEM data you are downloading does not use a vertical datum. ASP only understand ellipsoidal references such as WGS84. Vertical datums such as NAVD88 used by USGS's NED data products or EGM96 should be added to your DEM's elevations prior to use by ASP. Not doing this might not properly negate the parallax seen between the two images, though it will not corrupt the triangulation results. In other-words, we are saying you can sometimes get lucky ignoring the vertical datums on the input but do not recommend doing that. Also, you should note, that the geoheader attached to those types of files usually do not describe the vertical datum they used. That can only be understood by careful reading of your provider's documents.

The NASA SRTM square for our example spot in India is N26E080. Below are the commands for map projecting the input and then running through stereo. You can use any projection you like as long as it preserves detail in the imagery. Note also that we have added a seventh parameter to the stereo call where we provide the input low resolution DEM.

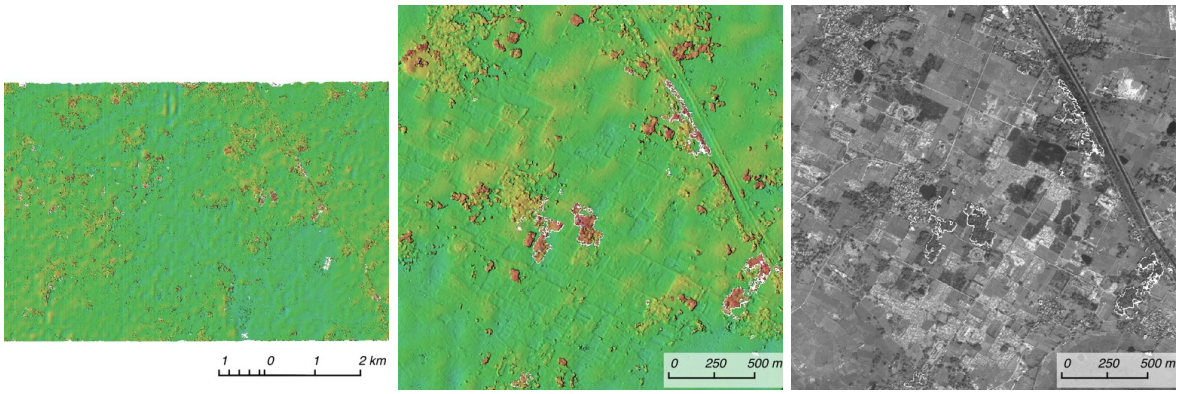


Figure 6.12: Example colorized height map and ortho image output.

Commands

The first step is downloading a void-filled SRTM tile to map project on to. In this example I used, `srtm_53_07.tif`, a 90 meter resolution tile from the CGIAR-CSI modification of the original NASA product [9].

```
> rpc_mapproject --t_srs "+proj=eqc +units=m +datum=WGS84" \
    --tr 0.5 srtm_53_07.tif \
    12FEB12053305-P1BS_R2C1-052783824050_01_P001.TIF \
    12FEB12053305-P1BS_R2C1-052783824050_01_P001.XML \
    left_mapped.tif
> rpc_mapproject --t_srs "+proj=eqc +units=m +datum=WGS84" \
    --tr 0.5 srtm_53_07.tif \
    12FEB12053341-P1BS_R2C1-052783824050_01_P001.TIF \
    12FEB12053341-P1BS_R2C1-052783824050_01_P001.XML \
    right_mapped.tif
> stereo left_mapped.tif right_mapped.tif \
         12FEB12053305-P1BS_R2C1-052783824050_01_P001.XML \
         12FEB12053341-P1BS_R2C1-052783824050_01_P001.XML \
         dg/dg srtm_53_07.tif
```

stereo.default

The stereo.default example file works generally well with all Digital Globe pairs. As well as they can anyways. Just set `alignment-method` to `homography`.

6.10 GeoEye Imagery / RPC Imagery

GeoEye provides imagery from Ikonos and the two GeoEye satellites. They provide only Rational Polynomial Camera (RPC) models. For the uninitiated, RPC represents four 20-element polynomials that map geodetic coordinates to image coordinates. Since they are easy to implement, RPC represents a universal camera model and can be had from many imaging providers such as RapidEye and Digital Globe. The only downside is that it has less precision in our opinion compared to the linear camera model provided by Digital Globe. For GeoEye, the only option is using RPC.

Our RPC read driver is GDAL. If the command `gdalinfo` can identify the RPC information inside the headers of your files, we will likely be able to see it as well. This means that sometimes we can get away with only providing a left and right image. This is specifically the case for GeoEye.

You can download an example stereo pair from GeoEye's website at [11]. When we accessed the site, we downloaded a GeoEye-1 image of Hobart, Australia. As previously stated in the Digital Globe section, these types of images are not ideal for Ames Stereo Pipeline. This is both a forest and a urban area which makes correlation difficult. ASP was designed more for modeling bare rock and ice. Any results we produce in other environments is a bonus but is not our objective.

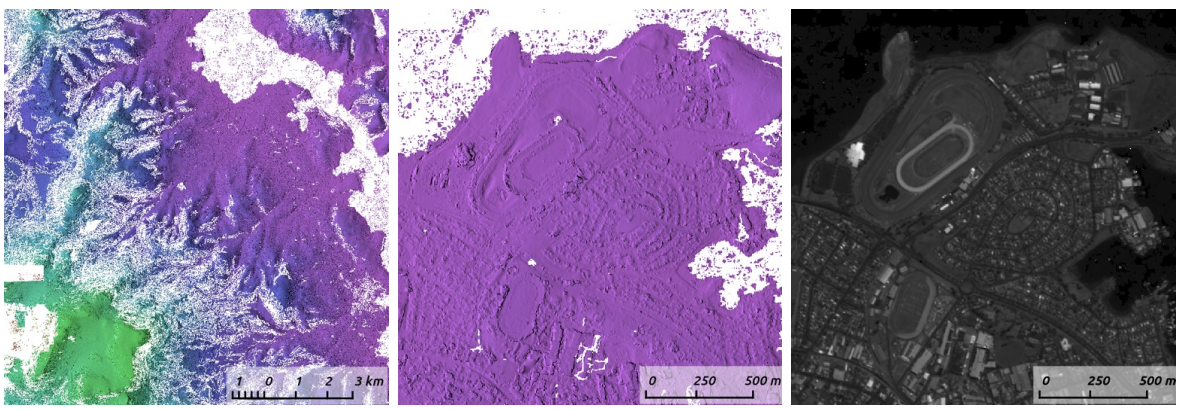


Figure 6.13: Example colorized height map and ortho image output.

Commands

```
> stereo po_312012_pan_0000000.tif po_312012_pan_0010000.tif geoeye/geoeye
```

stereo.default

The stereo.default example file works generally well with all GeoEye pairs. Just set `alignment-method` to `homography`.

6.11 Dawn (FC) Framing Camera

This is a NASA mission to visit two of the largest objects in the asteroid belt, Vesta and Ceres. After having orbited Vesta for a year and a half, they finally started releasing their imagery. Thankfully, USGS's Astrogeology department has been supporting the mission this entire time. They've had a Dawn camera model publicly available for at least the last 2 releases. Since ASP builds against USGS's ISIS software, we are able to leverage that model.

The framing camera on board Dawn is quite small and packs only a resolution of 1024x1024 pixels. This means processing time is extremely short. To it's benefit, it seems that the mission planners leave the framing camera on taking shots quite rapidly. On a single pass, they seem to usually take a chain of FC images that have a high overlap percentage. This opens the idea of using ASP to process not only the sequential pairs, but also the wider baseline shots. Then someone could potentially average all the DEMs together to create a more robust data product.

For this example, we downloaded the images `FC21A0010191_11286212239F1T.IMG` and `FC21A0010192_11286212639F1T` which show the Cornelia crater. We must be honest, we found these images by looking at the popular anaglyph shown on the Planetary Science Blog [15].

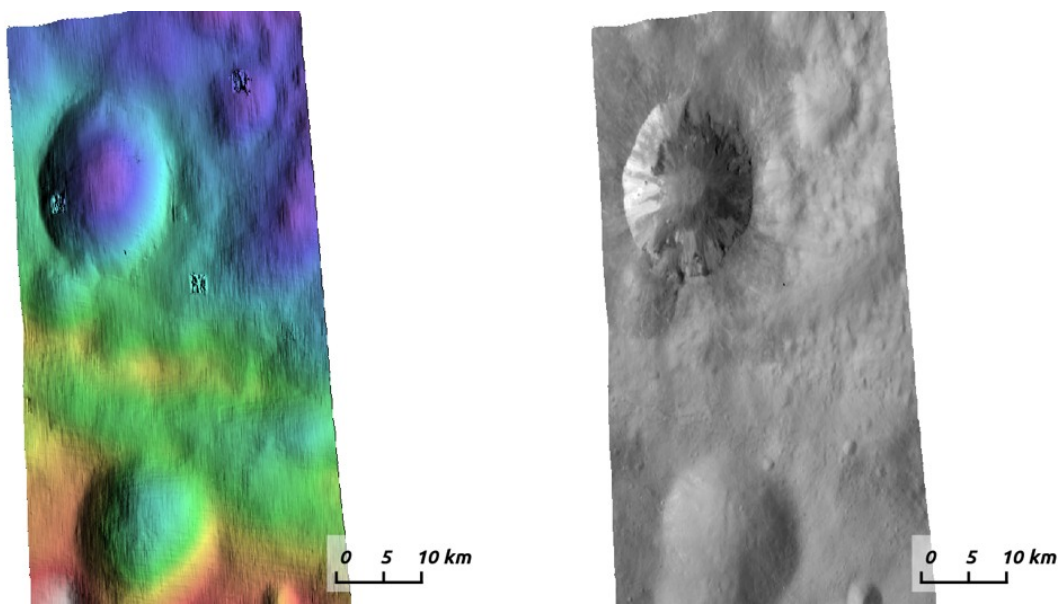


Figure 6.14: Example colorized height map and ortho image output.

Commands

First you must download the Dawn FC images from PDS.

```
ISIS3 > dawnfc2isis from=FC21A0010191_11286212239F1T.IMG \
                    to=FC21A0010191_11286212239F1T.cub
ISIS3 > dawnfc2isis from=FC21A0010192_11286212639F1T.IMG \
                    to=FC21A0010192_11286212639F1T.cub
ISIS3 > spiceinit from=FC21A0010191_11286212239F1T.cub
ISIS3 > spiceinit from=FC21A0010192_11286212639F1T.cub
ISIS3 > stereo FC21A0010191_11286212239F1T.cub \
               FC21A0010192_11286212639F1T.cub stereo/stereo
```

```
 ISIS3 > point2dem stereo-PC.tif --orthoimage stereo-L.tif \
--t_srs "+proj=eqc +lat_ts=-11.5 +a=280000 +b=229000 +units=m"
```

stereo.default

The stereo.default example file worked for this stereo pair. Just set `alignment-method` to `homography`.

Part III

Appendices

Appendix A

Tools

This chapter provides a overview of the various tools that are provided as part of the Ames Stereo Pipeline, and a summary of their command line options.

A.1 stereo

The `stereo` program is the primary workhorse of the Ames Stereo Pipeline. It takes a stereo pair of images that overlap and creates an output point cloud image that can be processed into a 3D model or DEM using the `point2mesh` or `point2dem` programs, respectively.

Usage:

`ISIS 3> stereo [options]` *`Left_input_image Right_input_image output_file_prefix`*

This release of the stereo pipeline has been specifically designed to process USGS ISIS `.cub` files. However, the stereo pipeline does have the capability to process other types of stereo image pairs (e.g. image files with a CAHVOR camera model from the NASA MER rovers). If you would like to experiment with these features, please contact us for more information.

The *`output_file_prefix`* is prepended to all output data files. For example, setting *`output_file_prefix`* to '`out`' will yield files with names like `out-L.tif` and `out-PC.tif`. To keep stereo pipeline results organized in sub-directories, we recommend using an output prefix like '`results-10-12-09/out`' for *`output_file_prefix`*. The `stereo` program will create a directory called `results-10-12-09/out` and place files named `out-L.tif`, `out-PC.tif`, etc. in that directory.

Table A.1: Command-line options for stereo

Option	Description
`--help|-h`	Display this help information
`--threads` *`integer(=0)`*	Set the number threads to use. 0 means use default defined in the program or in the .vwrc file
`--session-type|-t pinhole|isis|dg`	Select the stereo session type to use for processing. Usually the program can select this automatically for the file extension.
`--stereo-file|-s` *`filename(=./stereo.default)`*	Define the stereo.default file to use

`--left-image-crop-win` *arg*	Do stereo in this region [xoff yoff xsize ysize] of the left image [default: use the entire image].
`--entry-point|-e 1|2|3|4`	Pipeline entry point

More information about the stereo.default configuration file can be found in Appendix B on page 85. Similarly, `stereo` creates a lot of files, and they are all described in Appendix C on page 91.

A.1.1 Entry Points

The `stereo -e` *number* option can be used to restart a `stereo` job partway through the stereo correlation process. Restarting can be useful when debugging while iterating on `stereo.default` settings.

Stage 0 (Preprocessing) normalizes the two images and aligns them by locating interest points and matching them in both images. The program is designed to reject outlying interest points. This stage writes out the pre-aligned images and the image masks.

Stage 1 (Disparity Map Initialization) performs pyramid correlation and builds a rough disparity map that is used to seed the sub-pixel refinement phase.

Stage 2 (Sub-pixel Refinement) performs sub-pixel correlation that refines the disparity map.

Stage 3 (Outlier Rejection and Hole Filling) performs filtering of the disparity map and (optionally) fills in holes using an inpainting algorithm. This phase also creates a "good pixel" map.

Stage 4 (Triangulation) generates a 3D point cloud from the disparity map.

A.1.2 Decomposition of Stereo

The `stereo` executable is actually a python script that makes calls to seperate C++ executables for each entry point.

Stage 0 (Preprocessing) calls `stereo_pprc`. Multithreaded.

Stage 1 (Disparity Map Initialization) calls `stereo_corr`. Multithreaded.

Stage 2 (Sub-pixel Refinement) class `stereo_rfne`. Multithreaded.

Stage 3 (Outlier Rejection and Hole Filling) calls `stereo_fltr`. Multithreaded.

Stage 4 (Triangulation) calls `stereo_tri`. Single-Threaded.

All of the sub-programs have the same interface as `stereo`. Users processing a large number of stereo pairs on a cluster my find it advantageous to call these executables in their own manner. An example would be to run stages 0-3 in order for each stereo pair. Then run several sessions of `stereo_tri` since it is single threaded.

A.2 disparitydebug

The `disparitydebug` program produces output images for debugging disparity images created from `stereo`. The `stereo` tool produces several different versions of the disparity map; the most important ending with extensions `*-D.tif` and `*-F.tif`. (see Appendix C for more information.) These raw disparity map files can be useful for debugging because they contain raw disparity values as measured by the correlator; however

they cannot be directly visualized or opened in a conventional image browser. The `disparitydebug` tool converts a single disparity map file into two normalized TIFF image files (`*-H.tif` and `*-V.tif`, containing the horizontal and vertical, or line and sample, components of disparity, respectively) that can be viewed using any image display program.

The `disparitydebug` program will also print out the range of disparity values in a disparity map, that can serve as useful summary statistics when tuning the search range settings in the `stereo.default` file.

Table A.2: Command-line options for disparitydebug

Options	Description
`--help|-h`	Display this help
`--input-file` *`filename`*	Explicitly specify the input file
`--output-prefix|-o` *`filename`*	specify the output file prefix
`--output-filetype|-t` *`type(=tif)`*	Specify the outfile type
`--float-pixels`	Save the resulting debug images as 32 bit floating point files (if supported by the selected file type)

A.3 point2dem

The `point2dem` program produces a GeoTIFF terrain model or/and an orthographic image from a point cloud image produced by the `stereo` command.

Example:

```
point2dem output-prefix-PC.tif -o stereo/filename -r moon \
    --nodata-value -10000 -n
```

This produces a digital elevation model that has been referenced to the lunar spheroid of 1737.4 km. Pixels with no data will be set to a value of -10000, and the resulting DEM will be saved in a simple cylindrical map projection. The resulting DEM is stored by default as a one channel, 32-bit floating point GeoTIFF file.

The `-n` option creates an 8-bit, normalized version of the DEM that can be easily loaded into a standard image viewing application for debugging.

Another example:

```
point2dem output-prefix-PC.tif -o stereo/filename -r moon \
    --orthoimage output-prefix-L.tif
```

This command takes the left input image and orthographically projects it onto the 3D terrain produced by the Stereo Pipeline. The resulting `*-DRG.tif` file will be saved as an 8-bit GeoTIFF image in a simple cylindrical map projection.

A.3.1 Comparing with MOLA data

When comparing the output of `point2dem` to laser altimeter data, like MOLA, it is important to understand the different kinds of data that are being discussed. By default, `point2dem` returns planetary radius values in meters. These are often large numbers that are difficult to deal with. If you use the `-r mars` option, the output terrain model will be in meters of elevation with reference to the IAU reference spheroid for Mars: 3,396,190 m. So if a post would have a radius value of 3,396,195 m, in the model returned with the `-r mars` option, that pixel would just be 5 m.

You may want to compare the output to MOLA data. MOLA data is released in three 'flavors,' namely: Topography, Radius, and Areoid. The MOLA Topography data product that most people use is just the MOLA Radius product with the MOLA Areoid product subtracted. Additionally, it is important to note that all of these data products have a reference value subtracted from them. The MOLA reference value is NOT the IAU reference value, but 3,396,000 m.

So you cannot just compare the output of `point2dem` to the MOLA Topography data, since `point2dem` doesn't know about the Areoid.

In order to compare with the MOLA data, you can do one of two different things. You could operate purely in radius space, and have `point2dem` create radius values that are directly comparable to the MOLA Radius data. You can do this by having `point2dem` subtract the MOLA reference value by setting `--semi-major-axis 3396000` and `--semi-minor-axis 3396000`.

To get values that are directly comparable to MOLA Topography data, you'll need to run `point2dem` with the `--semi-major-axis` and `--semi-minor-axis` switches with the MOLA reference, to get something that is comparable with the MOLA Radius values. Then you'll need to obtain the MOLA Areoid data and scale it up to the DEM ground scale, and then subtract that areoid data from the model produced by `point2dem`. That resultant model can then be directly compared to the MOLA Topography data.

A.3.2 Post Spacing

Recall that `stereo` creates a pointcloud file as its output that you need to use `point2dem` on to create a GeoTIFF that you can use in other tools. The pointcloud file is the result of taking the image-to-image matches (which were created from the kernel sizes you specified, and the subpixel versions of the same, if used) and projecting them out into space from the cameras, and arriving at a point in real world coordinates. Since `stereo` does this for every pixel in the input images, the *default* value that `point2dem` uses (if you don't specify anything explicitly) is: the input image scale, because there's an 'answer' in the pointcloud file for each pixel in the original image.

However, as you may suspect, this is probably not the best value to use, because there really isn't that much 'information' in the data. The true 'resolution' of the output model is dependent on a whole bunch of things (like the kernel sizes you choose to use) but also can vary from place to place in the image depending on the texture.

The general 'rule of thumb' is to produce a terrain model that has a post spacing of about 3x the input image ground scale. This is based on the fact that it is nearly impossible to uniquely identify a single pixel correspondence between two images, but a 3x3 patch of pixels provides improved matching reliability. As you go to numerically larger post-spacings on output, you're averaging more point data (that is probably spatially correlated anyway) together.

So you can either use the `--dem-spacing` argument to `point2dem` to do that directly, or feel free to use your favorite averaging algorithm to reduce the `point2dem`-created model down to the scale you want.

If you attempt to derive science results from an ASP-produced terrain model with the default DEM spacing, expect serious questions from reviewers.

Table A.3: Command-line options for point2dem

Options	Description
`--nodata-value` *`float(=min-z)`*	Explicitly set the default missing pixel value. By default, the minimum z value in the model is used.
`--use-alpha`	Create images that have an alpha channel
`--normalized|-n`	Also write a normalized version of the DEM (for debugging)

--orthoimage *texture-file*	Write an orthoimage based on the texture file given as an argument to this command line option
--errorimage	Write an additional image whose values represent the triangulation error in meters
--fsaa *float(=3)*	Oversampling amount to perform antialiasing.
--output-prefix|-o *output-prefix*	Specify the output prefix
--output-filetype|-t *type(=tif)*	Specify the output file type
--x-offset *float(=0)*	Add a horizontal offset to the DEM
--y-offset *float(=0)*	Add a horizontal offset to the DEM
--z-offset *float(=0)*	Add a vertical offset to the DEM
--rotation-order *order(=xyz)*	Set the order of an euler angle rotation applied to the 3D points prior to DEM rasterization
--phi-rotation *float(=0)*	Set a rotation angle phi
--omega-rotation *float(=0)*	Set a rotation angle omega
--kappa-rotation *float(=0)*	Set a rotation angle kappa
--t_srs *string*	Target spatial reference set. This mimicks the GDAL option used on their tools.
--reference-spheroid|-r moon|mars	Set a reference surface to a hard coded value. This will override manually set datum information.
--semi-major-axis *float(=0)*	Set the dimensions of the datum in meters
--semi-minor-axis *float(=0)*	Set the dimensions of the datum in meters
--sinusoidal	Save using a sinusoidal projection
--mercator	Save using a Mercator projection
--transverse-mercator	Save using transverse Mercator projection
--orthographic	Save using an orthographic projection
--stereographic	Save using a stereographic projection
--lambert-azimuthal	Save using a Lambert azimuthal projection
--utm *zone*	Save using a UTM projection with the given zone
--proj-lat *float*	The center of projection latitude (if applicable)
--proj-lon *float*	The center of projection longitude (if applicable)
--proj-scale *float*	The projection scale (if applicable)
--dem-spacing|-s *float(=0)*	Set the DEM post size (if this value is 0, the post spacing size is computed for you)
--threads *int(=0)*	Select the number of processors (threads) to use.
--no-bigtiff	Tell GDAL to not create bigtiffs.
--tif-compress None|LZW|Deflate|Packbits	TIFF Compression method.
--cache-dir *directory(=/tmp)*	Folder for temporary files. Normally don't need to change.
--help|-h	Display this table

A.4 point2mesh

Produces a mesh surface that can be visualized in `osgviewer`, which is a standard 3D viewing application that is part of the open source OpenSceneGraph package. [1]

Unlike DEMs, The 3D mesh is not meant to be used as a finished scientific product. Rather, it can be used for fast visualization to create a 3D view of the generated terrain.

[1] The full OpenSceneGraph package is not bundled with the Stereo Pipeline, but the `osgviewer` program is. You can download and install this package separately from http://www.openscenegraph.org/.

The `point2mesh` program requires a point cloud file and an optional texture file (*output-prefix*-PC.tif and normally *output-prefix*-L.tif). When a texture file is not provided, a 1D texture is applied in the local Z direction that produces a rough rendition of a contour map. In either case, `point2mesh` will produce a *output-prefix*.ive file that contains the 3D model in OpenSceneGraph format.

Two options for `osgviewer` bear pointing out: the `-l` flag indicates that synthetic lighting should be activated for the model, which can make it easier to see fine detail in the model by providing some real-time, interactive hillshading. The `-s` flag sets the sub-sampling rate, and dictates the degree to which the 3D model should be simplified. For 3D reconstructions, this can be essential for producing a model that can fit in memory. The default value is 10, meaning every 10th point is used in the X and Y directions. In other words that mean only $1/10^2$ of the points are being used to create the model. Adjust this sampling rate according to how much detail is desired, but remember that large models will impact the frame rate of the 3D viewer and affect performance.

Example:

point2mesh -l -s 2 *output-prefix*-PC.tif *output-prefix*-L.tif

To view the resulting *output-prefix*.ive file use `osgviewer`.

Fullscreen:

```
> osgviewer output-prefix.ive
```

or Windowed:

```
> osgviewer output-prefix.ive --window 50 50 1000 1000
```

Inside `osgviewer`, the keys L, T, and W can be used to toggle on and off lighting, texture, and wireframe modes. The left, middle, and right mouse buttons control rotation, panning, and zooming of the model.

Table A.4: Command-line options for point2mesh

Options	Description
--help|-h	Display this help
--simplify-mesh *float*	Run OSG Simplifier on mesh, 1.0 = 100%
--smooth-mesh	Run OSG Smoother on mesh
--use-delaunay	Uses the delaunay triangulator to create a surface from the point cloud. This is not recommended for point clouds with noise issues.
--step|-s *integer(=10)*	Sampling step size for mesher.
--input-file *pointcloud-file*	Explicitly specify the input file
--texture-file *texture-file*	Explicitly specify the texture file
--output-prefix|-o *output-prefix*	Specify the output prefix
--output-filetype|-t *type(=ive)*	Specify the output file type
--enable-lighting|-l	Enables shades and light on the mesh
--center	Center the model around the origin. Use this option if you are experiencing numerical precision issues.
--rotation-order *order(=xyz)*	Set the order of an euler angle rotation applied to the 3D points prior to DEM rasterization
--phi-rotation *float(=0)*	Set a rotation angle phi
--omega-rotation *float(=0)*	Set a rotation angle omega
--kappa-rotation *float(=0)*	Set a rotation angle kappa

A.5 orbitviz

Produces a Google Earth Keyhole Markup Language (KML) file useful for visualizing camera position. The input for this tool is one or more `*.cub` files.

Table A.5: Command-line options for orbitviz

Options	Description
`--help|-h`	Display this help
`--output|-o` *`filename(=orbit.kml)`*	Specifies the output file name
`--scale|-s` *`float(=1)`*	Scale the size of the coordinate axes by this amount. Ex: To scale axis sizes up to earth size, use 3.66
`--use_path_to_dae_model|-u` *`fullpath`*	Use this dae model to represent camera location. *Google Sketch up can create these.*

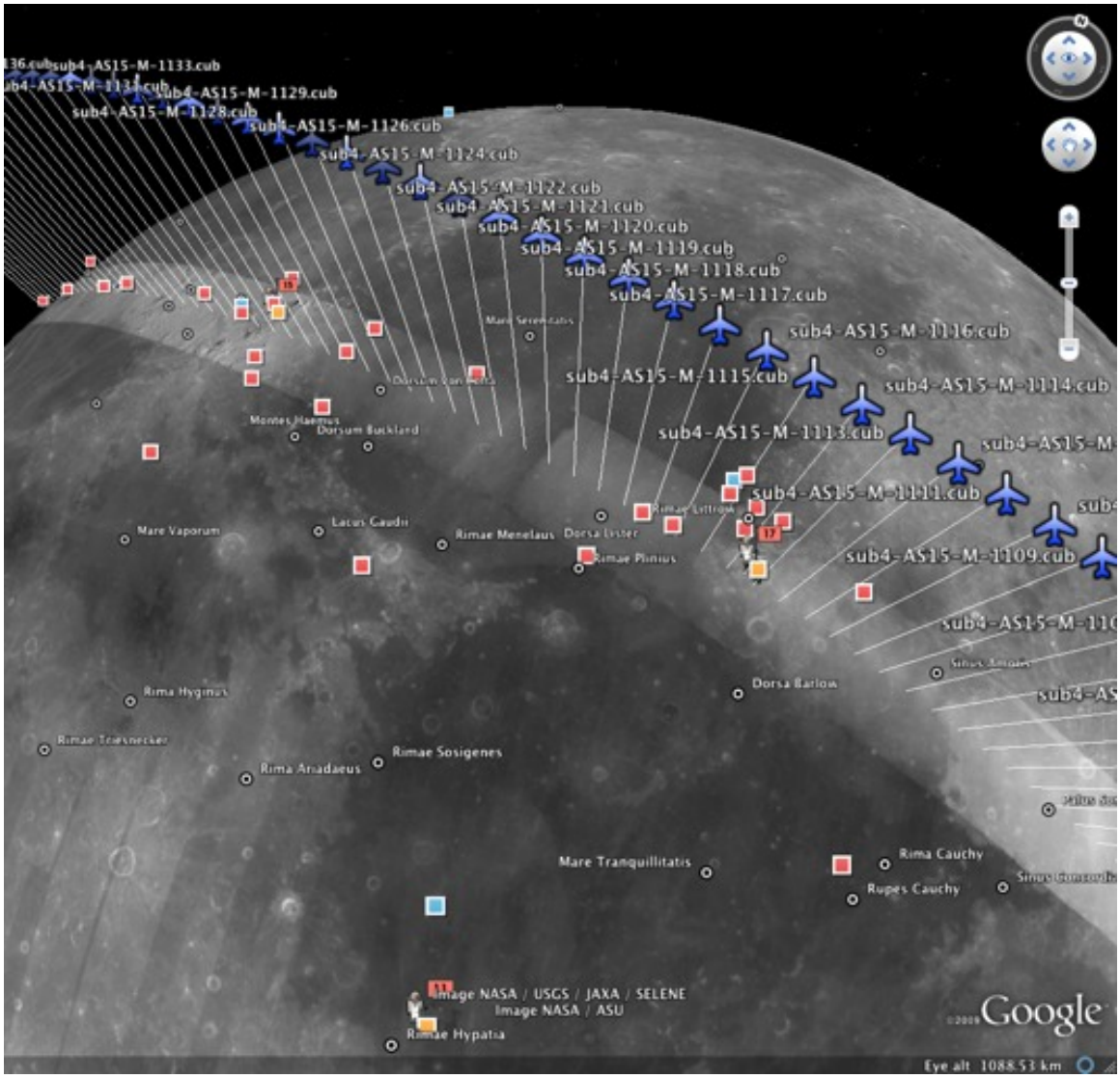


Figure A.1: Example of a KML visualization produced with `orbitviz` depicting camera locations for the Apollo 15 Metric Camera during orbit 33 of the Apollo command module.

A.6 cam2map4stereo.py

This program takes similar arguments as the ISIS3 `cam2map` program, but takes two input images. With no arguments, the program determines the minimum overlap of the two images, and the worst common resolution, and then map-projects the two images to this identical area and resolution.

The detailed reasons for doing this, and a manual step-by-step walkthrough of what `cam2map4stereo.py` does is provided in the disucssion on aligning images on page 18.

The `cam2map4stereo.py` is also useful for selecting a subsection and/or reduced resolution portion of the full image. You can inspect a raw camera geometry image in qview after you have run `spiceinit` on it, select the latitude and longitude ranges, and then use `cam2map4stereo.py`'s `--lat`, `--lon`, and optionally `--resolution` options to pick out just the part you want.

Use the `--dry-run` option the first few times to get an idea of what `cam2map4stereo.py` does for you.

Table A.6: Command-line options for cam2map4stereo.py

Options	Description
`--help|-h`	Display this help
`--manual`	Read the manual.
`--map=`*`MAP`*`|-m` *`MAP`*	The mapfile to use for `cam2map`.
`--pixres=`*`PIXRES`*`|-p` *`PIXRES`*	The pixel resolution mode to use for `cam2map`.
`--resolution=`*`RESOLUTION`*`|-r` *`RESOLUTION`*	Resolution of the final map for `cam2map`.
`--interp=`*`INTERP`*`|-i` *`INTERP`*	Pixel interpolation scheme for `cam2map`.
`--lat=`*`LAT`*`|-a` *`LAT`*	Latitude range for `cam2map`, where `LAT` is of the form *min:max*. So to specify a latitude range between -5 and 10 degrees, it would look like `--lat=-5:10`.
`--lon=`*`LON`*`|-o` *`LON`*	Longitude range for `cam2map`, where `LON` is of the form *min:max*. So to specify a longitude range between 45 and 47 degrees, it would look like `--lon=40:47`.
`--dry-run|-n`	Make calculations, and print the `cam2map` command that would be executed, but don't actually run it.
`--suffix|-s`	Suffix that gets inserted in the output file names, defaults to 'map'.

Appendix B

The `stereo.default` File

The `stereo.default` file contains configuration parameters that the `stereo` program uses to process images. The `stereo.default` file is loaded from the current working directory when you run `stereo` unless you specify a different file using the `-s` option. Run `stereo --help` for more information. The extension is not important for this file.

Below we will walk through the contents of the `stereo.default` and discuss its various parameters. If you want to start with a clean slate, you can copy the `stereo.default.example` file that is included in the top level of the Stereo Pipeline software distribution.

Note: The parameters that begin with '`DO_*`' are true/false options, when set to '1' they are 'on' or 'true,' and if set to '0' they are 'off' or 'false.' All parameters below have their default values listed after the parameter name.

B.1 Preprocessing

---

alignment-method (default = none)

When `alignment-method` is set to `homography`, `stereo` will attempt to pre-align the images by automatically detecting tie-points between images using a feature based image matching technique. Tiepoints are stored in a `*.match` file that is used to compute a linear homography transformation of the right image so that it closely matches the left image. Note: the user may exercise more control over this process by using the `ipfind` and `ipmatch` tools.

When `alignment-method` is set to `epipolar`, `stereo` will apply a 3D transform to both images so that their epipolar lines will be horizontal. This speeds of stereo correlation as it greatly reduces the area required for searching.

Epipolar alignment is only available when performing stereo matches using the pinhole stereo session (i.e. when using `stereo -t pinhole`*), and cannot be used when processing ISIS images at this time.*

force-use-entire-range (default = false)

By default, the Stereo Pipeline will normalize ISIS images so that their maximum and minimum channel values are ±2 standard deviations from a mean value of 1.0. Use this option if you want to *disable* normalization in the stereo pipeline and force the raw values to pass directly to the stereo correlations algorithms.

For example, if ISIS's `histeq` has already been used to normalize the images, then use this option to disable normalization as a (redundant) pre-processing step.

individual-normalize (**default = false**)

By default, the maximum and minimum valid pixel value is determined by looking at both images. Normalized with the same "global" min and max guarantees that the two images will retain their brightness and contrast relative to each other.

This option forces each image to be normalized to its own maximum and minimum valid pixel value. This is useful in the event that images have different and non-overlapping dynamic ranges. You can sometimes tell when this option is needed: after a failed stereo attempt one of the rectified images (`*-L.tif` and `*-R.tif`) may be either mostly white or black. Activating this option may correct this problem.

Note: Photometric calibration and image normalization are steps that can and should be carried out beforehand using ISIS's own utilities. This provides the best possible input to the stereo pipeline and yields the best stereo matching results.

B.2 Correlation

prefilter-mode (= 0,1,2,3) **(default = 2)**

This selects the pre-processing filter to be used to prepare imagery before it is fed to the initialization stage of the pipeline.

0 - None

1 - Subtracted Mean - This takes a preferrably large gaussian kernel and subtracts its value from the input image. This effectively reduces low frequency content in the image. The result is correlation that is immune to translations in image intensity.

2 - LoG Filter - Takes the Laplacian of Gaussian of the image, This provides some immunity to differences in lighting conditions between a pair of images by isolating and matching on blob features in the image.

3 - Sign of LoG - Not recommended for using. It was meant for an experimental XOR cost metric for correlation. This will still produce results. Though the results may not be as nice as one would like.

For all of the modes above, the size of the filter kernel is determined by the `prefilter-kernel-width` parameter below.

The choice of pre-processing filter must be made with thought to the cost function being used (see `cost-mode`, below). LoG filter preprocessing provides good immunity to variations in lighting conditions and is usually the recommended choice.

prefilter-kernel-width (= *float*) **(default = 1.4)**

This defines the diameter of the Gaussian convolution kernel used for the preprocessing modes 1 and 2 above. A value of 1.4 works well for LoG and 25-30 works well for Subtracted Mean.

corr-seed-mode (=0,1) (default = 1)

This parameter selects a strategy for how to solve for the integer correlation. It takes an integer value to index which strategy to take.

0 - None - Meaning, don't calculate a low resolution variant of the disparity image. This produces a strategy that is the same as the old style ASP.

1 - Low-Res Disparity - Calculate a low resolution version of the disparity from the L and R sub pictures. The results of this disparity will be used to narrow down the search range of individual tiles in the native resolution disparity image.

This is a useful option despite the fact that our integer correlation implementation does indeed use a pyramid approach. Our implementation can't search infinitely into lower resolutions due to its independent and tiled nature. This low resolution disparity seed is a good hybrid approach.

2 - Not implemented yet - It would be nice to have local affine fittings for each tile. Anyone interested in implementing?

For large images, bigger than MOC-NA, using the low resolution disparity seed is a definitive plus. Smaller images such as Cassini ISS or MER images should just shut this option off to save storage space.

corr-sub-seed-percent (= *float*) **(default=.25)**
When using `corr-seed-mode 1`, the solved for or user provided search range is padded by a percentage. The user can customize this value themselves with this option.

cost-mode (= 0,1,2) (default = 2)

This defines the cost function used during integer correlation. Squared difference is the fastest cost function. However it comes at the price of not being resilient against noise. Absolute difference is the next fastest and is a better choice. Normalized cross correlation is the slowest but is designed to be more robust against image intensity changes and slight lighting differences. Normalized cross correlation is about 2x slower than absolute difference and about 3x slower than squared difference.

0 - absolute difference

1 - squared difference

2 - normalized cross correlation

corr-kernel (= *integer integer*) **(default = 25 25)**
These option determine the size (in pixels) of the correlation kernel used in the initialization step. A different size can be set in the horizontal and vertical directions, but square correlation kernels are almost always used in practice.

corr-search (= *integer integer integer integer*)
These parameters determine the size of the initial correlation search range. The ideal search range depends on a variety of factors ranging from how the images were pre-aligned to the resolution and range of disparities seen in a given image pair. This search range is successively refined during initialization, so it is often acceptable to set a large search range that is guaranteed to contain all of the disparities in a given image. However, setting tighter bounds on the search can sometimes reduce the number of erroneous matches, so it can be advantageous to tune the search range for a particular data set.

Commenting out these settings will cause `stereo` to make an attempt to guess its search range using interest points.

The order of the four integers define the minimum horizontal and vertical disparity and then the maximum horizontal and vertical disparity.

xcorr-threshold (= *integer*) **(default = 2)**

Integer correlation to a limited sense performs a correlation forward and backwards to double check its result. This is one of the first filtering steps to insure that we have indeed converged to a global

minimum for an individual pixel. The `xcorr-threshold` parameter defines an agreement threshold in pixels between the forward and backward result.

Optionally, this parameter can be set to a negative number. This will signal the correlator to only use the forward correlation result. This will drastically improve speed at the cost of additional noise.

B.3 Subpixel Refinement

subpixel-mode (= 0,1,2,3) **(default = 2)**
This parameter selects the subpixel correlation method. These algorithms are arranged in order of decreasing speed and increasing quality. Parabola subpixel is very fast but will produce results that are only slightly more accurate than those produced by the initialization step. Bayes EM (mode 2) is very slow but offers the best quality. When tuning `stereo.default` parameters, it is expedient to start out using parabola subpixel as a "draft mode." When the results are looking good with parabola subpixel, then they will look even better with subpixel mode 2.

0 - no subpixel refinement

1 - parabola fitting

2 - affine adaptive window, Bayes EM weighting

3 - affine adaptive window, Bayes EM with Gamma Noise Distribution (experimental)

For a visual comparison of the quality of these subpixel modes, refer back to Chapter:4.

subpixel-kernel (= *integer integer*) **(default = 35 35)** Specify the size of the horizontal and vertical size (in pixels) of the subpixel correlation kernel. It is advantageous to keep this small for parabola fitting in order to resolve finer details. However for the Bayes EM methods, keep the kernel slightly larger. Those methods weight the kernel with a gaussian distribution, thus the effective area is small than the kernel size defined here.

B.4 Filtering

rm-half-kernel (= *integer integer*) **(default = 5 5)**
This setting adjusts the behavior of an outlier rejection scheme that "erodes" isolated regions of pixels in the disparity map that are in disagreement with their neighbors.

The two parameters determine the size of the half kernel that is used to perform the automatic removal of low confidence pixels. A 5×5 half kernel would result in an 11×11 kernel with 121 pixels in it.

rm-min-matches (= *integer*) **(default = 60)**
This parameter sets the *percentage* of neighboring disparity values that must fall within the inlier threshold in order for a given disparity value to be retained.

rm-threshold (= *integer*) **(default = 3)**
This parameter sets the inlier threshold for the outlier rejection scheme. This option works in conjunction with RM_MIN_MATCHES above. A disparity value is rejected if it differs by more than RM_THRESHOLD disparity values from RM_MIN_MATCHES percent of pixels in the region being considered.

rm-clean-passes (= *integer*) **(default = 1)**
Select the number of outlier removal passes that are carried out. Each pass will erode pixels that do not match their neighbors. One pass is usually sufficient.

disable-fill-holes (default = false)

Normally ASP will try to fill holes in the dispartiy map (caused by poor matching) with an inpainting algorithm. Inpainting is a convolution method that takes the values at the edges of holes and spreads those values inward.

Use this flag inorder to disable the filling of holes to leave only true calculated results in the output.

Note: you can always use the good pixel mask image (`*-GoodPixelMap.TIF`) to determine which pixels represent "real" data matched by the stereo correlator, and which pixels represent interpolated data produced by inpainting.

fill-holes=max-size (= *integer*) **(default = 100,000)**
This defines the maximum area of a hole that the inpainting technique should attempt. Default is 100,000 pixels.

B.5 Post-Processing

near-universe-radius (= *float*) **(default = 0.0)**

far-universe-radius (= *float*) **(default = 0.0)**
These parameters can be used to filter out triangulated points in the 3D point cloud by setting an near and far radius value from origin of the point cloud's coordinate system, [0,0,0]. For most ISIS cameras, the origin is the center of the body (e.g. the Moon or Mars), and is part of a body-fixed Cartesian coordinate system that rotates with the planet.

These settings are most useful for other stereo session types (e.g. pinhole), where the origin of the coordinate system is often one of the cameras in a stereo pair. In this case, these parameters can be used to reject pixels that are too close or too far from the camera system.

universe-center (**default = none**)
Defines the origin to use when filtering the output point cloud using the above near and far radius options. The available options are:

None - Disable filtering.

Camera - Filter in terms of radii from the left camera's center.

Zero - Filter in terms of radii from the target's center.

Appendix C

Guide to Output Files

The `stereo` tool generates a variety of intermediate files that are useful for debugging. These are listed below, along with brief descriptions about the contents of each file. Note that the prefix of the filename for all of these files is dictated by the final command line argument to `stereo`. Run `stereo --help` for details.

***.vwip** - image feature files

If `alignment-method homography` is enabled, the stereo pipeline will automatically search for image features to use for tie-points. Raw image features are stored in `*.vwip` files; one per input image. For example, if your images are `left.cub` and `right.cub` you'll get `left.vwip` and `right.vwip`. Note: these files can also be generated by hand (and with finer grained control over detection algorithm options) using the `ipfind` utility.

***.match** - image to image tie-points

The match file lists a select group of unique points out of the previous `.vwip` files that have been identified and matched in a pair of images. For example, if your images are `left.cub` and `right.cub` you'll get a `left__right.match` file.

The `.vwip` and `.match` files are meant to serve as cached tie-point information, and they help speed up the pre-processing phase of the stereo pipeline: if these files exist then the `stereo` program will skip over the interest point alignment stage and instead use the cached tie-points contained in the `*.match` files. In the rare case that one of these files did get corrupted or your input images have changed, you may want to delete these files and allow `stereo` to regenerate them automatically. This is also recommended if you have upgraded the Stereo Pipeline software.

***-L.tif -** rectified left input image

The left input image of the stereo pair, saved after the pre-processing step. This image may be normalized, but should otherwise be identical to the original left input image.

***-R.tif -** rectified right input image

Right input image of the stereo pair, after the pre-processing step. This image may be normalized and possibly translated, scaled, and/or rotated to roughly align it with the left image, but should otherwise be identical to the original right input image.

***-lMask.tif** - mask for left rectified image

***-rMask.tif** - mask for right rectified image

These files contain binary masks for the input images. These are used throughout the stereo process to mask out pixels where there is no input data.

***-align.exr** - pre-alignment matrix

The 3×3 affine transformation matrix that was used to warp the right image to roughly align with the left image. This file is only generated if `alignment-method homography` is enabled in the `stereo.default` file.

***-D.tif** - disparity map after the disparity map initialization phase

This is the disparity map generated by the correlation algorithm in the initialization phase. It contains integer values of disparity that are used to seed the subsequent sub-pixel correlation phase. It is largely unfiltered, and may contain some bad matches.

Disparity map files are stored in OpenEXR format as 3-channel, 32-bit floating point images. (Channel 0 = horizontal disparity, Channel 1 = vertical disparity, and Channel 2 = good pixel mask)

***-RD.tif -** disparity map after sub-pixel correlation

This file contains the disparity map after sub-pixel refinement. Pixel values now have sub-pixel precision, and some outliers have been rejected by the sub-pixel matching process.

***-F-corrected.tif** - intermediate data product

Only created when `alignment-method homography` is on. This is `*-F.tif` with effects of interest point alignment removed.

***-F.tif** - filtered disparity map

The filtered, sub-pixel disparity map with outliers removed (and holes filled with the inpainting algorithm if `FILL_HOLES` is on). This is the final version of the disparity map.

***-GoodPixelMap.tif** - map of good pixels

An image showing which pixels were matched by the stereo correlator (gray pixels), and which were filled in by the hole filling algorithm (red pixels).

***-PC.tif** - point cloud image

The point cloud image is generated by the triangulation phase of the Stereo Pipeline. It contains 3D locations for each valid pixel; stored as a 64-bit, 3-channel TIFF, with coordinates in a body-fixed planetocentric coordinate system. Each pixel in the point cloud image corresponds to a pixel in the left input image.

Note: it is unlikely that your usual TIFF viewing programs will visualize this file properly. This file should be considered a 'data' file, not an 'image' file. Other programs in the Stereo Pipeline, such as `point2mesh` and `point2dem` will convert the contents of this file to more easily visualized formats.

***-stereo.default** - backup of the stereo pipeline settings file

This is a copy of the `stereo.default` file used by `stereo`. It is stored alongside the output products as a record of the settings that were used for this particular stereo processing task.

Appendix D

Modifying SURF to output VW match files

SURF *v1.0.9* is a fast a relatively robust interest point algorithm. It is not open source, but it is freely available for academic uses at http://www.vision.ee.ethz.ch/~surf/. This software is currently only available for Windows and Linux 32 bit.

SURF creates it own results files. What is available online was probably only meant for demonstrations. What we've done is created a patch that allows the SURF match utility, `match.ln`, to create Vision Workbench match files. The patch is available as the `surf_match.patch` in the `examples/` directory of the Stereo Pipeline distribution.

D.1 How to apply and compile

First move to the directory containing your copy of the SURF v1.0.9 code. Then copy `surf_match.patch` to the active directory. At this point you are ready to start running the following commands.

```
> patch < surf_match.patch
> make match.ln
```

> *Note:*
> If you are unfortunate enough to run into an error such as *g++-4.0.2: Command not found*, don't worry. Edit `Makefile` at line 10 and 11 to refer to `g++` instead of `g++-4.0.2`.
>
> Also since you've incurred that error, you'll probably need to add an include to `<stdlib.h>` in `imload.cpp` in the same directory. This all stems from differences in using a newer version of g++.

D.2 Example of using SURF

For this example it is assumed you have a directory containing two images named `m1000254.png` and `r0901059.png` like in the example found in Section 5.1.1.

SURF code only works with images in the grayscale format PGM. A free Linux utility to convert the images is `mogrify`. That utility is part of the package `ImageMagick` and is likely to be available in most package managers.

Below are the commands to take an input of PNG files, process them with SURF, and then finally create a match file which can be used by `isis_adjust`.

```
> mogrify -format pgm m1000254.png r0901059.png
> surf.ln -i m1000254.pgm -o m1000254.surf
> surf.ln -i r0901059.pgm -o r0901059.surf
> match.ln -k1 m1000254.surf -k2 r0901059.surf \
         -im1 m1000254.pgm -im2 r0901059.pgm \
         -o out.pgm -m m1000254__r0901059.match
> rm m1000254.pgm r0901059.pgm *.surf
```

> It is important to note that though SURF is very good at performing matches it does not perform a step of RANSAC with its output. There may be a couple of outliers.

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