Processing And Analysis Of Mars Pathfinder Science Data At JPL's Science Data Processing Systems Section

Susan K. LaVoie, William B. Green, Allan J. Runkle, Douglass A. Alexander, Paul M. Andres, Eric M. DeJong, Elizabeth D. Duxbury, David J. Freda, Zareh Gorjian, Jeffrey R. Hall, Frank R. Hartman, Steven R. Levoe, Jean J. Lorre, James M. McAuley, Shigeru Suzuki, Pamela J. Woncik, John R. Wright

Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Drive, Pasadena, CA 91109
Phone 818-354-5677, Fax 818-393-6962.

Submitted to Journal of Geophysical Research, Planets, 12 February 1998

Revised 28 August 1998

[1]William B. Green. Author affiliation with Jet Propulsion Laboratory, present address at California Institute of Technology)

ABSTRACT

The **Mars Pathfinder mission** required new capabilities and adaptation of existing capabilities in order to support science analysis and flight operations requirements imposed by the in-situ nature of the mission. The **Science Data Processing Systems Section** of the Jet Propulsion Laboratory was responsible for the design, development and application of the system required to perform telemetry processing, distribution and archiving of data from the four primary science instruments, and support of flight operations through production of automatically generated stereo and color mosaics, terrain visualizations and animations. The system developed for Mars Pathfinder incorporated new capabilities in producing computer generated color mosaics, for cataloging and distribution of **science data**, and utilized new display technology to support science analysis and flight operations requirements. This paper describes the data processing performed to support the science and operations payload on the **Pathfinder Lander** and **Sojourner rover**.

1. INTRODUCTION

JPL's Multimission Image Processing Laboratory (MIPL) has had responsibility for processing imaging data returned by NASA remote sensing spacecraft for over two decades. The Mars Pathfinder (MPF) mission required new capabilities, and adaptation of existing capabilities from prior missions [Green et al., 1975, Jepsen et al., 1980, Levinthal et al., 1977, Liebes et al., 1977, Rindfleisch et al., 1971, Ruiz et al., 1977, Saunders et al., Soha et al., 1977, Soha et al., 1975] in order to support science analysis and flight operations requirements imposed by the in-situ nature of the Pathfinder mission. Pathfinder was the first landed spacecraft supported by MIPL since the Viking spacecraft in 1976, and was the first mission supported by MIPL in which image data were required to support navigation of a vehicle on the Martian surface. The science objectives of the mission, and the need to support rover deployment and navigation, required development of new capabilities and new data products that are described in this paper.

The overall data flow for science payload data from the Pathfinder lander and Sojourner rover is shown in Figure 1.

Telemetry data was transferred to the MIPL Pathfinder realtime system, which assembled packet level data and ancillary data into science data records for each instrument. The realtime system loads the initial science database with data records and associated ancillary data, enabling parameter-based queries and retrieval using a web-based system called the MPF Navigator. Remote science users were able to access the data via a JPL-developed capability called the "File Exchange Interface" or "FEI". FEI supports either individual queries or a subscription service that transfers data records that meet pre-specified criteria directly to subscriber sites as it is entered into the database.

Systematic processing included mosaic production, production of stereo data products including rover terrain visualizations and anaglyphs, specific image products for use as press releases, and animation and rendering of data visualization products. Specific data products were transferred to individual science teams, to the flight operations team, and to the Sojourner operations team, to a central web server used to support public access to released data via the Internet, and to a specific web site used by the press to access press release information. Data were released in a variety of digital and analog formats.

The remainder of this paper describes the processing performed in each area shown in Figure 1. The processing was performed utilizing facilities within the MIPL and the Digital Image Animation Laboratory (DIAL). DIAL is a system that is interfaced electronically with the MIPL facility and digital mission databases maintained by MIPL. DIAL includes specialized equipment for production of science visualization and animation data products.

2. SYSTEM ARCHITECTURE

In 1993 the MIPL was selected by the Mars Pathfinder project to supply science data processing capabilities to support surface operations. By July 4th, 1997, MIPL's responsibilities had grown to include the telemetry processing, distribution and archiving of data from the four primary science instruments, and support of flight operations through production of automatically generated stereo and color mosaics in a variety of projection types for use by Lander and Sojourner science and operations teams. The realtime displays and automatically generated mosaics were used for time-critical decisions on spacecraft health assessment, rover navigation, evaluation of science objectives, and fulfilling NASA's goal of rapid public release of science data.

The major requirements that influenced the architecture of the system that supported these capabilities were:

- Minimal cost through use or adaptation of existing MIPL capabilities
- Timing Requirements for generation of products to support flight operations
- Telemetry Processing Requirements
- Data Archive Requirements
- Distribution/Security Requirements
- User Interface

The remainder of this section describes the impact of these requirements on the system architecture.

Existing MIPL Capabilities. The MIPL system at JPL has continuously evolved over the past three decades by capitalizing on advances in computer technology. By 1992, the basic infrastructure to support image processing was in place on multiple UNIX platforms. The conversion to a UNIX system also allowed for the implementation of the client/server paradigm for a number of key services, database management, and data distribution [Green and Shames, 1994]. The high-level Mars Pathfinder server architecture (Figure 2) was developed by adapting the existing MIPL capabilities. In cases where the requirements were not met by an existing capability, components supporting other missions were used to create the specialized capability.

Timing Requirements. The timing requirements for generation of the mosaics on time scales of minutes to support critical flight operations activities (deployment of the Sojourner rover, rover navigation support, and Lander science data acquisition strategy development) dictated development of an automated processing system capable of mosaicking hundreds of images within minutes of receipt of data on the ground. A database driven system based on MIPL's Multimission Data Management Subsystem (MDMS) and a commercial database management system (Sybase) was designed to support this requirement. MDMS is a client/server package that provides an intuitive user interface to the database that contains all ancillary data relating to a science observation. An MDMS client interface is installed on local and remote user workstations, providing rapid data access for scientists and operations personnel.

Telemetry Processing Requirements. The telemetry processing system for Mars Pathfinder was based on adaptation of the basic framework and support libraries used within MIPL's multimission system to support Galileo and other planetary missions. This allowed for more attention to the unique characteristics of the instruments and resolution of serious ground processing problems caused by flight software constraints.

Data Archive Requirements. NASA required that all final mission data be archived by the Planetary Data System (PDS). MIPL produced science products complying with PDS format content and format standards. The PDS image format was defined as the standard transport format between the different Pathfinder science teams.

Distribution/Security Requirements. The baseline MIPL system includes the File Exchange Interface (FEI) which is a client/server implementation of a secure file management and distribution system. It uses a Kerberos authentication mechanism and a database system to support its capabilities. FEI capabilities used to support Pathfinder science teams were primarily the "subscription" and "fetch" options. Subscriptions allow scientists to request automated transfer of science data satisfying specific criteria. Whenever data of the specified type arrives in the system, it is automatically sent to the user. Users can request all data from a specific instrument, or subsets of instrument data that meet more refined search criteria. The fetch option allows the user to specify the exact data files, and the system will immediately transfer the data to their workstation.

User Environment. Most of the science teams on the Mars Pathfinder project had their own image processing capabilities using different image formats, different protocols, and different operating environments. Because the team members were busy with their own tasks, it became apparent that there would not be enough time to train the team members in the specifics of all the MIPL tools. For this reason, it was decided to implement a Web-based browser that would allow an easy way to query our database, browse images, generate FEI fetch command lists, and construct simple products. The existing web-based Planetary Image Atlas (Section 4.2) provided the core capabilities and was adapted for Pathfinder.

3. REALTIME DESIGN

The purpose of MIPL's Realtime subsystem is to obtain instrument telemetry packets from the project's Ground Data System (GDS) and build an Experimental Data Record (EDR) representing the sensor and engineering data corresponding to an observation. Once the EDR has been created, it is quickly displayed for an initial assessment of the instrument's health and operation. As the software supporting these capabilities executes, anomalies, and tracking information are recorded into a running log and displayed at the Realtime Engineer's console to aid in error diagnostics and operational status.

The design of the realtime subsystem was an updated version of the realtime system that supported the Voyager 2 fly-by of Uranus and Neptune. The subsystem consists of three multimission programs (RTCNTRL, RTLOGGER, and RTDSPLOG) and project specific programs, (telemetry processing, and instrument display). For Mars Pathfinder, there were four project specific programs: MPFTELEMPROC, MPFIMBUILDAPX, MPFIMBUILDIMP, and MPFIMBUILDRVR.

RTCNTRL, RTLOGGER, RTDSPLOG These are the set of programs which are responsible for parameter verification, processing control and recording error and status messages. The programs can be used in a batch or interactive mode, using the X-window system for parameter and command selection. The realtime system is set-up to read text files that define the parameters for the subsystem's programs, isolating code changes to the modified program.

(MPF)TELEMPROC This is the program which processes telemetry packets and predicted SPICE kernels or database information and generates the EDR products which will be used in later processing.

(MPF)IMBUILDxxx This is a program that will read instrument specific EDR data files and build a displayable image from that data. The displayable image typically includes a mask with annotations. Once the image is built, it will be displayed on an X-window device. The "xxx" of the program name refers to the specific instrument supported, IMP, RVR or APX.

Figure 3 illustrates how the programs of the realtime subsystem interact. If there is a requirement to process different telemetry sets or streams, this structure can be instantiated multiple times, each instantiation processing one telemetry stream independent of the other. Although not shown, it is possible to control telemetry streams from different projects simultaneously.

The heart of this subsystem is the telemetry processor, MPFTELEMPROC. It is responsible for formulating and transmitting a telemetry query request to the project's Telemetry Delivery System (TDS), the source of all the mission's telemetry data. Once the TDS starts sending telemetry packets to the telemetry processor, the packets are identified and inserted into the appropriate EDR. Depending upon the design of the telemetry packets and the operational procedures for the instrument, this task can be implemented with automatic data validation and fault detection or will require visual inspection and special handling procedures.

Normal telemetry processing also performed is the accounting of the telemetry associated with each EDR, an analysis of basic statistics of the science data (e.g., data range, average value, standard deviation, etc.) and cataloging the EDR in the central database for easier identification and retrieval. Depending upon the instrument and operating mode, the realtime task may require additional capabilities to decompress the packet data, and integrate command parameters not available from the telemetry.

Many problems can occur as the telemetry travels the millions of kilometers from Mars to Earth. The most common problem is that packets are lost. Since each observation is made of several packets, the telemetry processor must determine when it is not useful to wait for the missing packet(s) and finish the EDR even though it will contain gaps. Occasionally just the opposite happened, the same packet was received more than once. This was a caused by the GDS system and multiple transmissions of critical packets from the spacecraft. These were simply ignored because error encoding was performed on all of the telemetry, guaranteeing the packets would be identical.

Mars Pathfinder was a very capable spacecraft, operational procedures also complicated the telemetry processing task. The spacecraft had the ability to stage hundreds of images into eleven different transmission queues. Depending upon the objectives for the day, any number of these queues would be allocated a percentage of the down-link bandwidth. This usually meant that 4 to 5 different images would be multiplexed in the telemetry at a given time. The telemetry subsystem required the additional capability to maintain up to eleven images simultaneously as it incorporated telemetry packets with the correct image.

4. DATABASE DESIGN

The database system was a central component to MIPL's support of Mars Pathfinder. It was used to support MIPL operational functions as well as aid the science teams. Operationally the database was used by the telemetry processing subsystem, automated mosaic generation, file distribution subsystem and the archive mastering software. The science teams use the database by means of a Web-based data browser, generic database applications for specialized tasks, and the client application of the file distribution subsystem.

The structure of the database was derived from the basic operation of the instruments and the ground data system, and estimates of the amount of data to be inserted, updated, queried and extracted. Observed science data and a small amount of related engineering data was returned in the telemetry stream. The ground data system was then responsible for taking this telemetry, creating the EDR data file and cataloging ancillary information pertaining to the EDR.

Past mission experience indicated that a typical instrument can be supported by a design using two database tables, a command table and an EDR table. The command table contains the command parameters that are needed to construct and annotate the data sets for scientific analysis. Most of the command parameters are not available from the spacecraft telemetry. The EDR table contains the scientific and operational ancillary data needed to support scientific investigations and operations. The content of these tables is determined from the science and operations requirements as they relate to the instrument's characteristics. Because the specifics of the Pathfinder instruments are outside of the scope of this article, only the characteristics that affected the design will be included.

Of the four Pathfinder instruments, the IMP was the most complex and required additional database support. Two additional constraints that the operation of the IMP imposed were its ability to generate up to four images per observation, and the fact that much of the instrument operation could be reconfigured by uplinking flight parameters. To handle these capabilities, additional tables for observation and flight parameters were implemented. The observation table contained information that was common to all four image data sets, such as pointing information and exposure time. The flight table contained information that affected every observation from a certain point in time until modified, such as the defined image area returned.

These four tables, Command, Flight, Observation and EDR, contained all of the information to identify scientifically useful data sets, and perform a moderate level of automatic validation. The IMP required all four of these tables, the Rover required the standard Command and EDR tables, while the APXS and the MET were supported by just EDR tables. While all four instruments required an EDR table, the content of the table was customized for the each instrument.

4.1 FILE EXCHANGE INTERFACE (FEI)

The File Exchange Interface (FEI) is a "Kerberized" (utilizing Kerberos authentication) client/server application used to move files between client sites and a data center (in this case MIPL). Kerberos was developed through Project Athena at MIT and provides a means of securely authenticating users over a network using encrypted passwords and time-stamped network packets.

MIPL administers FEI Servers to manage project data. Both local and remote sites run the FEI Client program (FEI) to transfer this data to and from their home institutions and MIPL. FEI works with Kerberos and maintains its own individualized user access control, thus FEI users do not require accounts on any machine at a data center to acquire it's data, as is the case with FTP. And unlike FTP, the FEI user doesn't need to know the physical location of data products. FEI stores and controls access to data by fileType, the user need know only the fileType they are interested in and the FEI server knows where to find the data.

FEI also provides a method to automatically push files to client sites as soon as they are generated via FEI subscriptions. A subscription for a fileType is submitted once by the user and runs continuously, instructing the FEI Server to push new files to the user's local disk as soon as they are added to the FEI server without further intervention on the part of the user.

In addition to running as a stand-alone application, FEI was incorporated into a Web-based browser, the MPF Navigator (described below), which freed the user from needing to know the FEI fileType to acquire data. Via the MPF Navigator the user need only select descriptive information about the data, such as the azimuth/elevation coordinates and/or the day the data was transmitted (to name only a few possible criteria); the Navigator then formulates the query syntax, connects to the correct database(s), locates the data and returns the result list which can then be manipulated by the user depending on further actions they wish to perform.

4.2 MPF NAVIGATOR

Organizing, locating and distributing data in support of Mission Operations and Science Data Analysis is a fundamental requirement for Flight Projects. An existing capability, the Planetary Image Atlas, provides a mechanism to quickly and intuitively query distributed data systems to locate and acquire publicly released planetary data without requiring an intricate knowledge of database organization or the physical location of the data products. By utilizing existing World Wide Web (WWW) technology, the Atlas supports any platform, in any location around the world provided the user has a Java-enabled Web browser. Although some data systems can be very complex, the Atlas strives to make science data access and analysis easy for researchers and is based on the assertion that users should not need an intimate understanding of the data organization to begin interacting with the collection.

Mars Pathfinder was the first planetary mission to adopt the Atlas to support active mission operations, calling their adaptation the MPF Navigator. The Atlas provided the core capabilities of the MPF Navigator while allowing the implementation of additional project-specific routines, database information and security restrictions. These core capabilities include two standardized user interfaces (a visual map-based Java interface and a HyperText Markup Language (HTML) text-based user interface) from which the user can: formulate search criteria, browse thumbnails or full resolution images and PDS labels, retrieve data in a wide variety of data formats, generate adhoc database reports, and order large datasets.

The Atlas map-based Java interface, is designed to allow for consistent interaction with any terrestrial body. The MPF Navigator adaptation (Figure 4) presents the user with a selection of Mars Pathfinder mosaics which can be in one of several map projections. Once selected, the mosaic is presented in a separate window where mouse pointer movements constantly update an Azimuth/Elevation coordinate display. This gives the user instant feedback for the orientation of the mosaic, as well as, a context for any desired sub-area for further analysis. The Java Map objects understand the lander orientation (quaternion) such that the Azimuth/Elevation coordinates are presented in MPF Local coordinates (i.e. North is 0 degrees).

The user may scribe out a sub-area on the mosaic by clicking-and-dragging with the mouse. Once selected, this sub-area will be used as one of many possible search criteria for database queries. This interface is designed to be a stand-alone query mechanism or be an aid to the text-based query mechanism so the user can augment the search parameters further (e.g. by filter, camera, and sequence selection). The Mars Pathfinder adaptation opted to augment the map interface with the text interface as it better suited the project needs. Once initiated, the MPF search returns the set of Engineering Data Records (EDRs) which comply with these search parameters and display the results in a Web browser. The mosaic remains displayed in a separate window from the Web browser which allows for quick iteration and keeps a context for the search results.

The text-based interface allows users to click on buttons and/or input values using common browser forms to build their database query. The browser forms display an Index Card Tab icon along the top of each page. Each tab form can contain distinct search criteria. Clicking on the tabs moves the user from page to page allowing them to incorporate the criteria from different pages in their search. Parameters left unspecified are not included in the search (will not be a factor in reducing the result set). The core Atlas forms-building capability accepts as input project defined search parameters for display and selection, thus providing a means for projects to tailor search criteria forms to their unique needs.

After formulating and submitting their search via the map or text interfaces, the user can select from a number of processing options. Like the forms-building capability, the Atlas core processing-options capability accepts project defined processing options, again allowing the project to tailor a Navigator to their needs. The MPF Navigator adaptation took advantage of this flexibility to incorporate the capability to generate FEI commands to securely transfer the search result set to their site and provide a direct link to the Navigation and Ancillary Information Facility's (NAIF) Experimenters Notebook developed and maintained in a separate organization; as well as utilizing the Atlas core capabilities to browse thumbnail or full images of the data, download individual images in various formats directly from the Web page, and generate detailed adhoc database reports to fully describe the data located.

Utilizing the Planetary Image Atlas design made it easy to equip the MPF Navigator with an interface to quickly and easily query the database based on a variety of search criteria and incorporate secure data distribution using the File Exchange Interface (FEI). The MPF Navigator coupled with FEI made it possible to provide automatic data distribution and database access in virtually realtime to the project in locations around the world, and paved the way for future missions.

5. MOSAIC GENERATION

The camera model selected to represent the IMP cameras was developed specifically for ground based stereo ranging [Yakimovsky and Cunningham, 1978]. It consists of five vectors C,A,H,V,O and a set of radial distortion coefficients R. This model is a thick lens approximation. Each vector has the following meaning:

C locates the camera entrance pupil in the reference frame of choice.
A is a unit vector normal to the image plane directed towards the exit pupil.
H is the vector sum of a vector along Charge Coupled Device (CCD) rows and A.
V is the vector sum of a vector along CCD columns and A.
O is a unit vector along the optical axis.

H and V contain the camera scale and CCD axis center and are not easily interpreted intuitively.

If P is a point in the scene then the corresponding image locations x and y can be computed (for the simpler case of A=O) from

$$x = \frac{(P-C)H}{(P-C)A}$$

$$y = \frac{(P-C)V}{(P-C)A}$$

The model is convenient to use because it can be translated by changing C and can be pointed by rotating A,H,V, and O.

Each camera model can be obtained from independent measurements of cardinal points. This is a laborious exercise. Instead we image, at several distances, a test target consisting of rows of surveyed holes. The target is itself surveyed in the desired coordinate system. A camera model is extracted directly from an analysis of the location of the holes in the images. This process takes only a few minutes and is relatively foolproof.

In order to use this model the vectors C,A,H,V, and O are rotated from the calibrated pointing orientation to the commanded azimuth and elevation for that image. Vector C permits the camera to be repositioned. In practice two operations are performed to orient a camera model for an image of interest. First the camera is rotated about its pivot point and the pivot point is translated to the deployed position (calibration was performed in the stowed position). Then a rotation is performed about the spacecraft origin to cause the camera reference frame to coincide with the spacecraft tilt on the planets surface. These rotations assure that stereo data are in local mars coordinates. CAHVOR values are available but have not been published.

IMP mosaics can contain upwards of 200 images. The CAHVOR camera model is used to assemble mosaics since it understands the relation between object and image points. A pixel in one image can be ray traced to a surface plane and then ray traced into any other image (points above the horizon are seen as behind the camera and can be "seen" by other camera positions). It remains only to define the output camera model, either as a perspective camera, or as a relation between azimuth and elevation. The resulting mosaics would register to sub pixel if the commanded pointing actually represented the physical camera pointing, however, a random backlash of as much as 15 pixels causes the actual pointing to be unknown. It becomes necessary to determine that camera pointing which, given the camera model, produces a seamless mosaic of the terrain. Portions of the spacecraft cannot be accurately mosaicked because they represent three dimensional structures which the camera views from different directions.

We make use of tiepoints to arrive at the correct camera pointing. Software acquires one tiepoint between each image overlap pair, resulting in up to 500 tiepoints per mosaic. These points can be determined automatically, however, the uncertainty in pointing and changes in lighting conditions dictate some manual inspection. Given these tiepoints, a search is made for that set of ideal camera pointing commands which result in camera models which ray trace each tiepoint in one overlap pair to the corresponding point in the other overlapping image. We use a deterministic downhill search based upon the simplex method [Press et al., 1986].

There were two uses for the image mosaics. The first was the obvious assembly of small pieces into a larger field of view. This included tilting the camera model in the Mars coordinate system to model a tilted spacecraft which resulted in mosaics with a level horizon beginning and ending at Mars north. The second application was to provide each day to the rover planning team a small stereo mosaic which was registered to a fixed reference image, facilitating the triangulation of way points for the next day's maneuvering.

Several types of mosaics were generated for Mars Pathfinder using the IMP camera. The basic types are listed here:

Perspective stereo mosaics. Figure 5 illustrates a stereo pair with the right eye on the left and the left eye on the right. One can observe stereo by crossing one's eyes, registering the images, and then refocusing. These are perspective projections with horizontal epipolar lines. The mosaics themselves behave as though the "camera" which took them was an IMP with a much larger field of view. The images are in the Lander reference frame and are tilted to reflect the position of the lander relative to the horizon.

Cylindrical mosaics. Figure 6 illustrates such a mosaic with azimuth and elevation grid lines superimposed behind the image tiles, the delineated boundaries of which construct a grid . In this case each pixel represents a fixed angle in azimuth and elevation. Rows are of constant elevation in Mars coordinates. The horizon is level, and column one (left edge) begins clockwise from Mars north.

Polar mosaics. Figure 7 illustrates a polar mosaic. This is, along with Figure 6, an equal angle mosaic. Concentric circles represent constant projected elevation. Mars nadir is at the convergent center and the horizon is corrected for lander tilt. North is up.

McAuley projection. Figure 8 illustrates a stereo pair of McAuley projections, invented at MIPL and named for its inventor, right eye on the left and left eye on the right. This is a perspective projection similar to Figure 5 except that the "camera" is not fixed but follows the columns of the mosaic as it sweeps around. In this way the near field, which suffers from camera parallax, remains undistorted, and true stereo images can be generated which comprise 360 degrees. The horizon is not level in order to preserve epipolar viewing. Figure 9 shows another mosaic in the McAuley projection but with a horizon leveled by moving the completed mosaic along columns.

Vertical projection. Figure 10 illustrates a vertical view made by ray tracing x,y points back through the camera to image coordinates. It assumes that the field is a plane tangent to the Martian surface with up pointing north. This is not an orthonormal rendering but was found to be useful for rapid initial orientation.

Color registration. Not all of the multispectral IMP images taken from the same position registered initially. Common misregistrations were sub pixel but still noticeable. Occasionally there were large excursions of 10 or 20 pixels between spectral bands. These misregistrations were corrected by correlating a large patch at the center of each image with the same area in all the spectral bands and shifting the images until they registered. This operation was performed autonomously. Sub pixel translations reduced color fringes to nearly undetectable levels.

6. COLOR PROCESSING

The production of true color images entails three primary steps: (1) conversion of the individual pixels into radiance units; (2) conversion of the radiances into CIE chromaticity coordinates; (3) conversion of the chromaticities back into those RGB values which cause the eye to perceive the correct color when viewing the image on a particular device. Complete mosaics were generated in each filter position using the above methods [Maki et al., this volume]. Each image was converted to spectral radiance during the assembly of the mosaic. This entailed applying a multiplicative responsivity correction which was quadratic with temperature as in

$$\text{radiance} = (DN) \;/\; (tRG)$$

where DN was the camera response, G the flat field correction, t the exposure time, and R the responsivity.

A spectrum was then constructed for each pixel by fitting a spline through the spectral radiance points, using as many filters as were available. Typically three filters located at 443nm, 531nm, and 671nm were available, but occasionally those located at 480nm and 600nm were also available. X, Y, and Z tristimulus values were computed by integrating the spectrum with the three color matching functions [Wyszecki and Stiles, 1982]. Tristimulus values represent the amount of three primary colors necessary to match the perceived color of a radiant spectral distribution. These colorimetric units are independent of any instrument and represent the color of the scene. Lastly the tristimulus values were converted to chromaticity coordinates and from there to *Lab* coordinates in preparation for conversion into the gamut of a display device. Chromaticity coordinates are the tristimulus values ratioed to their sum, resulting in values from 0 to 1 which are independent of brightness. *Lab* is a coordinate system in which perceived color and luminance differences are approximately uniformly distributed.

A color table was created for the display device by recording the chromaticity values of many combinations of RGB values. It was then possible to interpolate within this calibration cube to determine the RGB values required to re-create each of the desired chromaticity coordinates. This process took place in a linear *Lab* space. Candela software written by Candela Ltd. of Burnsville, MN was used to assist in the case of out of gamut conditions. The resulting images cause the eye to perceive true color when viewed under a D65 illuminant with appropriate surround lighting.

The right eye IMP camera had red ,green, and blue filters but the left eye had no green. In order to construct color stereo images it became necessary to synthesize a green image for the left eye. This was accomplished by determining the relationship between red, green, and blue for the right eye by least squares, and then applying this relationship to the left eye red and blue filters to construct an artificial green. The relationship used was

$$\text{green} = A\ \text{red} + B\ \text{blue} + C \;+\; D\ \text{red} \;/\; \text{blue}$$

where typical values for the terrain were:

$$A{=}0.260829,\ B{=}0.836880,\ C{=}{-}10.741461,\ D{=}3.244069 \text{ for filters 0 and 5}$$

This process produced a green that, in conjunction with the existing left eye red and blue, formed color images with hues indistinguishable from color images generated from the right eye camera.

7. DATA VISUALIZATION

7.1 TERRAIN VISUALIZATION

Visualization products were generated from three dimensional datasets produced by stereo correlation on matching left-right image pairs from the IMP camera system. The datasets were in the form of texture mapped polygonal objects (Figure 11) used by the rover team to support rover navigation planning. Software written to produce these products was run locally on the "rover control" workstation.

The dataflow (Figure 12) starts with the IMP image pairs with corrected pointing information as discussed in Section 5. Linearization is performed to re-project the image so that parallel image planes are simulated and stereo offset will only occur along rows of pixels. This linearized image pair is the input to a one dimensional fast correlator developed by the rover navigation team. It is capable of producing high correlation rates, on the order of one to two minutes per pair. The corrected pointing information is also input to the correlator which produces a file where each pixel is an x,y,z coordinate in mars surface fixed reference frame. This file is registered with the original left eye image. This x,y,z "image" is then filtered to remove out-of-range coordinates and other spikes and filled to remove small portions of missing data. The x,y,z coordinates are treated as separate bands in the image and standard filtering and filling algorithms are applied to each band. The images are then triangulated based on the connectivity established by the pixel ordering in the images. Since this image is projected outward from the camera, four neighboring pixels will be shared by two triangular polygons. Finally, the linearized image is applied as a texture map to the meshed data. From this point conversions can be performed to any popular format that supports texture mapping, including Virtual Reality Modeling Language (VRML), Inventor, OBJ, etc. An additional step of generating an orthonormalized projection was performed in preparation for generating physical scale models of the landing site using rapid prototyping technology. This orthonormalized elevation image was then meshed and a solid model prepared. The height field representation was useful for this process because of the ability to merge multiple range files while maintaining the integrity of the solid geometry.

These products were then delivered to the rover operations and engineering teams to assist in landed operations. Texture mapped meshes were prepared within a matter of minutes. A separate program converted the topographic data into Computer Aided Design file format, and a 1/15 scale physical Laminated Object Model (Figure 13) was prepared in a matter of days using a commercial vendor.

7.2 VRML IMPLEMENTATION

Virtual Reality Modeling Language (VRML) was used to provide easily-viewable 3D geometry to Mars Pathfinder personnel and the public. VRML allows for interactive manipulation of two and three dimensional data. Most personal computers can run the free, commercially available VRML viewers from within their web browsers or in a stand-alone viewer, enabling a wide audience to view the data on low-cost computers. The use of VRML for Mars Pathfinder by various institutions and individuals resulted in many members of the public downloading and installing a VRML browser so that they, too, could see the data.

Converting Mars Pathfinder mosaics and associated terrain information into VRML data was a multi-step process, requiring stereo correlation, range map generation, and the partitioning of the entire data set into a form suitable for VRML. In 1997 the primary users of VRML were developers of web-based multi-user games and other commercial products. The resulting crop of VRML authoring tools facilitated development of VRML worlds for commercial use and other applications such as architecture, short animations, free-form organic geometry, and modeling. Unfortunately the tools at that time did not help with the ingestion of remotely-sensed data nor did they create results usable for the intended target audience of scientists. Problems encountered were due to the use of large images as texture maps and large polygonal models. In order for VRML to be useful as a scientific analysis tool it was necessary to provide access to full-fidelity data, so work-arounds were implemented. To this end, software was written which partitioned the images and geometric data into smaller pieces so that VRML browser limitations did not significantly impact the visual results when viewing the VRML world.

The VRML worlds that team members generated for Pathfinder fell into two main categories. The first involved projection of the tiles of a panoramic IMP mosaic image onto the inside of a faceted cylinder, one image tile per polygon. The science team could view the entire image data in an interactive manner within a web browser (and when this projection was displayed on a HDTV monitor (Figure 14) the science team was able to interact with a large area of the entire image). This tiled, paste-it-on-a-cylinder approach was used primarily because of its simplicity and because only the 2D image mosaic was used. One other factor was that VRML browsers imposed strict limitations on the maximum size of texture maps, no larger than 256x256 pixels. Since the full Pathfinder panorama mosaic was many times larger than that limit, the decision was made to chop up the textures into small, full-fidelity image tiles. The cylindrical approach is not much different than technologies like QuicktimeVR (QTVR), but it was a fast way to let the science team look at the 2D and 3D image data quickly on their HDTV monitors using fast 3D graphics hardware and free browser software. Once members of the public got their hands on the VRML data, though, they added features including a heads-up-display indicating the viewer's heading.

The second category of VRML data sets that we generated used tiled, pyramided, texture-mapped 2 1/2D and 3D terrain models. This permitted users to move around the terrain at will, and the VRML browser swapped in higher-resolution tiles as the user got closer to certain areas, lower-resolution tiles as they got farther away – a technique widely used in computer graphics. Figure 15 shows one such scheme. Again, this approach worked moderately well on the then-current VRML browsers, but browser limitations again required some tricks to make the data usable.

Recently more advanced methods of partitioning large terrain geometry data sets and their associated texture images have become available. One such method uses Java and VRML and was written by M. Reddy of SRI and delivered to the VRML Consortium's geoVRML Working Group. The geoVRML Working Group has proposed that the SEDRIS Geographic Reference Model be adopted to deal with coordinate systems. Evaluation of the Java 3D API (J3D) and the Java Advanced Imaging API (JAI) is underway and hopefully these new technologies will address some of the shortcomings found with VRML. It is expected that JAI and Java3D will be better for developing platform-independent, interactive 3D science analysis tools. VRML will likely become one of Java3D's most important file formats, though mainly for loading geometry, coordinate system information, and behavior (i.e. animation of 3D objects over time). Java3D will not have its own native file format, and VRML seems well-positioned to continue to be widely used. Another reason for VRML's continued use is that Java3D fits fairly well with the VRML architecture. The use of VRML is not a dead-end; the same VRML data should be viewable even as the next generation of 3D browsers, API's and specifications come into mainstream use.

7.3 HIGH DEFINITION TELEVISION IMAGES AND ANIMATION

Mars Pathfinder was NASA's first planetary mission to use stereo High Definition Television (HDTV) technology to support mission operations and science analysis. This support included: (1) real-time display of image mosaics, (2) selection of press release images, (3) creation of high resolution animations, and (4) archiving of digital image and animation products.

JPL's Digital Image Animation Laboratory (DIAL) is equipped with state-of-the-art HDTV production and distribution equipment, and is integrated with the MIPL system described earlier. Because the Mars Pathfinder science/mission operations and MIPL/DIAL areas are located in different buildings, separate HDTV monitors were installed in each area through optical fibers so that the images and animations created in MIPL and DIAL could be simultaneously viewed by the Mars Pathfinder project personnel. The system was used to display mosaics from the IMP camera in 1920 pixels by 1080 lines. This resolution conforms to the SMPTE274 standard.

The video mode of an Silicon Graphics ONYX workstation located in DIAL was switched to the HDTV mode and used to enable the scientists interactively select and review press release images. The system was used to display mosaics from the IMP camera in 1920 pixels by 1080 lines. While the video output was fed to the monitors of the Pathfinder operations area through optical fibers, this workstation could be controlled from another workstation which allowed scientists in the operations area full control of the selection process. Figure 16 shows an example of the selection screen.

An HDTV digital frame buffer, "MovieVideo" from DVS, was connected to a Silicon Graphics O2 workstation through its SCSI interface. This memory-based system can store up to 256 HDTV frames (about 8 seconds) and play back in realtime. Using its built-in VTR control functions, animation segments can be automatically loaded to this framebuffer for 256 frames at a time, then recorded on a video tape automatically. The output from this framebuffer is a 1.5Gbps HDTV parallel digital interface (SMPTE274-compatible) which can be connected to a VTR for recording, or used for display on a HDTV monitor.

For recording video from the workstation and the digital frame buffer, Panasonic D-5 digital video recorder system was used. This system consists of a VTR which can record a maximum of 2 hours of digital video (SMPTE 259M, 360Mbps), and a HDTV processor used for a intra-frame compression/decompression of a serial HDTV signal (SMPTE 292M, 1.5Gbps) to a 360Mbps signal using a discrete cosine transform (DCT) compression algorithm. Even though about 4.5 to 1 compression is applied, there is no recognizable loss of picture quality after recording and the details of mosaics from the IMP camera were generally preserved, enabling high quality recording in digital format. Figure 17 is a sample frame from a cylindrical-mosaic based animation. Figure 18 is a sample frame from a spherical projection based animation.

8. PRESS AND PUBLIC AFFAIRS PRODUCTS

JPL and MIPL have a long history of producing products for release through press conferences and briefings for use in newspapers, journals, and on television. Traditionally, during high profile encounters or landings, realtime data display was available to the press, and hard copy products were distributed to the press approximately 24-48 hours after data receipt (depending on the product complexity) in the form of photographic prints and video tapes.

As the Pathfinder landing approached and the excitement built around the world, it became clear that data would need to be released much more rapidly. Everyone wanted to share the excitement of Pathfinder's successful landing and view the first images of the surface. At this point, the Mars Pathfinder Project made some historic decisions; the IMP and Sojourner camera images from Mars would be immediately viewable by the public, all press releases products would be distributed at full resolution in electronic form only (no prints), and the first press conference would include high resolution color image mosaics constructed from many individual IMP images and would be held less than two hours after receipt of the first images.

Making the first images from Mars immediately viewable by the public was the simplest to accomplish. The MIPL Realtime subsystem produces a display for use as an assessment of the instrument's health and operation. This display for the IMP instrument was piped to video broadcast channels for viewing at JPL and via NASA TV. As the engineers and scientists caught their first glimpse from Pathfinder, so did the world.

Although the electronic release of all press release products is not a new concept, Pathfinder is the first mission to release the data at full resolution and to completely eliminate hardcopy prints as a distribution media. Two WWW sites at JPL are set up to enable access to these full resolution products (the Planetary Photojournal and the JPL Home Page), but it was clear that the data needed to be replicated on as many sites as possible so that the press and the public could access the data they needed quickly. MIPL developed procedures to automate the generation and dissemination of these products in a variety of popular formats (TIFF, GIF, JPEG) to the Photojournal and the JPL Home Page, to the Mars Pathfinder Home Page and its numerous mirror sites, as well as to a private "press only" site. This new "electronic only" release policy was so popular with all involved, it has become the standard for all other missions.

The first press conference, less than two hours following receipt of the first images, posed more difficult problems. The critical release would be a mosaic showing the Rover on the Lander, and the surrounding Martian terrain (called the "Mission Success" panorama). Not only did the color mosaic need to be generated and approved for release, it needed to be converted to a variety of formats suitable for use on the WWW. Software and procedures were developed to correct the images for camera distortion, mosaic images from each filter together (39, 256 X 248 pixel images per filter), map project the mosaics to create a perspective view, perform an approximate color balance, and display the result on HDTV monitors for approval; all in 15 minutes. Approximately 30 minutes was reserved for science and project review of the high resolution mosaics, and selection of products for press release. Following selection, format conversion was performed into multiple formats, captions for the releases were written by science team members, and data were transferred electronically to web sites accessible by the press and general public. These products were available in all required formats as the start of the press conference. This pattern was generally followed for the first week of the mission, when daily press conferences continued in response to the demands from press and public.

The procedures developed to support producing and disseminating these press release products were used throughout the mission and have been adopted by subsequent missions. Press release products included all of the variety of products discussed throughout this paper.

9. PLANETARY DATA SYSTEM ARCHIVAL PRODUCTS

All NASA planetary missions are required to deliver their products to the PDS for long term archive. The goal of the PDS is to begin working with the missions very early in their development so that the archive requirements are well understood. Working together from the start, MIPL and the PDS Imaging Node, which reside in the same organization, resolved data format and standards issues, delivery requirements and data flow so that EDR level (raw) data flowing out of the realtime subsystem required only minor modification prior to ingestion into the archive.

A PDS mission archive consists of raw instrument data as acquired by the spacecraft, the derived instrument data (when available) that have undergone rectification processes, and the supporting elements necessary to make full use of the data. The supporting elements include ancillary data for calibration and geometric characterization, documentation describing the observational histories and data organization, summary files that index the data, and software to access and process the data.

This mission archive is often separated into a number of datasets, one per instrument and/or data processing level (raw or derived). Pathfinder is producing a raw and derived archive dataset for each of the four primary science instruments. MIPL, in collaboration with the PDS Imaging Node, is producing the raw archive datasets for the IMP, Rover, APXS and MET, and portions of the derived archive for the IMP and Rover (mosaics and color products). The Pathfinder mission archive will be produced on CD-ROM (approximate quantities: 5 raw data volumes and 12 derived data volumes), and will be accessible via the MPF Navigator (discussed earlier).

10. CONCLUSION

The system developed for Mars Pathfinder incorporated several innovations based on the demands imposed by the time constraints of an in-situ operations scenario and the demands for rapid release of highly processed instrument data to the public. New systems for automated mosaicking based on pre-flight camera models, for color reconstruction based on pre-flight radiometric calibration data, for electronic distribution of data based on a variety of criteria for different users, and for display of science instrument on newly available high resolution digital display equipment were produced. Systems utilized for the first time to support Mars Pathfinder will become the baseline for future planetary exploration missions.

ACKNOWLEDGMENTS

The authors wish to thank the Mars Pathfinder project management team for encouraging innovation and creativity within a flight project environment with strict operational deadlines and firm requirements. We especially thank Al Sacks, John Wellman, Richard Cook, Tony Spear, Brian Muirhead, Matthew Golombek, and Rob Manning for encouraging us to bring new capabilities to this mission. The support of Bill Tuk, Kris Capraro, Curt Hahn, Dave Hodges, Chris Cordell, Mike Mueller, Larry Goforth, Maher Hanna, Greg Earle, Ray Bambery in helping MIPL and DIAL function effectively in support of flight missions is gratefully acknowledged. The efforts of the Multimission Data Management System development team, including John Rector and Jeff Jacobson, and the long hours put in by Carol Stanley as the backup realtime engineer are hereby acknowledged. It was a pleasure working with the instrument PIs, including Peter Smith, Tim Schofield, and Tom Economou on this project. We thank the rover team, and especially Brian Cooper and Jake Matijevic, for their encouragement and assistance. We thank Tom Handley for his continuing support of this activity. The support of the Telemetry and Missions Operations Directorate and the Mars Exploration Directorate at JPL is gratefully acknowledged.

The Planetary Image Atlas and the Planetary Photojournal were designed and developed by the Planetary Data System (PDS) in collaboration with the Solar System Visualization Project (SSV). The URLs are: http://www-pdsimage.jpl.nasa.gov/PDS/public/Atlas/Atlas.html and http://photojournal.jpl.nasa.gov.

High Definition Television technology support was provided by a prototype stereo HDTV system which was recently added to JPL's Visualization and Analysis Testbed (VAT). The VAT is part of the Digital Image Animation Laboratory (DIAL) and Multimission Image Processing Laboratory (MIPL) and is an element of JPL's end-to-end testbed. The VAT was developed by the Solar System Visualization (SSV) project and New Millennium Program (NMP).

Work described in this paper was carried out by the Mars Pathfinder Project at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

Green, W. B., P. L. Jepsen, J. E. Kreznar, R.M. Ruiz, A. A. Schwartz and J. B. Seidman, Removal of Instrument Signature From Mariner 9 Television Images of Mars, *Appl. Opt. 14*, 105-114, 1975.

Green, W. B., and P. M. B. Shames, "Use of Multimission Facilities to Reduce the Cost of Operations on Low Cost Planetary Missions--A Mars Pathfinder Approach", Proc. IAA Conference on Low Cost Planetary Missions, 1994.

Jepsen, Paul L. et. al., "Voyager Image Proecessing at the Image Processing Laboratory, *Journal of British Interplanetary Society 33*, 315-322, 1980.

Levinthal, E. C., W. B. Green, K. L. Jones, and R. Tucker, Processing the Viking Lander Camera Data, *J. Geophys. Res. 82,* 4412-4420, 1977.

Liebes, S., and A. A. Schwartz, Viking 1975 Mars Lander Interactive Computerized Video Stereophotogrammetry, *J. Geophys. Res. 82,* 4421-4429, 1977.

Maki, J. N., J. J. Lorre, P. H. Smith, R. D. Brandt, and D. J. Steinwand, The Color of Mars: Spectrophotometric Measurements at the Pathfinder Landing Site, *J. Geophys. Res.*, this volume.

Press,W. et.al., *Numerical Recipes*,p.292 (amoeba),Cambridge University Press, 1986.

Rindfleisch, T. C., J. A. Dunne, H. J. Frieden, W. D. Stromberg, and R. M. Ruiz, Digital processing of the Mariner 6 and 7 pictures. *J. Geophys. Res. 76,* 394-417, 1971.

Ruiz, R. M., D. A. Elliott, G. M. Yagi, R. B. Pomphrey, M. A. Power, K. W. Farrell, J. J. Lorre, W. D. Benton, R. E. Dewar, and L. E. Cullen, IPL processing of the Viking Orbiter Images of Mars, *J. Geophys. Res. 82,* 4189-4202, 1977.

Saunders, R. S., A. J. Spear, P. C. Allin, R. S. Austin, A. L. Berman, R. C. Chandlee, J. Clark, A. V. Decharon, E. M. DeJong, D. G. Griffith, J. M. Gunn, S. Hensley, W. T. K. Johnson, C. D. Kirby, K. S. Leung, S. T. Lyons, G. A. Hichales, J. Miller, R. B. Morris, A. D. Morrison, R. G. Piereson, J. F. Scott, S. J. Shaffer, J. P. Slonski, E. R. Stofan, T. W. Thompson and S. D. Wall, Magellen Mission Summary, *J. Geophys. Res. 97*, No. E8, 13067-13091, 1992.

Soha, J. M., D. J. Lynn, J. A. Mosher, N. N. Thayer and D. A. Elliott, IPL Processing of the Mariner 10 Images of Mercury, *Journal of Applied Photographic Engineering*, 3, No. 2, 82-92, 1977.

Soha, J. M., D. J. Lynn, J. J. Lorre, J. A. Mosher, N. N. Thayer, D. A. Elliott, W. D. Benton and R. E. Dewar, IPL Processing of the Mariner 10 Images of Mercury, *J. Geophys. Res. 80*, No. 17,2394-2414, 1975.

Yakimovsky,Y. and R. A. Cunningham, System for Extracting Three-Dimensional Measurements from a Stereo Pair of TV Cameras, *Computer Graphics and Image Processing 7*, 195-210, 1978.

Wyszecki,G. and W. Stiles,*Color Science: Concepts and Methods, Quantitative Data and Formulae*, 2nd Edition, 156,John Wiley & Sons, 1982.

CAPTIONS

Figure 1. Mars Pathfinder Science Data Flow

Figure 2. Mars Pathfinder Server Architecture. The circles represent servers, boxes represent data storage and large arcs represent the client users/programs/processes that use the servers. Data flows are shown by solid lines, control or commands are shown by dashed lines.

Figure 3. Realtime Subsystem. Data sinks and sources are represented by boxes, processes are represented by ellipses, and X display devices by circles. The critical control flows are shown as solid lines, the data flows are shown by dashed lines.

Figure 4. MPF Navigator Map-based User Interface. The MPF Navigator, a part of the Planetary Image Atlas, provides a mechanism to quickly and intuitively query distributed data systems to locate and acquire planetary data via a Java-enabled Web browser.
URL: http://www-pdsimage.jpl.nasa.gov/PDS/public/Atlas/Atlas.html

Figure 5. Perspective Stereo Mosaic (left eye on right, right eye on left).These are perspective projections with horizontal epipolar lines.

Figure 6. Cylindrical Mosaic with azimuth and elevation grid lines superimposed behind the image tiles.

Figure 7. Polar mosaic with horizon corrected for lander tilt and north up.

Figure 8. Stereo Pair of McAuley Projections Mosaic (left eye on right, right eye on left)

Figure 9. McAuley Projection with horizon leveled

Figure 10. Vertical Projection with north up.

Figure 11. Terrain Visualization Texture Mapped Meshes

Figure 12. Terrain Visualization Processing Flow

Figure 13. 1/15 scale physical Laminated Object Model created from the topographic data

Figure 14. VRML world generated from the projection of the tiles of an IMP mosaic panorama onto the inside of a faceted cylinder. The scientist used a web browser and an HDTV monitor to interact with a large area of the entire panorama.

Figure 15. VRML world tiling scheme used with texture-mapped 2 1/2D and 3D terrain models. The VRML browser swaps in higher-resolution tiles as the user moves closer to certain areas and lower-resolution tiles as they move farther away.

Figure 16. HDTV press release selection screen.

Figure 17. Sample frame from a cylindrical mosaic based animation.

Figure 18. Sample frame from a spherical projection based animation.

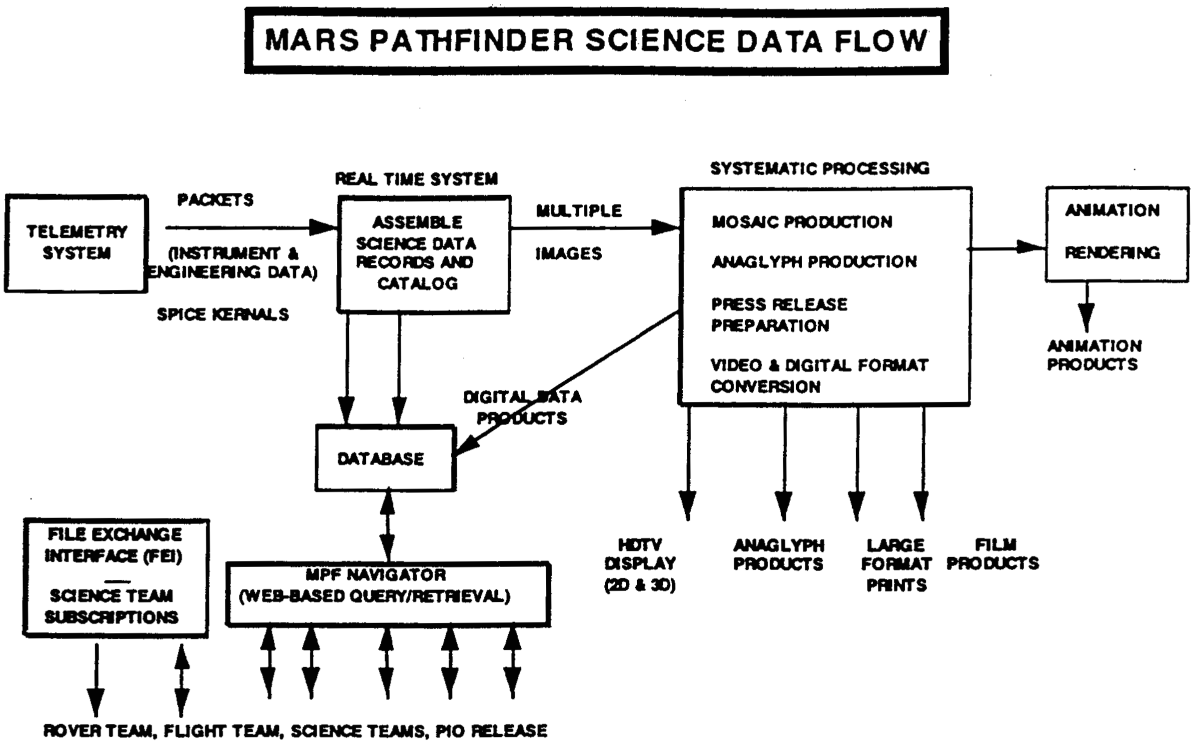


Figure 1. Mars Pathfinder Science Data Flow

Figure 1

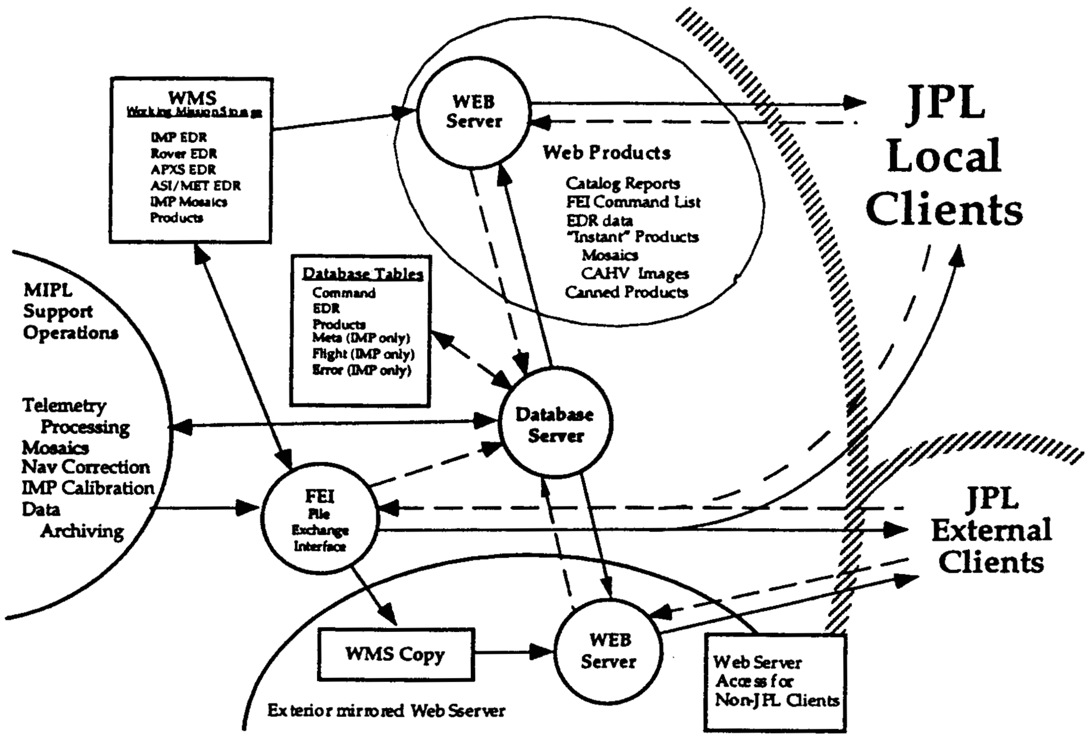


Figure 2. Mars Pathfinder Server Architecture

Figure 2

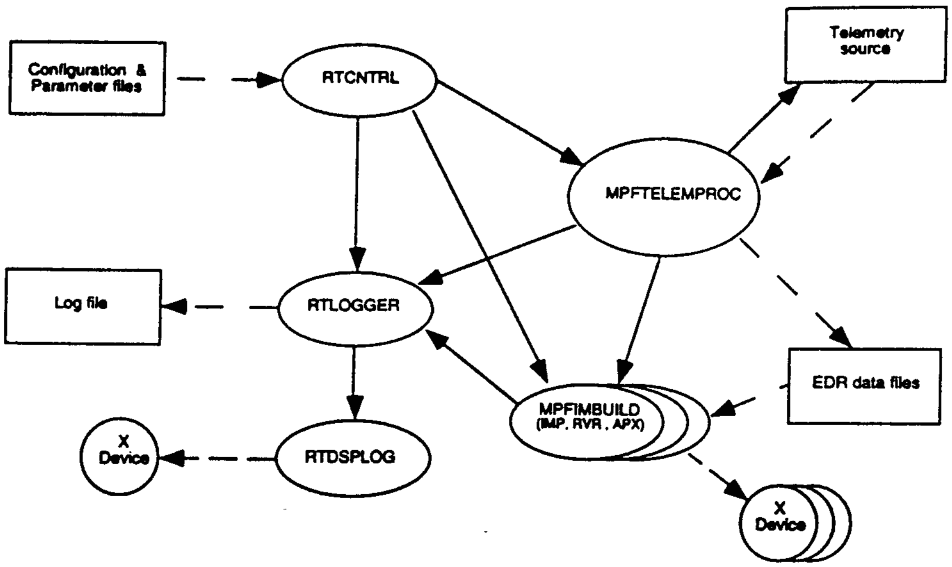


Figure 3. Realtime Subsystem

Figure 3

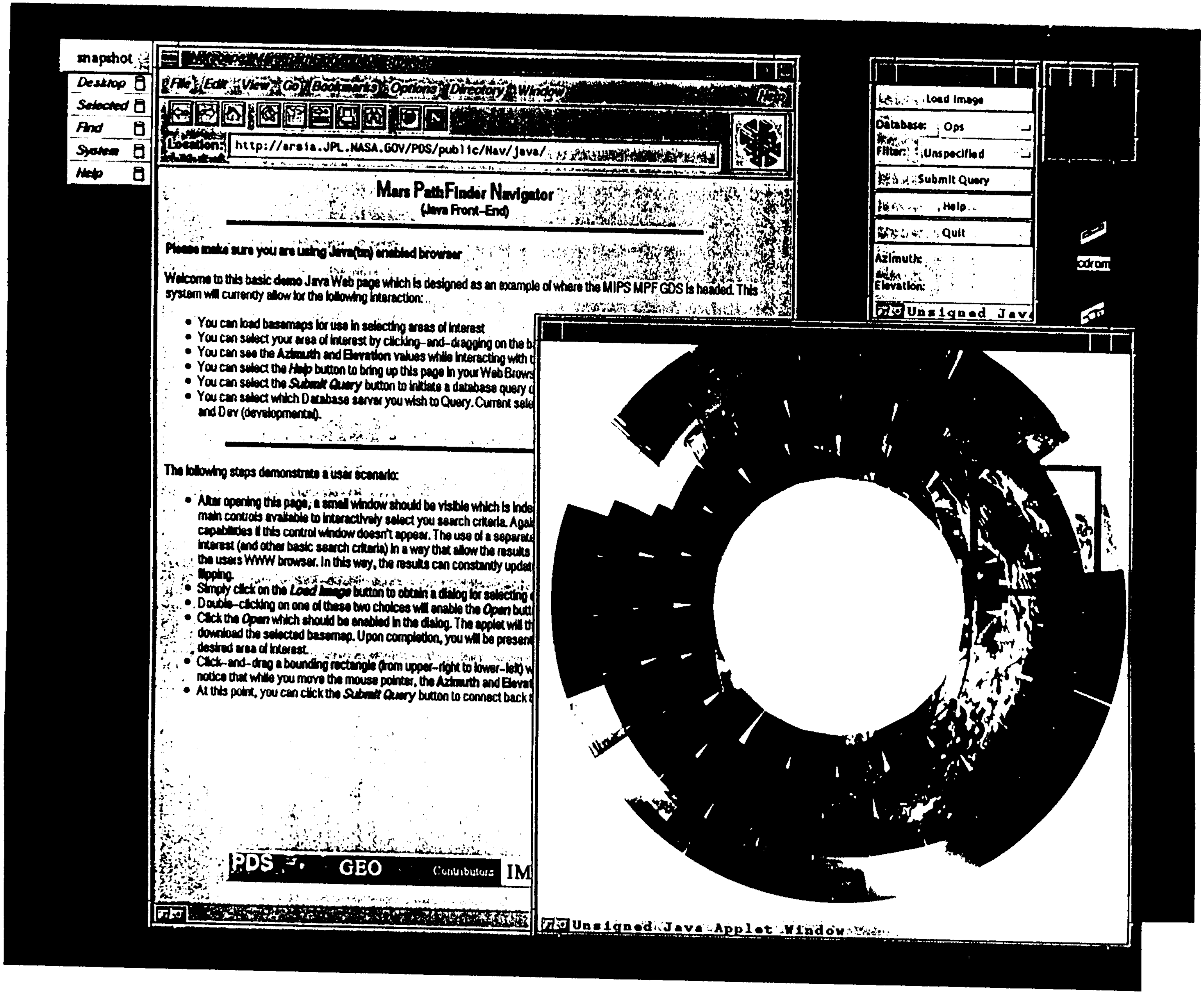

snapshot
Desktop
Selected
Find
System
Help
File Edit View Go Bookmarks Options Directory Window Help
Location: http://arsia.JPL.NASA.GOV/PDS/public/Nav/Java/
Mars PathFinder Navigator
(Java Front-End)
Please make sure you are using Java(tm) enabled browser
Welcome to this basic demo Java Web page which is designed as an example of where the MIPS MPF GDS is headed. This system will currently allow for the following interaction:
You can load basemaps for use in selecting areas of interest
You can select your area of interest by clicking-and-dragging on the b
You can see the Azimuth and Elevation values while interacting with t
You can select the Help button to bring up this page in your Web Brows
You can select the Submit Query button to initiate a database query o
You can select which Database server you wish to Query. Current sele
and Dev (developmental).
The following steps demonstrate a user scenario:
After opening this page, a small window should be visible which is inde
main controls available to interactively select you search criteria. Agai
capabilities if this control window doesn't appear. The use of a separate
interest (and other basic search criteria) in a way that allow the results
the users WWW browser. In this way, the results can constantly updat
flipping.
Simply click on the Load Image button to obtain a dialog for selecting
Double-clicking on one of these two choices will enable the Open butt
Click the Open which should be enabled in the dialog. The applet will th
download the selected basemap. Upon completion, you will be presen
desired area of interest.
Click-and-drag a bounding rectangle (from upper-right to lower-left) w
notice that while you move the mouse pointer, the Azimuth and Elevat
At this point, you can click the Submit Query button to connect back
PDS
GEO
Contributors
IM
Load Image
Database: Ops
Filter: Unspecified
Submit Query
Help
Quit
Azimuth:
Elevation:
Unsigned Jav
cdrom
Unsigned Java Applet Window

Figure 4

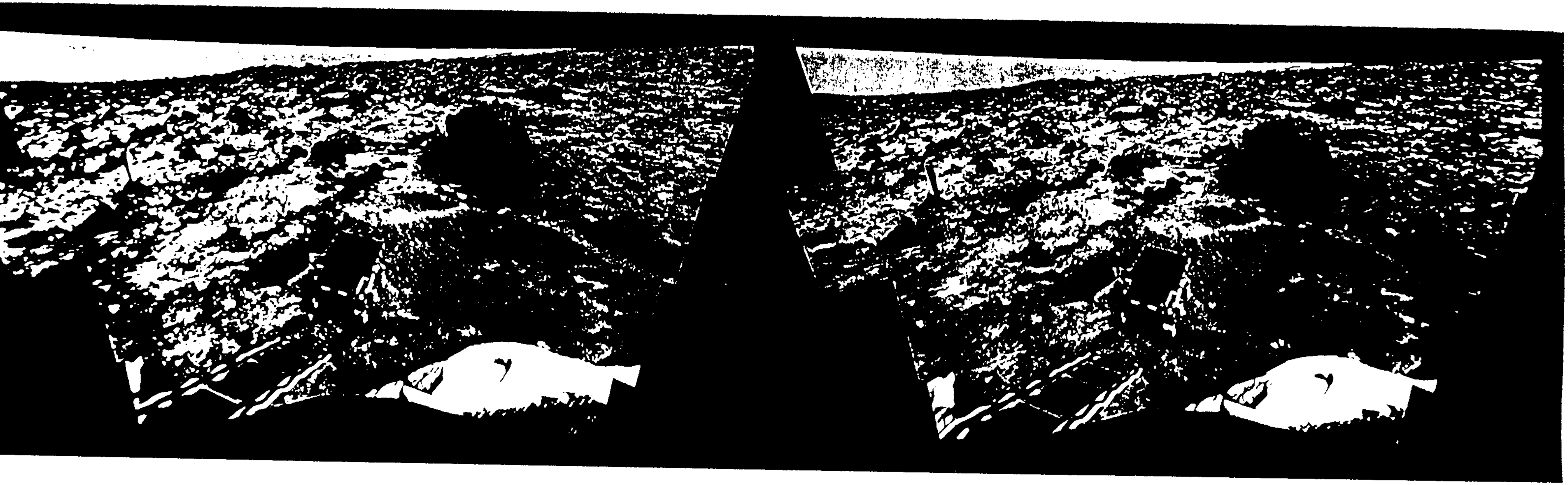


Figure 5

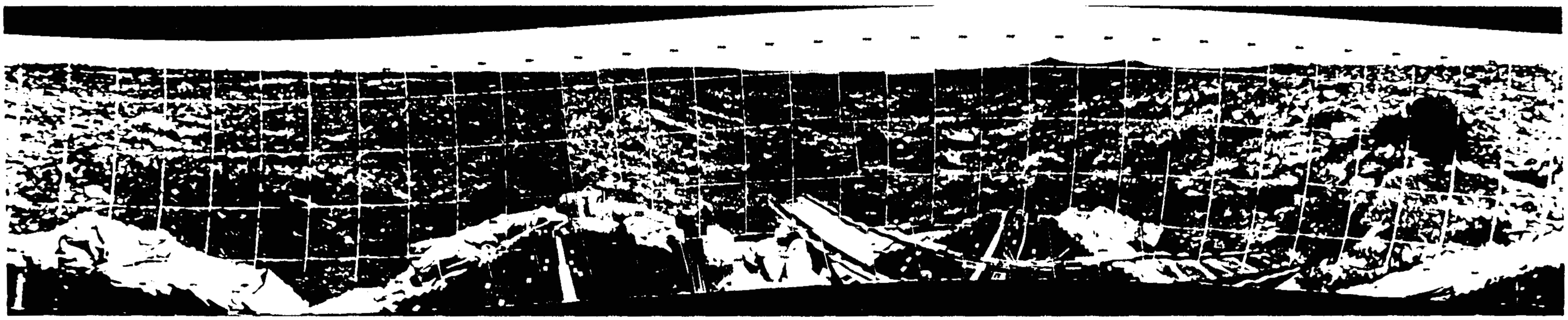


Figure 6

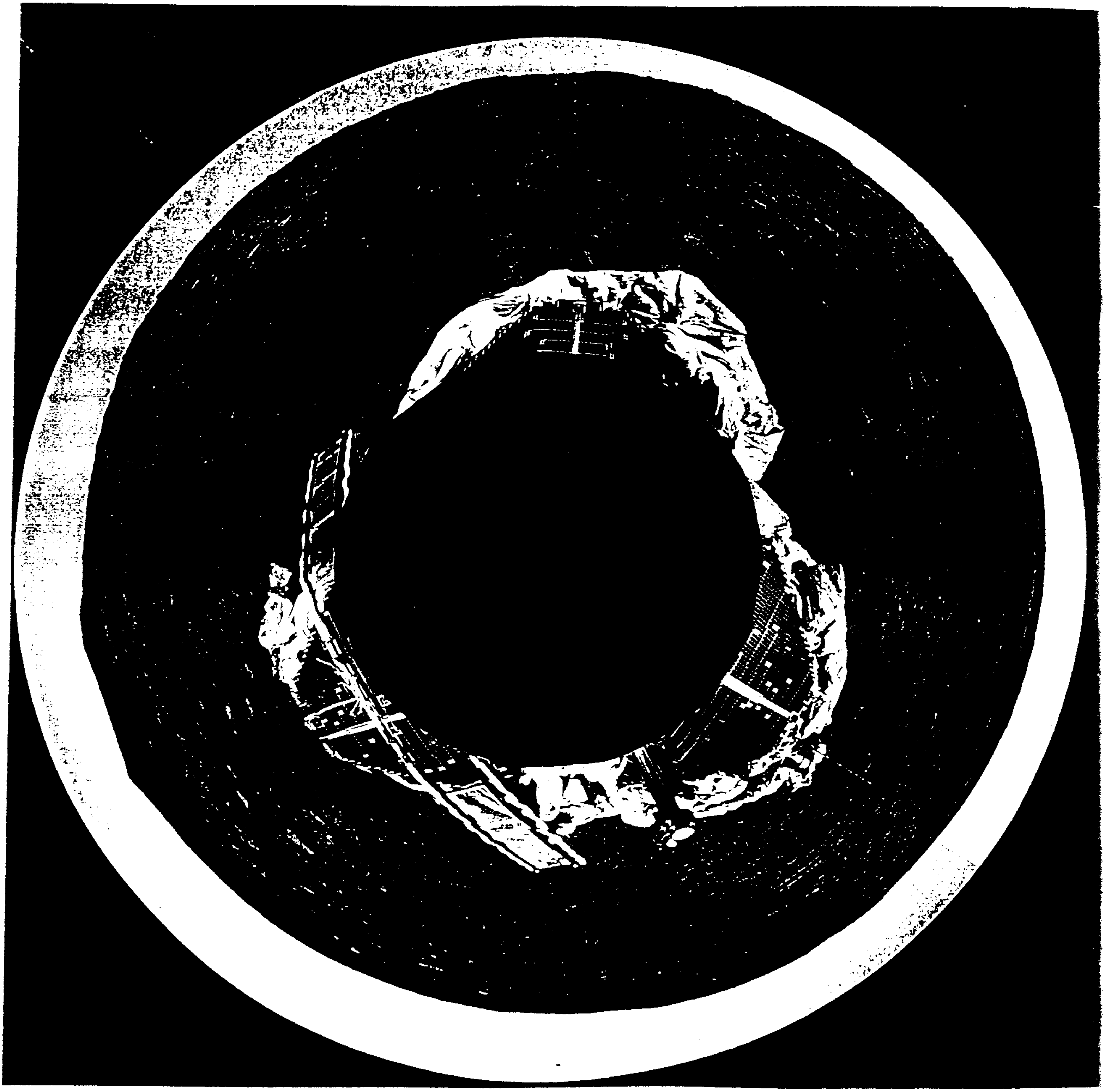


Figure 8

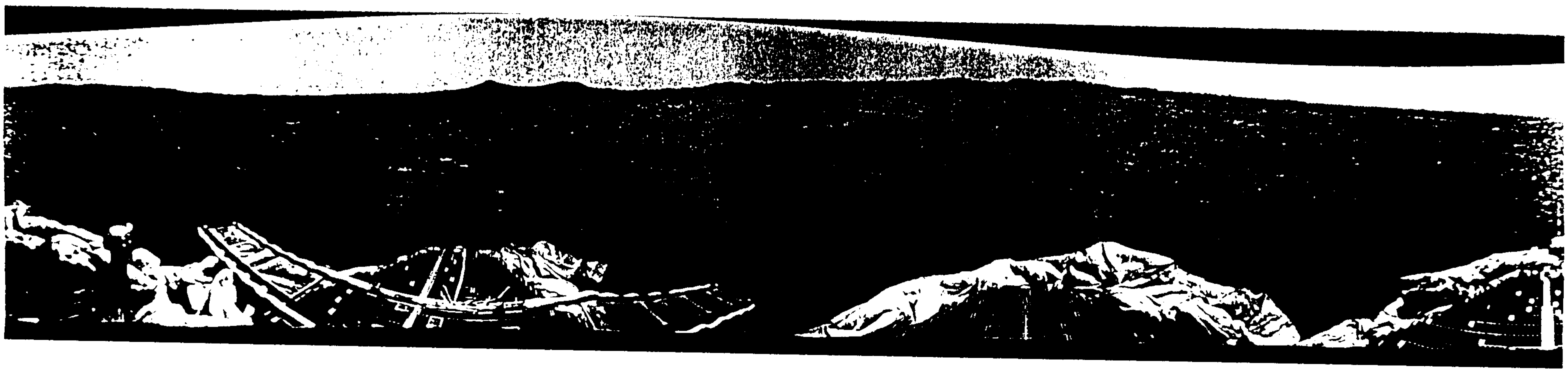


Figure 9

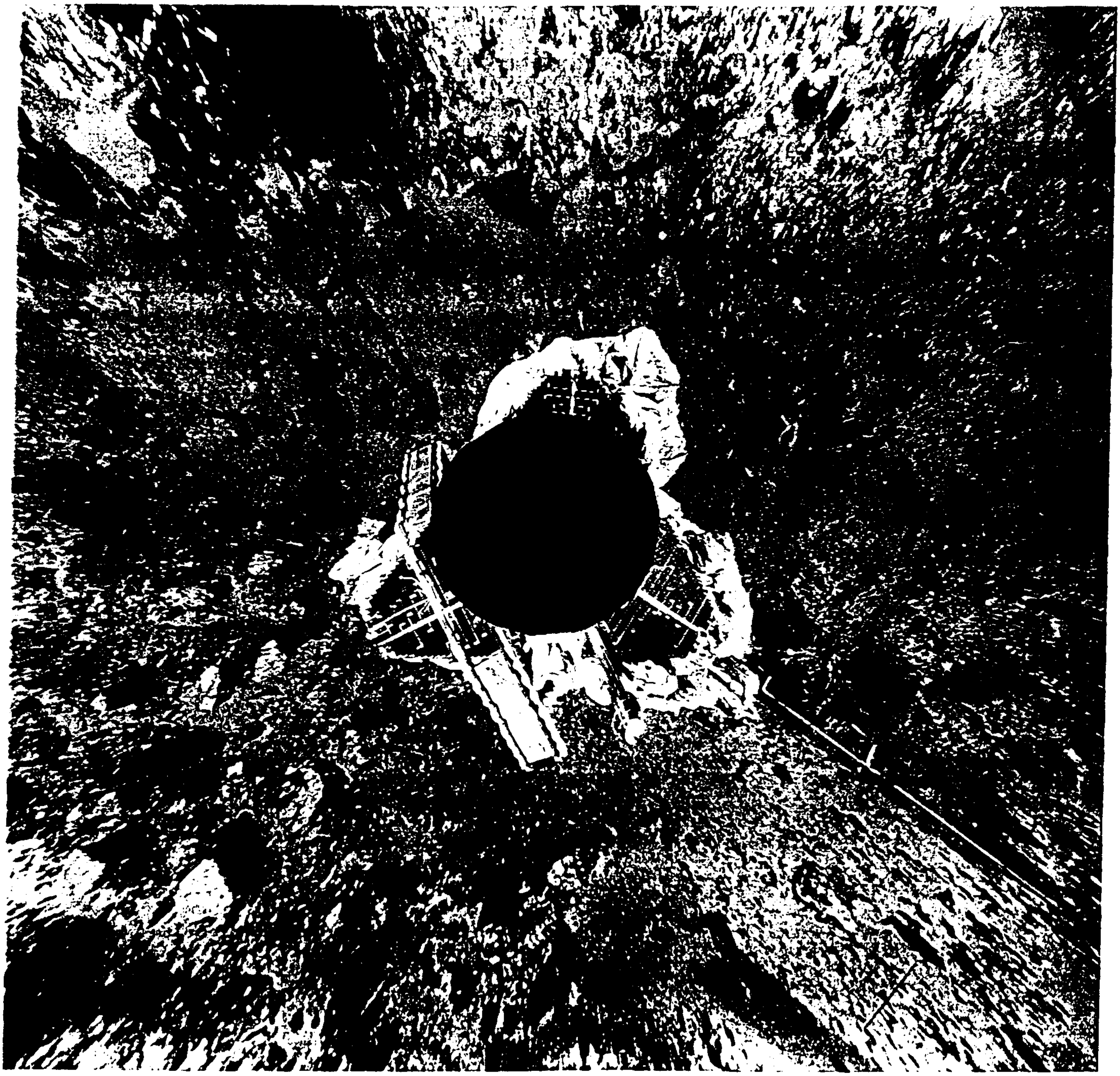
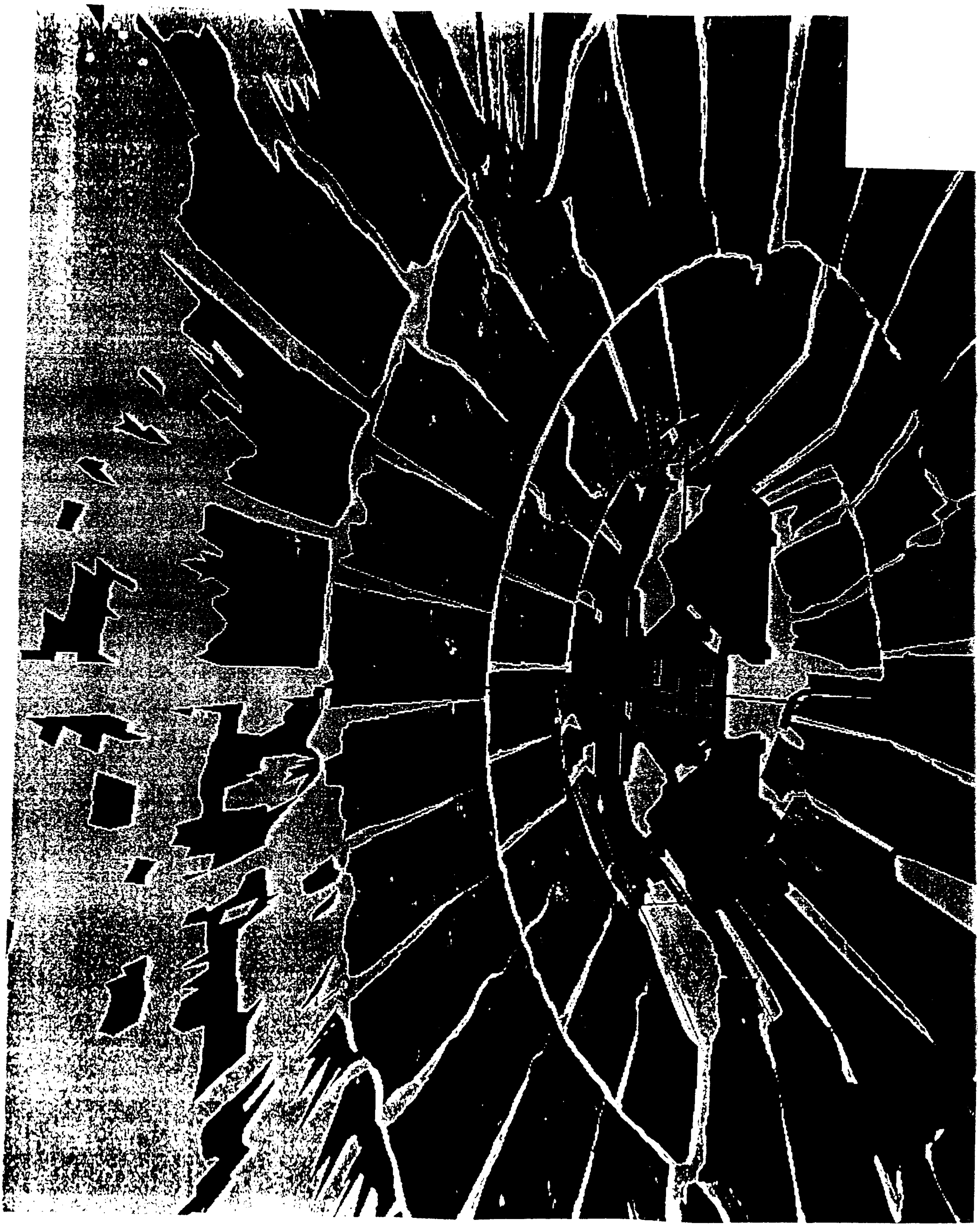


Figure 10



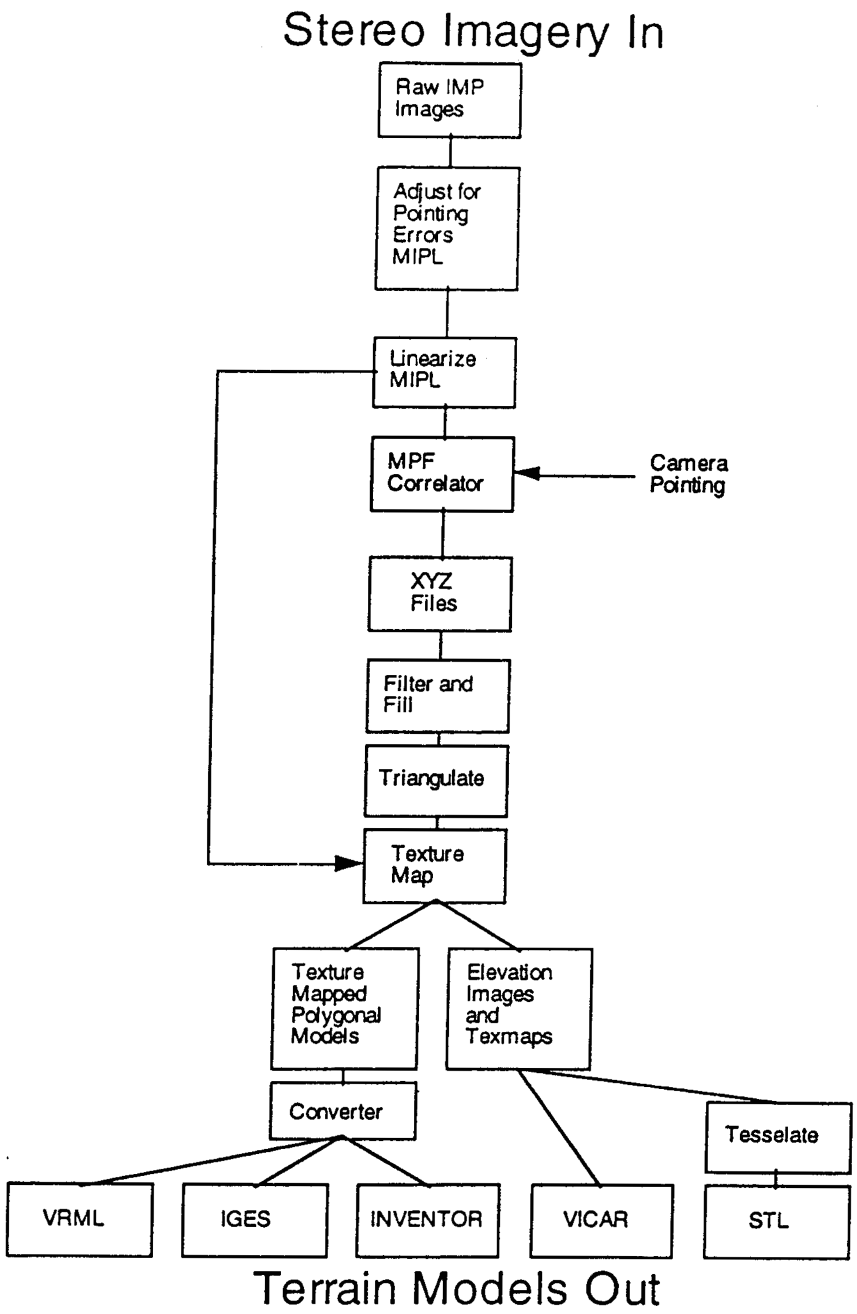


Figure 12. Terrain Visualization Processing Flow

Figure 12

Figure 13

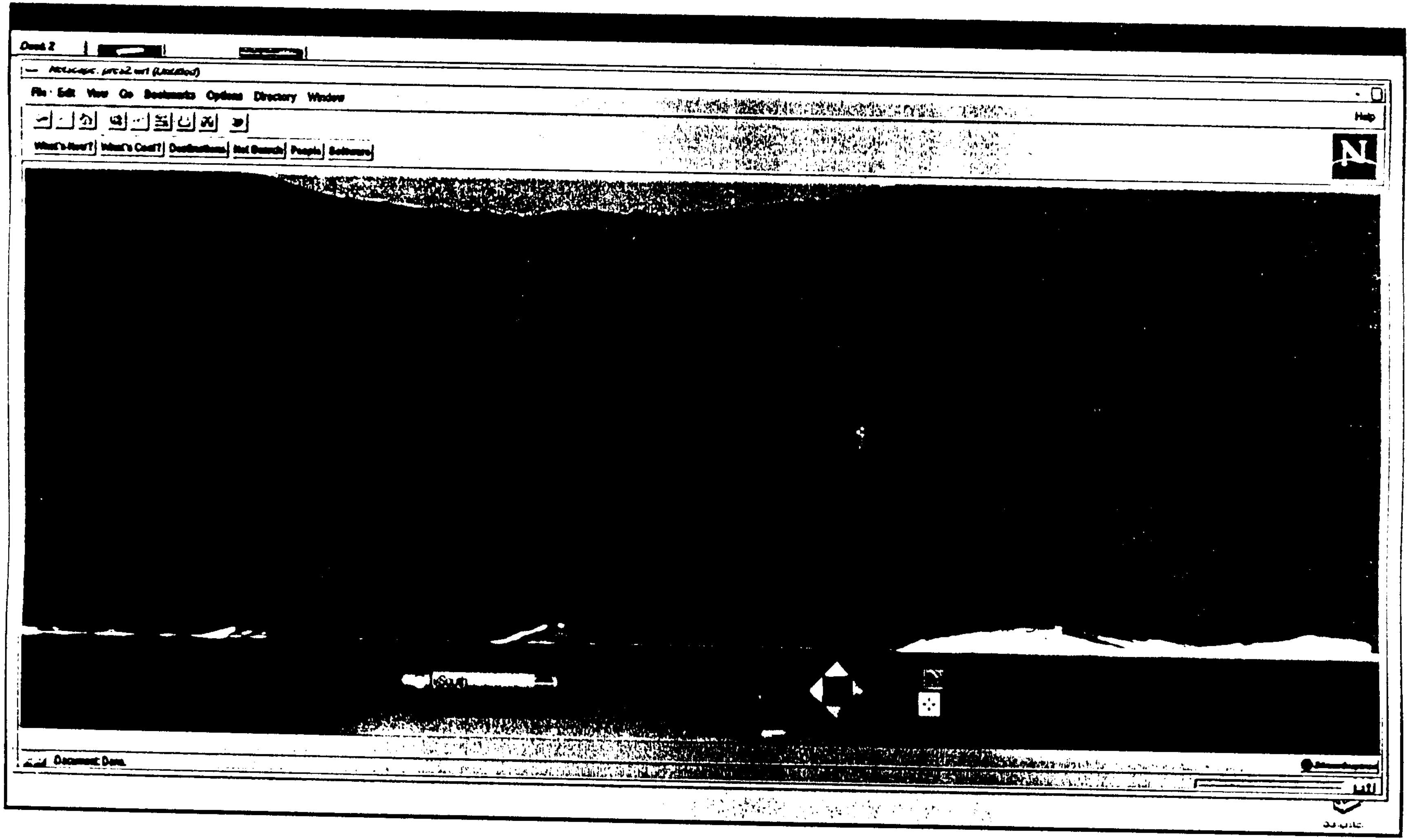

File Edit View Go Bookmarks Options Directory Window
Help
What's New? What's Cool? Destinations Net Search People Software
Document: Done.

Figure 14

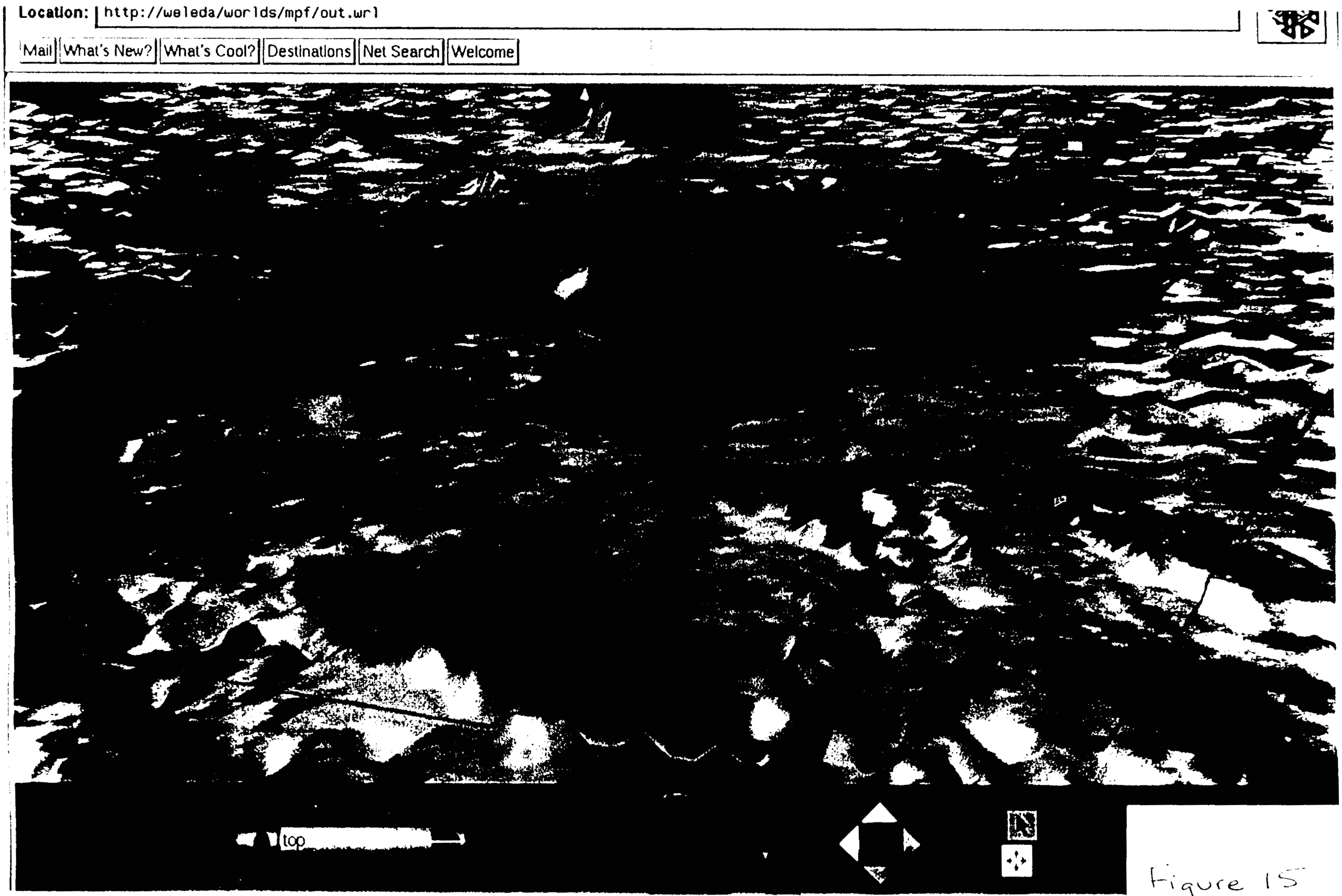

Location: http://weleda/worlds/mpf/out.wrl
Mail
What's New?
What's Cool?
Destinations
Net Search
Welcome
top

Figure 15

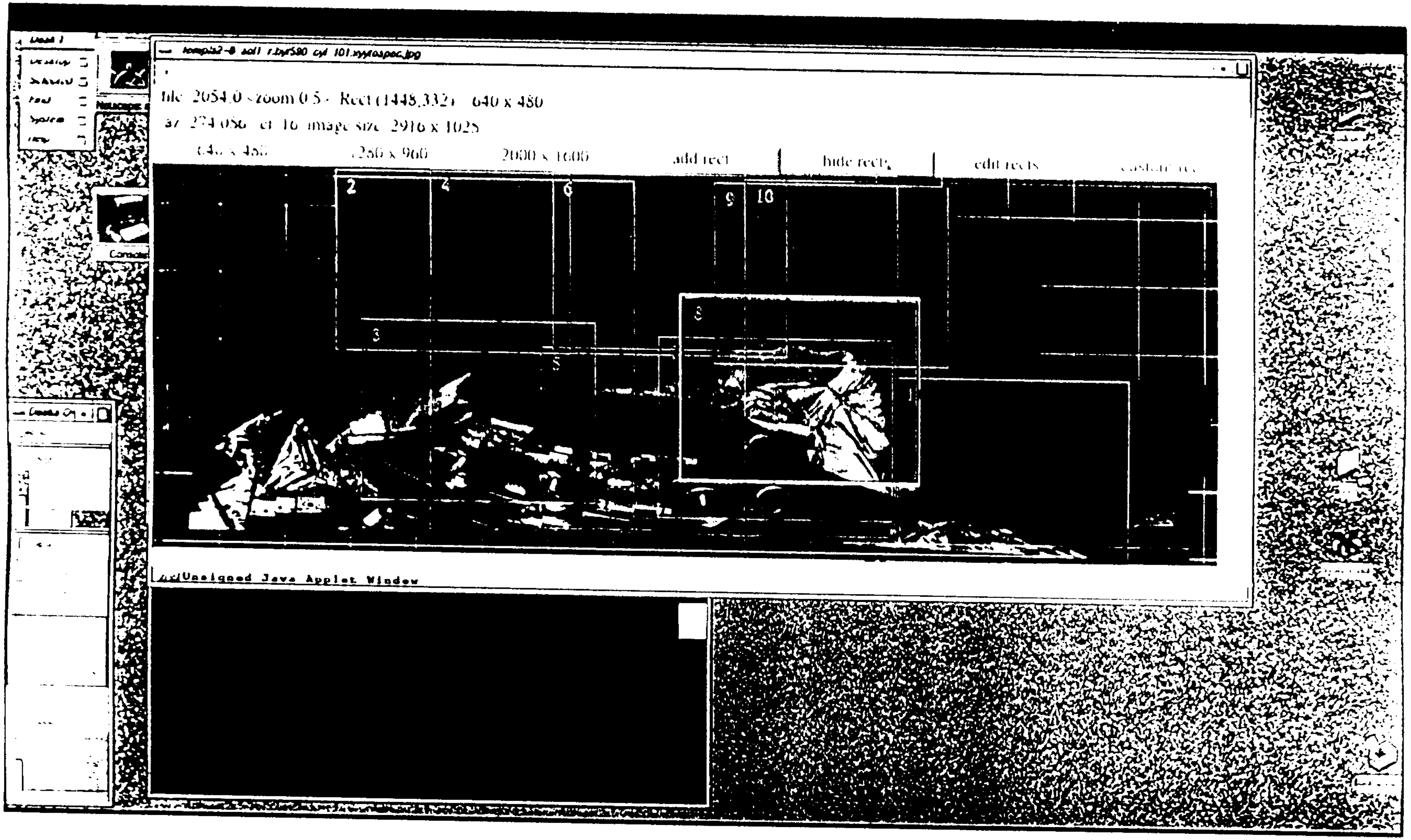


Figure 16

Figure 17

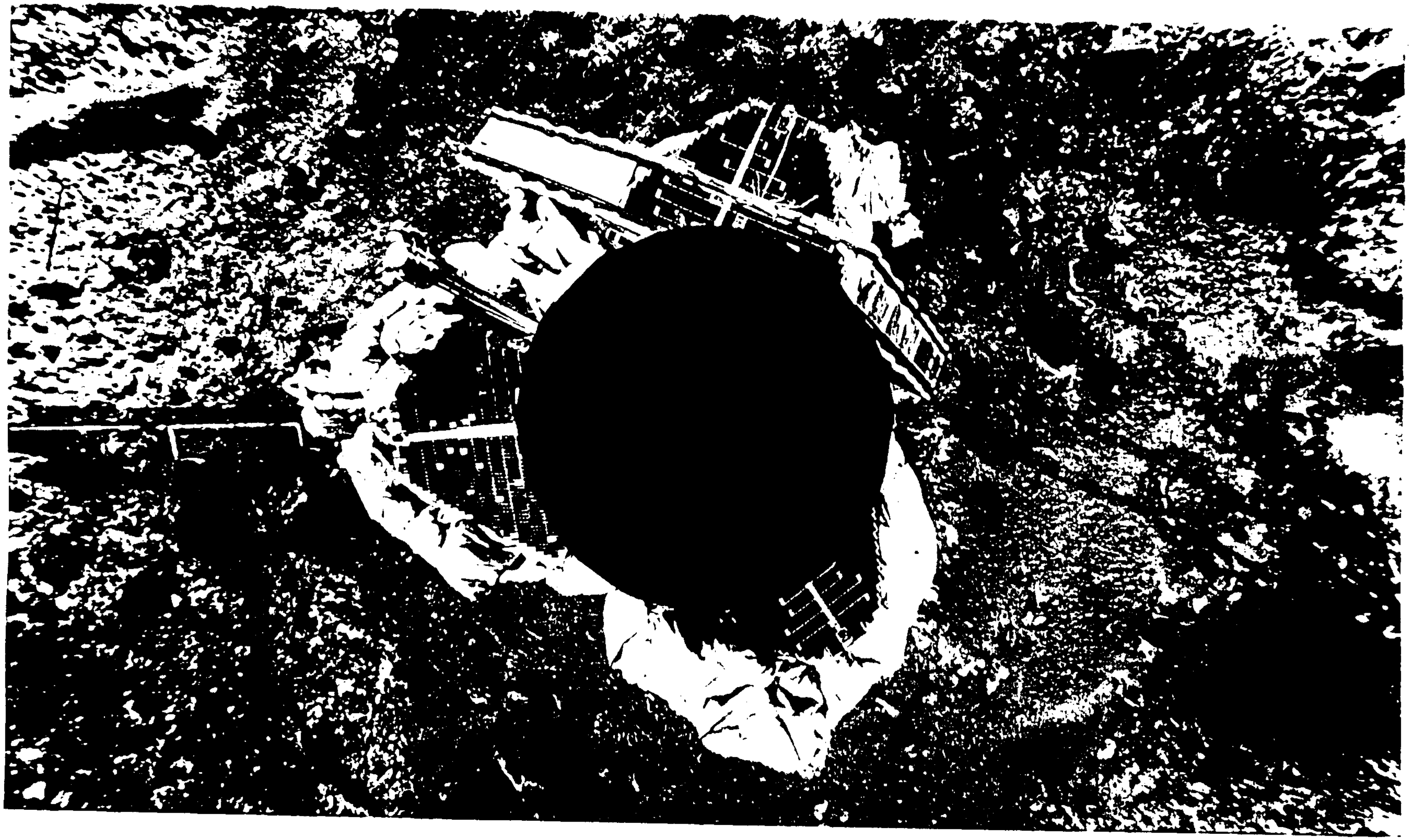


Figure 18