A PROLOG-BASED MARS INFORMATION SYSTEM

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ABSTRACT

An experimental Mars Information System (MIS) has been developed to select Viking Orbiter images of Mars suitable for photogrammetric analysis including automated stereo matching and automated mosaicing. The selection of images can be expressed in terms of a set of high level rules written in the logic programming language of Prolog. An interface to a set of low level functions is used to perform image geometry and other calculations, make searches for, and retrieve data from a spatial database of named cartographic features and raster map images. Examples will be shown of the use of the system for asking high level queries about spacecraft image coverage in relation to Mars geography and geology. MIS will be valuable in identifying images that are likely to carry important information about specific types of Martian surface processes.

Key words: Cartographic, GIS, Knowledge Base, Photogrammetry, Stereoscopic

1. INTRODUCTION

The Mars Information System (MIS) was originally developed to assist in the process of selecting Viking Orbiter images of Mars suitable for automated stereo matching work. This performs a vital role in the EXODUS (Extra-terrestrial Orbital DEMs for Understanding Surfaces) project (Muller et al, 1992) whose main aim is to produce a global Digital Elevation Model (DEM) map Mars, at $\frac{1}{128}^\circ$ per grid-point, using automated stereo matching and shape from shading techniques (Day et al, 1992). The resultant DEMs will then be combined with ortho images to produce oblique terrain views of regions of geological interest which are studied by a team of planetary geologists at the Department of Earth Sciences of the Open University (Thornhill et al, 1992).

The images used by the EXODUS project were originally taken by vidicon cameras on board two US spacecraft, Viking Orbiters 1 and 2, which were placed into orbit around Mars in 1976. Although the Viking Orbiter mission was not primarily a topographic mapping mission, of the approximately 52000 digital images returned (Snyder et al, 1981), a small selection were designed explicitly for stereo mapping and other combinations of pairs were stereo by chance. However because images were taken at a variety of different ranges, illumination and viewing angles, and through different filters, the task of finding chance stereo image pairs on which the stereo matcher would operate, could potentially be quite time consuming. A system known as the Image Retrieval and Processing System (IRPS) (Slavney & Guinness, 1989), which forms part of NASA's Planetary Data System (PDS) (Jansma, 1992), can be used to greatly speed up this process by listing images contained between latitude and longitude limits defining the region that we wish to stereo match. However, based upon information contained in Slavney & Guinness (1989), it appears that although IRPS can produce a list of candidate images, the onus is on the user to make use of associated tabulated camera position, orientations, and image corner latitudes and longitudes, for more complex queries such as trying to establish which image pairs overlap and have adequate base to height ratios. An alternative approach to finding stereo pairs was to use the Viking Orbiter stereo catalogue (Blasius et al, 1980), however the criteria used by this catalogue applied to manual stereo viewing and were not the same as those used by the automatic stereo matcher.

The EXODUS project has access to some 13472 Viking Orbiter images held at UCL. It became apparent whilst using IRPS in conjunction with the Viking Orbiter Stereo Imaging Catalog, that a faster and more flexible approach to search for candidate stereo pairs was needed. Based upon earlier experience gained in building a Prolog rule-based system for cartographic name placement, NAMEX (Cook & Jones, 1990), it had been found that Prolog provided both a means of programming a problem directly in terms of rules which govern the process, and as an experimental environment in which one could test out new data and algorithms. It was therefore decided to experiment with a Prolog-based system for selecting stereo image pairs. This became known as MIS (Mars Information System). Additional image selection roles are demonstrated here using MIS and these now include mosaicing, shape from shading, colour composites, temporal studies and finding examples of specific Martian processes.

2. MIS DESCRIPTION

MIS is similar to NAMEX in that it is a hybrid Prolog-based system where high level queries and problems can be expressed in a logic program of English-like Prolog predicates, facts, and primitives. This hybrid nature allows the benefits of Prolog's ability to manipulate high level symbolic data and its inference mechanism (backtracking) to be realised whilst utilising the data processing efficiencies and fast numerical analysis capabilities of low level procedural languages, for which Prolog has no particular current advantage. Low level functions are accessed via Prolog primitives calling low level procedural routines written in FORTRAN77 and Kernigham and Ritchie 'C'. Presently (May 1992) MIS consists of approximately 1000 lines of Prolog, 50 lines of C, and 1000 lines of FORTRAN code.

The low level routines which perform data processing and numerical analysis are largely implemented in FORTRAN. The C component of the low level procedures is used as a communication interface between the Prolog primitives and FORTRAN, and for specifically selected tasks involving the high speed processing of raster data. The kind of tasks performed by the low level routines include camera modelling; detection of control point containment within images; the computation of image centres and corners; a model of the spheroids of Mars (Wu, 1981) and Phobos (Duxbury, 1991); overlap detection between two or more images; and the scanning of specified regions in a raster based-map.

Most of the data utilised by MIS was obtained from NASA CD-ROMs (NASA, 1988, 1992A), and include a gazetteer, a $\frac{1}{4}°$ per pixel geological raster map of Mars, and Viking Orbiter camera event and geometry data. Additional data was supplied by the USGS Flagstaff in the form of a file containing 4505 USGS control point locations (Wu & Schafer, 1984); a set of improved camera event and geometry data (Wu et al, 1982) and a $\frac{1}{64}°$ per grid-point DEM for the whole of Mars (NASA, 1992C). Pre-processing of all of these data was necessary to convert them into a form suitable for MIS. The gazetteer contained feature names, locations and sizes – these were converted into Prolog facts. The DEM data had to be resampled to a standard $\frac{1}{4}°$ per pixel raster map format. A new Viking Orbiter image geometry and event file was also generated by combining the Viking Orbiter CD-ROM data with the smaller set of USGS improved data. The USGS records replaced corresponding CD-ROM records and were given a higher quality value.

2.1 Prolog Primitives

A Prolog primitive is a basic command which performs a single specific operation via low level procedural routines. Prolog primitives control these low level routines by passing command and control codes, and data, via a central *command* routine. The *command* routine then instructs the other routines to read or write data, or to perform data processing, or calculations. The outcome of a command is returned to a Prolog primitive either as a flag to indicate a successful completion or as data which will subsequently be used by Prolog. The use of Prolog primitives effectively shields the user from the complexities of the low level procedural routines.

An example of a Prolog primitive is: *limb(Image)*. This takes an image name, passes this to a low level routine which then identifies the appropriate image record and calculates the rays through each corner of the image. If any corner ray fails to intersect with the planet then the primitive succeeds and the limb of the planet is visible.

Another example is: *stereo_illumination(Image1, Image2, Value)*. This passes the names of two images, which overlap, to a low level routine which then computes the solar altitude and azimuth for each image. The altitude and azimuth information is then used to calculate the ends of shadow tips from a unit high object on the surface of Mars at the centre of each image. The value returned (x10), known as the "stereo illumination difference", is the unit difference between the tips of both shadows. This value was used as an approximation as to how suitable stereo image pairs are, illumination-wise. A large illumination difference value indicates that shadows present in both images will have changed significantly and as a result the stereo matcher will fail.

Most of the Prolog primitives which call low level routines are generally concerned with images and features. Some of these primitives make use of other Prolog statements to perform simple high to low level data translation tasks, and vice versa, during interaction with low level procedural routines. Appendix 1 lists a small selection of the Prolog primitives used by MIS.

2.2 Prolog facts

There are two classes of Prolog facts used in MIS, "comprehensive" and "example" facts. "Comprehensive" facts are where a complete set of facts are available such as all the named features on Mars. "Example" facts apply to cases where the information being presented is incomplete and the facts available are only representative. This latter type of Prolog fact is prefixed by the word "example". Approximately one thousand cartographic features are stored as Prolog facts and each contains a feature name, location, size, and feature class. Circular structures such as craters or volcanoes are represented by centre locations and a diameter (km). Linear and area features are currently represented by longitude and latitude limits of an enclosing bounding rectangle, and a length (km) e.g.

feature('Copernicus', 169.0, -50.0, 280, crater).

feature('Olympus Mons', 133.0, 18.0, 540, volcano).

feature('Ma'adim Vallis', 184.0,181.0,-28.0,-16.0, 955, sinuous valley).

It was decided to utilise the existing USGS map sheet and quadrant system notation (Greeley & Batson, 1991) to specify default regions in which stereo matching would take place. The fact *map_limits* contains the map sheet number, the quadrant, and the map's longitude and latitude limits. If required, a new user defined non-USGS map sheet area can be defined by asserting an additional *map_limits* fact e.g.

map_limits('Olympus Mons area', map,128,140,12,25).

The *geology_at_feature* Prolog primitive (Appendix 1) can access raster data which represents a geological map. The pixel values returned by this primitive correspond to different geological units. The *geological_unit* fact acts as a key linking this unit number with a high level description of the geology e.g.

geological_unit(11, 'permanent ice').

geological_unit(51, 'knobby hummocky terrain').

There are also some facts which are not directly usable by the predicates in MIS, but which have been included so that various constants and physical values for Mars can be looked up without consulting a textbook e.g.

atmosphere('carbon dioxide', 95.32, percent,carr).

When performing stereo matching using images selected by MIS, a record is kept of all the images which produced successful and unsuccessful stereo matches. This information is stored in *example_stereo_pair* facts so that future searches for stereo pairs could avoid unnecessary calculation e.g.

example_stereo_pair('635A83', '603A41', good).

example_stereo_pair('323S41', '639A92', bad).

It is often necessary to find images which illustrate a particular type of feature. Descriptions of all the Viking Orbiter images are not generally available in digital form, although catalogues of images containing clouds (Jansma, 1992) and image clarity (Bolef et al, 1982) do exist. To solve this problem, two sources of example descriptive information can be used and entered as lists in Prolog facts. The first source is from photographic illustrations and captions contained in geological books and papers about Mars. The second source is from visual interpretation of images which are recorded whenever members of the EXODUS project view an image in the course of their work. A reference key, indicating the source of the information is included with these facts. Some of the words used in the image descriptions may be unfamiliar to users, therefore "dictionary" facts are included where explanations are needed. A third potential source might be image understanding routines which scan images or DEMs for particular features.

example_image('041A11', [volcano, caldera, 'orographic clouds'],carr).

example_image('437S03',['boomerang shaped structures'] ,cook).

dictionary('orographic clouds', 'clouds formed during uplift of air over large scale features').

Books and scientific papers are also a useful source of facts about estimated crater retention age of features on Mars. In the example below, the typical, minimum, and maximum estimated ages (thousand million years) of Olympus Mons are given (Carr, 1981).

example_crater_age('Olympus Mons', 0.1, 0.1, 0.3, 'billion years', carr).

Finally, some of the Prolog predicates to be discussed

in section 3.1, on stereo image pair selection, rely upon constant values or limits. These can be expressed as "rule" facts. In the examples below, which refer to the selection of stereo image pairs, the first argument acts as a rule identifier. The second argument is acted upon by the predicate using this fact. The final argument is used either as a comment statement or as a unit specifier e.g.

rule('maximum stereo precision value', 1000, metres).
rule('maximum difference in solar altitude', 5, degrees).
rule('maximum difference in solar azimuth', 45, degrees).
rule('maximum stereo illumination difference', 10, 'x10').
rule('maximum stereo IFOV', 650, metres).
rule('minimum overlap proportion', 0.05, fraction).

These particular values were tightly chosen so as to improve the chances of the selected image pairs matching, and a height precision of better than 1km. Such tight criteria may result in a smaller number of stereo pairs being selected and consequently poor spatial coverage (See Figure 1). To improve spatial coverage, "rule" fact values can be relaxed, however this is usually at the expense of the proportion of the images which can be matched or with a lower height precision.

2.3 Prolog predicates

Prolog predicates are assertions of facts or rules, which may be expressed in terms of other predicates (Clocksin and Mellish, 1981). This is illustrated in the *moderate_size_feature* predicate described below:

moderate_size_feature(Name):–
    feature_size(Name,Size),
    between(10, Size, 50).

feature_size(Name,Size):–
    feature(Name,Lon,Lat,Size).

feature_size(Name,Size):–
    feature(Name,Lat1,Lat2,Lon1,Lon2,Size).

The purpose of this predicate is to determine whether a cartographic feature can be given an arbitrary class of "moderate_size". A feature is defined as "moderate" if it is between 10 and 50km in diameter or length. A second predicate, *feature_size* is used to return the size of a feature. This is necessary because there are two classes of feature, circular and areal/linear, and the latter has longitude and latitude ranges. A selection of some of the standard predicates used by MIS is given in Appendix 2.

3. APPLICATIONS

3.1 Selection of stereo pairs

Experiments undertaken during the EXODUS project have shown that the selection of candidate stereo image pairs, solely based upon image overlaps and having a sufficiently good base to height ratio, does not necessarily guarantee that they will successfully automatically stereo match. Early results suggested that even though the stereo matcher uses radiometric normalization, the BRDF of the surface changes the appearance of features dramatically (Muller et al, 1992). Other factors include

whether the images were taken through different filters, whether one or other of the images was too foreshortened, or whether the Sun's altitude was too low. The following predicate is used to list out candidate stereo pairs for a given map sheet:

```
list_map_stereo_pairs(Map,Quad):-
    build_image_list_for_a_map(Map,Quad,List),
    remove_images_from_list_if_poor_quality(List,List1),
    build_stereo_combination_list(List1,List2),
    select_stereo_pair(Image1,Image2,List2),
    suitable_stereo_pair(Map,Quad,Image1,Image2),
    output_stereo_pair_details(Map,Quad,Image1,Image2),
fail.
```

The method by which MIS selects stereo pairs was initially to build a list of all the images contained within a given map sheet. Some of the individual images in this list may have key characteristics which indicate that they are poor quality images for stereo matching. For instance it was found that images which were taken when the spacecraft was less than 20° above the horizon at the image centre, or which contained the limb of the planet, were unsuitable for stereo matching due to severe foreshortening. Images where the solar altitude was less than 5° above the horizon at an image centre, were also unsuitable for stereo matching due to the presence of shadow effects. It was also possible to eliminate images from the list if they had previously been shown to be generally unsuitable for stereo matching. This process of eliminating images of poor quality for stereo matching will typically reduce the list of images by half.

Next, an ordered list of all possible combinations of stereo images pairs is produced. This is achieved by passing the list of candidate image pairs via a Prolog primitive to a low level procedural routine that specialises in searching for image pairs which overlap, which were taken through the same filter, and which had IFOV resolution ratios not exceeding 2.5:1. The latter had been found to be an upper limit in experiments involving the stereo matching Viking Orbiter images (Day et al, 1992). Image pairs selected from this list are then examined one pair at a time to establish whether they satisfy suitable stereo criteria. If an image pair fails to satisfy the criteria, backtracking occurs and an alternative image pair is examined. If an image pair is proven to be suitable though, the images and other associated attributes are printed out (Appendix 2), then the predicate is forced to fail and backtracks to try the next stereo pair. The predicate that determines whether a stereo pair is suitable for stereo matching is given by:

```
suitable_stereo_pair(Map,Quad,Image1,Image2):-
    rule('maximum stereo precision value', V, metres),
    stereo_precision(Image1,Image2,Stereo_value),
    Stereo_value =< V,
    image_centre(Image1,Lat1,Lon1,Res1_m),
    image_centre(Image2,Lat2,Lon2,Res2_m),
    rule('maximum stereo IFOV',Ifov,metres),
    Res1_m =< Ifov, Res2_m =< Ifov,
    rule('maximum stereo illumination difference', I,'x10'),
    stereo_illumination(Image1,Image2,Diff),
    Diff =< I,
    rule('minimum overlap proportion', F, fraction),
    overlap(Map,Quad,Image1,Image2,Fraction),
```

```
    Fraction >= F,
    solar_altitude_difference_rule(Image1,Image2),
    solar_azimuth_difference_rule(Image1,Image2),
    not(example_stereo_pair(Image1,Image2,bad)).
```

The stereo image pair selection rules implemented here are as follows:

- Height precision (largest IFOV pixel resolution of the two images divided by the base to height ratio) must not exceed the value given by the rule fact e.g. 1000m.
- Neither IFOV pixel resolutions must exceed the value given by the rule fact e.g. 650m [*].
- The stereo illumination difference value should not exceed the amount specified by the rule fact e.g. 10.
- In the map region concerned, the proportion of image overlap to total image area must be greater than or equal to the ratio defined by the rule fact e.g. 0.05
- The solar altitude difference rule rejects all image pairs where the difference in solar altitude is greater by more than the amount specified in the rule fact e.g. 5°.
- The solar azimuth difference rule rejects all image pairs where the azimuth difference exceeds that defined by the rule fact e.g. 45° (Blasius et al, 1980).

An example run of this predicate is given below and lists out candidate stereo image pairs, fractional overlap, IFOV pixel resolutions (m) and estimated height precisions (m).

```
| ?- list_map_stereo_pairs(mc11,ne).

220S35 257S67 Ovlp.=0.22 Res: 722 618 Precision=910
342S06 620A74 Ovlp.=0.13 Res: 739 723 Precision=571
378S06 620A75 Ovlp.=0.11 Res: 809 725 Precision=653
378S06 620A76 Ovlp.=0.66 Res: 809 734 Precision=831
750A07 814A07 Ovlp.=0.18 Res: 619 833 Precision=902
750A07 859A07 Ovlp.=0.23 Res: 619 573 Precision=677
753A08 768A61 Ovlp.=0.37 Res: 577 648 Precision=438
```

To find out what control points are likely to be available in a given image, the following Prolog primitive can be used:

```
| ?- control_points_in_image('753A08',List).

List = [2324, 10410, 10411, 10417, 20496, 21264, 21269,
21270, 21277, 21278, 21279, 21280, 21282, 21290,
23246, 25736, 26796, 26798, 26832, 26833]
```

3.2 Selection of images for mosaicing

Although experiments in automated mosaicing have so far only involved a small number of images, MIS was of great assistance in testing out which combination of images would be suitable for forming a mosaic. The following rules were used:

- All images must have been taken with the same filter.
- Image overlap between individual image pairs, making up the mosaic, must be greater than 10% of the combined image pair area.

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[*] It has been found that it is sometimes acceptable for one IFOV to exceed 650m, but this rule has not been used in this particular example.

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- All the images must be taken under similar illumination conditions so as to avoid shadow differences appearing along mosaic seams. The stereo illumination difference measure should not exceed 10 units.

- If possible, select images taken from the same orbit or closely spaced in time so as to avoid localised atmospheric effects associated with dust or clouds.

- If possible, choose images that have already been radiometrically corrected.

- All images should have similar view angle conditions, preferably near nadir so as to avoid parallax effects showing up near seams.

- The ratio of largest and smallest IFOV resolutions of the images used must not differ by more than two.

- Select images which are not previously known to be of poor quality.

The selection criteria for images used for the production of colour composites are similar to those used in the mosaicing. One difference though is that we wish to find three images which overlap but which were taken through different filters. The majority of Viking Orbiter images acquired by the EXODUS project appear to have been taken in red and violet light, along with a smaller number of blue, minus blue and green filter images. As a result of this, any colour composite produced will almost certainly be a false colour where the blue colour contribution is represented by a violet image, the green colour contribution is represented by blue, minus blue or green, and the red colour contribution by itself. Another selection criterion was that all three images should overlap each other by at least 10% of the total image coverage area.

3.3 Selection of images for shape from shading

MIS has been used to select images for shape from shading work (Day et al, 1992). The requirements for selecting an image for this type of work are that their camera position and orientation should be accurately known, and the images must be radiometrically corrected. MIS has also been used to select a suitably close range image of Phobos on which shape from shading was successfully applied (Murray et al, 1992).

3.4 Selection of images for temporal studies

Most features on Mars were imaged by the Viking Orbiters from many different illumination angles. MIS can be used to produce a list of images of a given feature which is sorted by solar azimuth. Such sequences of images, if taken from near nadir positions can be used for BRDF studies (Muller et al, 1992) and also for estimating relative heights from shadow length measurements. Also, images taken under similar illumination conditions, but sorted by time can be used for studying changes in the polar caps and the development of dust storms.

3.5 Geographical query

The example below illustrates the use of Prolog primitives for asking the following geographical query: find "moderately sized" craters on Mars which lie in "knobby hummocky terrain", and which are below 1km in altitude. The

"fail" on the end of the query is used to force it to back track and write out alternative solutions. e.g.

```
| ?- crater(Name),
    moderate_size_feature(Name),
    geology_at_feature(Name,'knobby hummocky terrain'),
    height_at_feature(Name,Height), Height < -1.0,
    nl,write(Name),
    fail.
```

Kirsanov
Nutak
Zuni

If we now wished to see what images were available for the crater Kirsanov, these can be found as follows:

```
| ?- list_images_by_feature('Kirsanov').
```

Image: 227S33 Resolution: 312.6 m/pixel
Image: 239S54 Resolution: 356.8 m/pixel
Image: 247S32 Resolution: 364.7 m/pixel ... etc

4. CONCLUSION

The Mars Information System described in this paper has been successfully used during the EXODUS project to select images suitable for automated stereo matching. In addition, it has been demonstrated to be a very flexible system for investigating what image coverage of Mars is available at UCL for several other applications which include mosaicing, shape from shading, colour composites and examples of specific Martian processes. The high level nature of MIS has encouraged its use, and as a result new queries are frequently being put to it by the members of the EXODUS team.

It is planned that MIS will control an end to end system for DEM production from Viking Orbiter and Mars Observer images using stereo matching and shape from shading techniques (Muller et al, 1992). In particular it will coordinate the selection of images and control points used to form a photogrammetric block of a given region of Mars, and also to record the storage and processed state of image and DEM data.

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Appendix 1 - A selection of MIS Prolog primitives

- *base_to_height_ratio(Image_left,Image_right,Ratio).*
- *control_point(Serial_no,Lon,Lat,Height_km).*
- *control_points_in_image(Image,List_of_ctrl_points).*
- *filter(Image,Filter).*
- *geology_at_feature(Feature,Geological_unit).*
- *geology_at_image_center(Image,Geological_unit).*
- *height_at_image_centre(Image,Height_km).*
- *height_at_feature(Feature,Height_km).*
- *image_centre(Image,Longitude,Latitude,Resolution).*
- *image_containment(Image,Longitude,Latitude).*
- *image_corner_latitudes(Image,Latitude_list).*
- *image_corner_longitudes(Image,Longitude_list).*
- *number_of_images_in_database(No).*
- *overlap(Image1,Image2).*
- *planet(Image,Planetary_body).*
- *resolution_ratio(Image1,Image2,Ratio).*
- *solar_alt_az(Image,Altitude,Azimuth).*
- *spacecraft(Image,Orbiter).*
- *spacecraft_alt_az(Image,Altitude,Azimuth).*
- *stereo_precision(Image1,Image2,Precision_m).*
- *stereo_resolution_ratio(Image1,Image2,Ratio).*
- *sub_solar_lat_lon(Image,Latitude,Longitude).*
- *sub_spacecraft_lat_lon(Image,Latitude,Longitude).*

Appendix 2 - A selection of MIS Prolog predicates

- *between(A,Num,B).*
- *description_of_feature(Feature,Description).*
- *intersection_of(List1,List2,Intersection_list).*
- *largest_element(List,Maximum).*
- *list_image_storage_locations(List_of_images).*
- *list_images_containing_feature(Feature).*
- *list_images_containing_lat_lon(Lat,Lon).*
- *list_images_on_a_map(Map,Quad).*
- *member(Element,List).*
- *reverse(List,Reverse_list).*
- *smallest_element(List,Minimum).*
- *sort(List,Sorted_list).*
- *union_of(List1,List2,Union_list).*
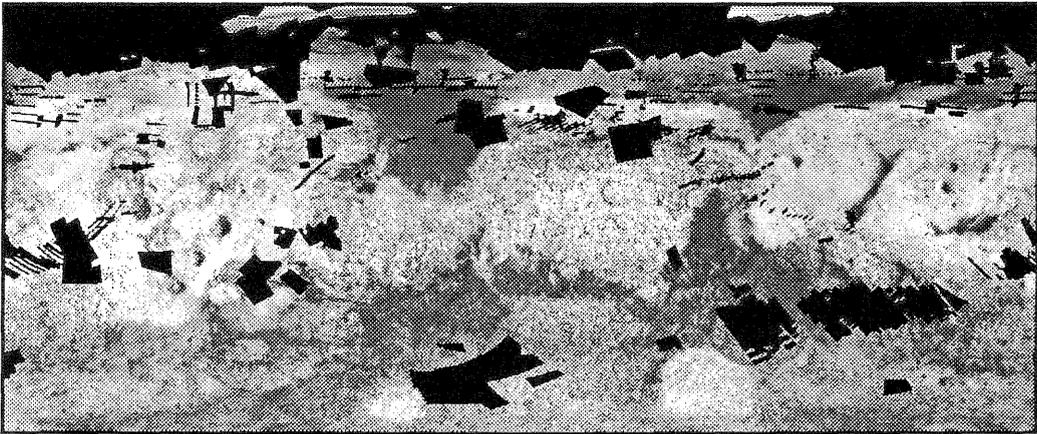
Figure 1 Cylindrical Equidistant projection of Mars (180°W to 180°E, 75°N to 75°S) showing stereo coverage (height precision better than 1km) as black shading - based upon the 13472 Viking Orbiter images records contained in MIS. The background map is the $\frac{1}{4}°$ per grid point USGS Flagstaff digitized airbrush map of Mars (NASA, 1992B). The image and stereo pair selection criteria are as specified in section 2.2 and section 3.1.