

COMBINING MARS DATA IN GRASS GIS FOR GEOLOGICAL MAPPING

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ABSTRACT:

Geo Information Systems (GIS) are standard tools in the Earth sciences whenever different geographic data sets must be combined. GIS became increasingly popular in the field of planetary research as well, due to the increasing amount of data from recent planetary missions, in particular to Mars. However, as the available GIS packages are designed for the standard terrestrial coordinate systems, several obstacles have to be overcome to implement a geodetic accurate and consistent database for other solar system bodies. In the past decade, parameters describing the rotation and shape of Mars have changed several times. Therefore, today, the digital data products available to the science community incorporate several different reference surfaces and map projections.

In this paper we describe the required steps to integrate Digital terrain Models (DTMs) and images of *Mars Global Surveyor*, *Viking* mosaics, and supplementary geologic information in a single database under the open source GIS GRASS (Geographic Resources Analysis Support System) environment. The different possible reference frames are discussed. The derived GIS database is currently being used to map the global distribution of tectonic faults on Mars. Finally, there are excellent prospects to use GRASS GIS for the analysis and geologic interpretation of image data from the High Resolution Stereo Camera aboard *Mars Express*. As the software and its source code are released under a free license, scientists may take the opportunity to gather work experience with a planetary GIS at no costs and with the opportunity to modify the software to their specific needs.

1. INTRODUCTION

The past decade has seen an increasing number of planetary space missions, returning large volumes and various types of scientific data. Therefore, GIS technology became increasingly popular in this field owing to its ability to create multilayered databases for comparison studies (e.g. [3]–[5]). Our goal was to create a global GIS database for planet Mars incorporating the various datasets available to date. The database relies on the GRASS software, which is available as open source from the internet [13].

2. CARTOGRAPHIC STANDARDS ON MARS

Beginning in 1976, the definitions of the body-fixed coordinate systems of all planets and satellites along with size and shape parameters for mapping are updated and published by the Working Group of Cartographic Constants and Rotational Elements of the Planets and Satellites of the International Astronomical Union (IAU) on a regular basis [8].

2.1 Coordinate systems

There are two coordinate systems approved and recommended by IAU for planetary mapping:

- “Planetocentric/east”: -90° to $+90^\circ$ north planetocentric latitude / 0° to 360° east longitude.
- “Planetographic/west”: -90° to $+90^\circ$ north planetographic latitude / 0° to 360° west longitude.

Earth, Moon and Sun do not match with this definition for traditional reasons [8]. For Mars cartography, the planetographic/west system was used until recently. There is a recommendation of the Mars Geodesy/Cartography Working Group (MGCWG) to only employ the planetocentric/east system in future products [2].

2.2 Horizontal Reference

The IAU reports also state the parameters necessary to define the geodetic base of the Mars GIS. In particular these are: the angle W_0 defining the prime meridian in respect to the inertial coordinate system (see [8]) and the radii of the biaxial ellipsoid. These values have been updated several times during the last decades (Table 1).

2.3 Vertical Reference

The MOLA team released a planetary radii model and a topographic elevation model (elevation above the areoid, i.e. the geoid for Mars) [10]. The two datasets have been approved by IAU to be the reference surface models for Mars [9].

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IAU definition	Equatorial radius [km]	Polar radius [km]	W_0 [°]	$W_0 - W_{0(IAU2000)}$ [°]
IAU1985	3393.40	3375.80	176.729	0.099
IAU1988/IAU1991	3397.00	3375.00	176.868	0.238
IAU1994	3397.00	3375.00	176.901	0.271
IAU2000/IAU2003	3396.19	3376.20	176.630	0

Table 1: Excerpt of IAU Reports. [8], [9]

3. CARTOGRAPHIC PRINCIPLES OF GRASS

To implement a geodetic accurate and consistent database, which is essential for comparative analyses, all datasets have to be transferred to the same geodetic reference frame (i.e. the same coordinate system/projection, W_0 and reference surface).

3.1 Coordinate Systems

GRASS supports a variety of different coordinate systems and projections. These can be divided in two groups:

3.1.1 Planar Coordinate System – Map Projection: GRASS supports a large number of conventional (GRASS term “other”) map projections (e.g. Transverse Mercator) using metre, yard, etc. as map units. Measurements of distances, areas or volumes are quantified in map units and are flawed by distortions of the map projection. Under consideration of the errors, these coordinate systems are suitable for investigations within local regions close to the centre of projection.

3.1.2 Ellipsoidal Coordinate System – Database Projection: On ellipsoidal and accordingly spherical bodies, angular units are being used to define a certain location at the planets surface (GRASS term: “lat/lon”). Raster data then fit to the simple cylindrical database projection (also known as geographic or “unprojected”), i.e. longitude and planetographic latitude are assigned to the GRASS internal planar x/y coordinate system ($x \sim$ longitude; $y \sim$ planetographic latitude). No map properties are preserved as with most conventional map projections. The simple cylindrical database projection is similar to the spherical form of the cylindrical equidistant map projection.

In contrast to measurements within a planar coordinate system, distances in the latitude/ longitude coordinate system are determined by true geodetic measurements and therefore no errors are imposed. For this reason, we opted to base our database on this coordinate system. Nonetheless, GRASS was developed for the terrestrial geographic coordinate system, which holds some differences over the IAU systems for Mars:

- Longitude ranges from -180° to $+180^\circ$ increasing east.
- Latitude is always assumed to be planetographic.

Changing definitions of the prime meridian (W_0) are not supported.

3.2 Horizontal Reference

GRASS supports any user-defined sphere or biaxial ellipsoid. The radii have to be enlisted in the file etc/ellipsoid.table (see Table 2).

3.2.1 Planetographic Latitude: As within GRASS all ellipsoidal latitudes are interpreted to be planetographic, datasets of this latitude definition could be used directly with the appropriate ellipsoid. However, recent datasets in the planetocentric/east coordinate system would have to be reprojected for this purpose. The required resampling process may reduce data quality. It should be mentioned that working with planetographic latitudes using a spherical reference surface instead the ellipsoidal one would cause a loss of accuracy similar as described in 3.2.3 and APPENDIX A.

3.2.2 Planetocentric Latitude: According to Duxbury et al. [2], all future Martian datasets are recommended to fit to the planetocentric/east coordinate system. However, GRASS assumes all latitudes to be planetographic. The only possibility to directly work with planetocentric datasets is to use a sphere as the reference body. In this case planetographic and planetocentric latitude coincide. To conform to future datasets, we chose this system/reference body for our GIS database. The drawbacks of this solution are the reduced accuracy of distance or area measurements due to the less accurate approximation of the planet by a sphere instead of a more precisely fitting biaxial ellipsoid (see 3.2.3) and the necessity to reproject older data from the ellipsoid to a sphere.

3.2.3 Estimation of Errors due to the Spherical Approximation: The simplification that is made by choosing a spherical GIS database for Mars (see chapter 3.2.1) would not influence point positions – the measurements of latitude and longitude itself – but distances and areas derived from these ellipsoidal parameters using spherical formulae.

While such errors at the equator are negligible – small deviations occur due to the slight difference between spherical radius and equatorial axis –, distances differ by 0.6 % at the poles. Areal errors are about twice as much and rise up to 1.2 %. If larger latitude ranges are surveyed, the particular errors are intermediate accordingly. In conclusion it should be pointed out, that the errors act systematically and measurements give almost too large results that increase with latitude. For a detailed investigation – including graphs of such errors versus latitude – see Appendix A.

3.3 Vertical Reference

As the GRASS database already is projected (i.e. two dimensional), no vertical reference is required in the first place, though topographic elevation may be implemented as attribute information. We incorporated the MOLA Mission Experiment Gridded Data Record (MEGDR) topography [11] dataset (see chapters 2.3 and 5).

4. IMPLEMENTATION

We implemented a number of global datasets for Mars, assortments of which are listed in Table 2 along with their cartographic parameters.

ID	Dataset	IAU Def.	Latitude	Equat. Radius [km]	Polar Radius [km]	W_0 [°]	Ref.
(1)	Geologic Map		graphic	3393.40	3375.73		[14]
(2)	MDIM [*] 1		graphic	3393.40	3375.73	176.646	[14]
(3)	MDIM 2.0		graphic	3396.00	3376.80	176.725	[6]
(4)	MSSS ^{**} Atlas		graphic	3396.00	3376.80	176.725	[15]
(5)	MOLA MEGDR	IAU 2000	centric	3396.00	3396.00	176.63	[11]
(6)	TES ^{***}	IAU 2000	centric	3396.00	3396.00	176.63	[16]
(7)	MDIM 2.1 (except the poles)	IAU 2000	centric	3396.19	3396.19	176.63	[1]
(8)	MDIM 2.1 (poles)	IAU 2000	centric	3376.20	3376.20	176.63	[1]

Table 2: Geodetic properties of raster datasets (mosaics, geology, heights) implemented in DLR GRASS GIS.

As a consequence of the slightly different coordinate system definitions stated in chapter 3.1.2, we chose to utilize a spherical coordinate system on a sphere of $r=3396$ km to conform with the MGCWG recommendation (see chapter 2.1). A unique W_0 of 176.630° , according to IAU2000, was selected.

GRASS provides a module to directly import raster data in raw format. Registration information are latitude and longitude of the four edges of the file. 16 MOLA MEGDR (5, see Table2) topography tiles were imported in raw format using the (converted) registration information from the accompanying Planetary Data System (PDS) labels. TES (6, see Table2) multi-band mineral data in raw format were divided into single band files prior to import. As we used a sphere as the reference body, no resampling of the planetocentric MOLA and TES data was necessary. MDIM2.1 (7 and 8, see Table2) compiled with latitude definition as well, so the import of this dataset was also straightforward.

Datasets with a different definition of the prime meridian were corrected by shifting the longitudes prior to import into GRASS. In the same step, all registration information was converted to the GRASS longitude range (see chapter 3.1.2).

Subsequent to W_0 correction and removal of the attached PDS header, all 28 tiles of the MSSS atlas were read as raw data. GRASS' ability to reproject data from the ellipsoid (4, see Table 2) to the sphere was used to transfer the tiles to the planetocentric reference frame of the database. The reprojection from ellipsoid to sphere was also necessary for the geologic map (1, see Table 2) after W_0 correction and import. Nevertheless, as it was compiled on a much older base, this

* Mars Digital Image Mosaic
** Malin Space Science Systems
*** Thermal Emission Spectrometer:
Various Minerals, Surface Emissivity, Albedo

dataset does not register very well to recent data. Still it is the only global geologic data available.

Point data (e.g. MOLA) were read from standard ASCII tables along with associated attribute information.

5. APPLICATION

Once the database was created as a foundation, this data base found a wide variety of applications. To name one example, we used GRASS to compile a dataset of tectonic surface faults. MOLA maps artificially lit from varying azimuth angles were used as a basis for the mapping. Hence, contrary to mapping from an image base, where the light conditions have to be taken as is, we were able to avoid any sampling bias due to illumination geometry.

On the MOLA base map, the surface faults data were conveniently extracted by visual interpretation, stored, and analyzed. Each surface fault was stored in a number of equally-spaced (250m) points. Thus, we collected a total set of 3642 thrust faults and 3746 normal faults, ranging from lengths between 8 and 1445 km. The total length of all faults was approx. 600,000 km. Using the geologic map, each fault was then assigned to a geologic region and a specific surface age (see Figure 1).

We expect that our data set, globally more homogeneous than that of previous studies, which can now be examined under a variety of aspects: spatial variations of fault patterns, length statistics, correlations of surface faults with age, or sequence of formation. Specifically, we intend to use this digital data base to generate synthetic sets of Mars quake catalogs for simulations of the performances of future seismometer network on Mars.

In addition to the already mentioned import, projection and vector editing tools, GRASS provides a vast amount of other data im-/export, processing, analysis and visualization routines. The reader is referred to [7] and [13] for more information.

6. CONCLUSIONS

The number and diversity of available datasets render GIS technology an especially suitable tool for scientific studies on Mars. Keeping the geodetic properties of the individual Mars datasets and GRASS' coordinate system definitions in mind, the application of GRASS in planetary research turns out to be straightforward.

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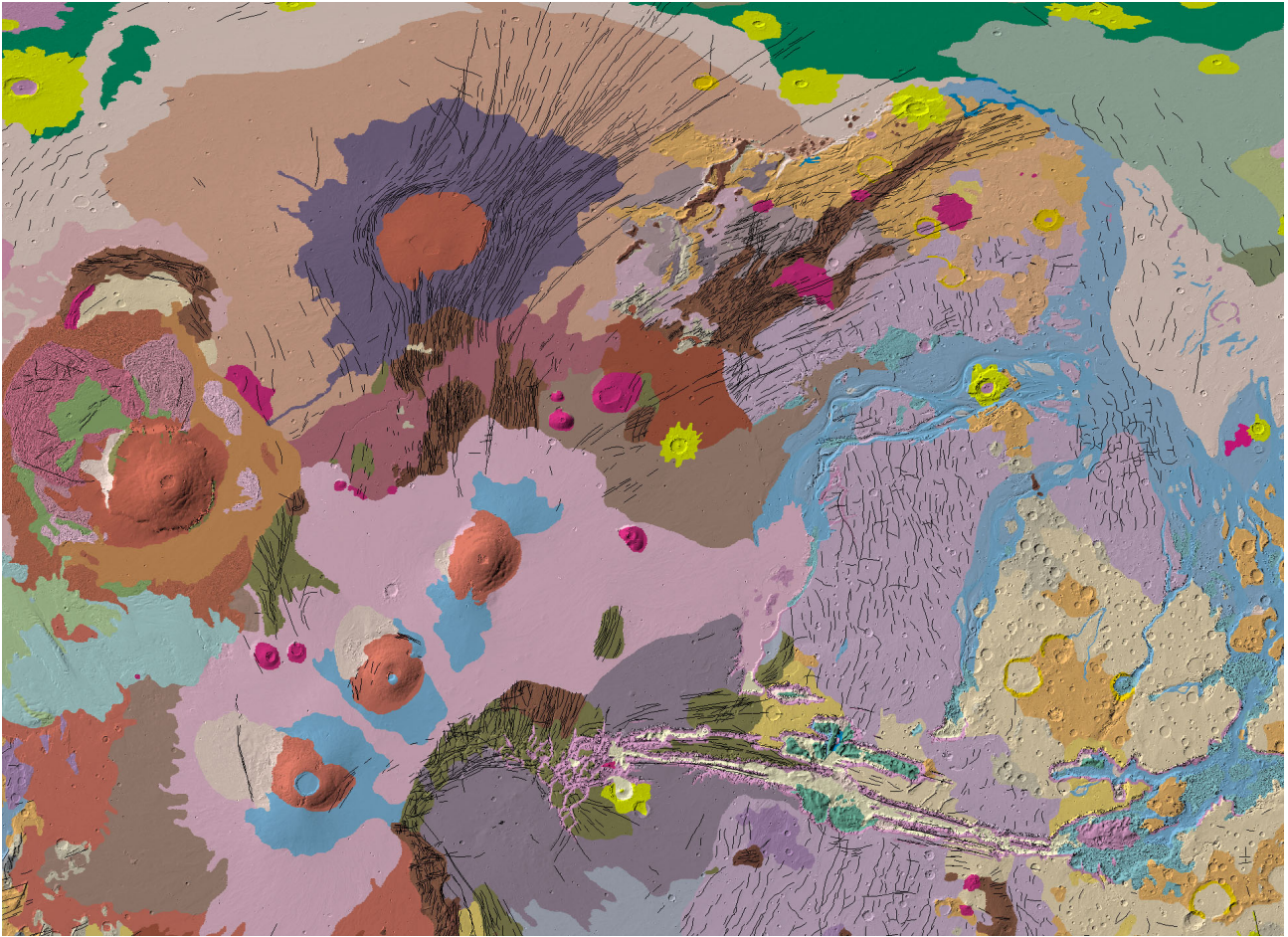


Figure 1: Geologic map of Mars and the mapped faults (shown in black) .

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APPENDIX A / ERROR ESTIMATION

Basically, a quantification of distortions that occur to a map projection is given through Tissot's indicatrix. The semi-major axes h and k of this infinite ellipse give the scales along projected meridians and parallels and the areal scale accordingly. GRASS considers these distortion scales for the simple cylindrical database projection, which is a representation of the spherical coordinate system. Therefore, it provides error-free distance and area measurements. Taking a sphere, such scales of a cylindrical projection are [12, formulae (4-2), (4-3)]:

$$h_s = \frac{1}{r} \frac{dy}{d\varphi} \quad (1)$$

$$k_s = \frac{1}{r \cos \varphi} \frac{dx}{d\lambda} \quad (2)$$

where h_s, k_s = spherical distortion scales
 r = spherical radius
 φ = latitude
 λ = longitude
 x, y = map projection coordinates

Since we use planetocentric latitudes that parameterize an ellipsoidal surface, the effective scales of such a projection have to be given for a biaxial ellipsoid. These scales read [12, formulae (4-22), (4-23)]:

$$h_e = \frac{(1-e^2 \sin^2 \varphi_g)^{3/2}}{a(1-e^2)} \frac{dy}{d\varphi_g} = \frac{(1-e^2 \sin^2 \varphi_g)^{3/2}}{a(1-e^2)} \frac{dy}{d\varphi} \frac{d\varphi}{d\varphi_g} \quad (3)$$

$$k_e = \frac{(1-e^2 \sin^2 \varphi_g)^{1/2}}{a \cos \varphi_g} \frac{dx}{d\lambda} \quad (4)$$

where h_e, k_e = ellipsoidal distortion scales
 a = equatorial axis of the ellipsoid
 e = eccentricity of the ellipsoid

φ = latitude (any type)
 φ_g = planetographic latitude
 λ = longitude

Following that, a quantification of errors within GRASS measurements can be given by the relation of the ellipsoidal scales and the corresponding spherical ones that are considered anyway. With the derivation of planetocentric with respect to planetographic latitude [12, formula (3-28)]:

$$\frac{d\varphi_c}{d\varphi_g} = (1-e^2) \frac{\cos^2 \varphi_c}{\cos^2 \varphi_g} \quad (5)$$

where φ_c = planetocentric latitude

these relative scales become:

$$h' = \frac{h_e}{h_s} = \frac{r}{a} (1-e^2 \sin^2 \varphi_g)^{3/2} \frac{\cos^2 \varphi_c}{\cos^2 \varphi_g} \quad (6)$$

$$k' = \frac{k_e}{k_s} = \frac{r}{a} (1-e^2 \sin^2 \varphi_g)^{1/2} \frac{\cos \varphi_c}{\cos \varphi_g} \quad (7)$$

$$s' = h'k' = \frac{r^2}{a^2} (1-e^2 \sin^2 \varphi_g)^2 \frac{\cos^3 \varphi_c}{\cos^3 \varphi_g} \quad (8)$$

While h' and k' give the extreme values of distance measurement errors in meridian or parallel direction, s' is the deviation of areas (Fig. 2). These parameters – even that in parallel direction – solely depend on latitudes and not on longitudes.

For Mars, the scales h' and k' are almost equal (but not identical – the difference would scale up with larger eccentricity). Therefore, distance measurement errors within GRASS do not depend on azimuth in this case.

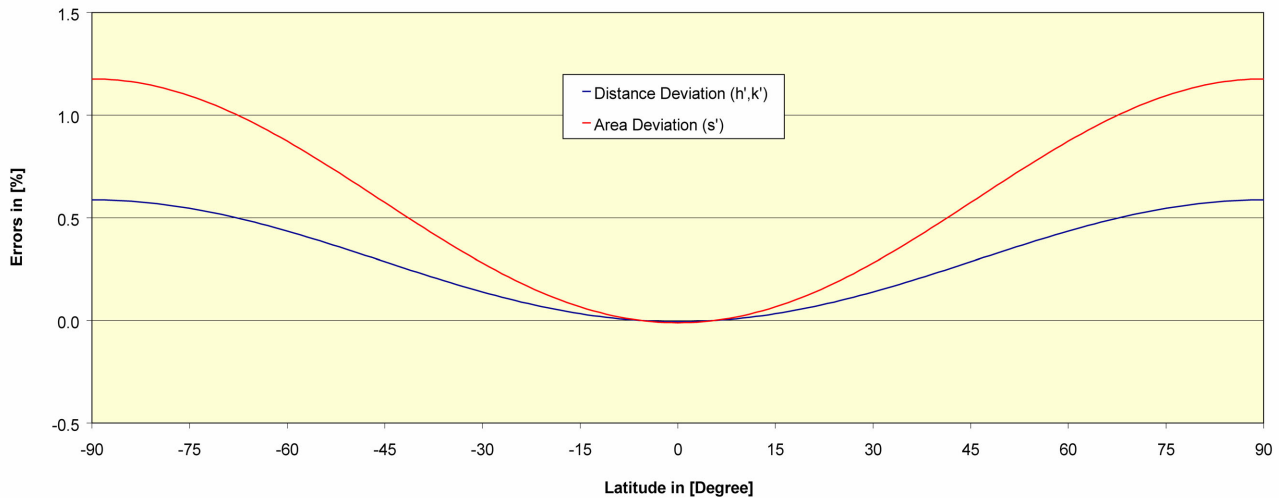


Figure 2. Overview of the error values for Mars, if ellipsoidal planetocentric latitudes are assumed to be spherical. Body definitions follow the IAU 2000 conventions as given by table 2.