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Executive Summary / Abstract:

This document introduces the acquisition, processing, and exploitation of three-dimensional data for planetary-science applications, with particular attention to geological modeling. It also provides a list of open source technologies and software that can be freely explored, which can provide additional value to the scientific workflow. Proprietary software if available with academic licenses are also mentioned.

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Introduction to D data

The use of three-dimensional data to represent and approximate reality has been a primary goal for many physical sciences since the introduction of the first computers and software capable of processing and visualisation. It goes without saying that the ability to capture 3D data and computational power needed to process them has been growing together with the data quality and resolution in the last decades. with the actual performance of present-day computers such types of analytic techniques are now easily accessible also for a wider use.

Any science that deals with the geometric arrangement and the distribution of observations in space might benefit from building three-dimensional representations of the studied objects or representation of computation and/or experimental outputs, which can serve several purposes:

The first one is of course visualisation: the human brain is tuned to process depth information in order to build a satisfactory conceptual model of reality. This observation explains the great interest in the various technologies for computer graphics, Virtual Reality and immersive visualisation, which can provide enhanced exploratory experiences for the analysis of scientific data (Le Mouélic et al., 2020).
A second goal of 3D data exploitation is consistency. By creating a "virtual" representation of the phenomena under investigation the scientist is challenged to produce a representation that must be as geometrically consistent in space as possible. Two-dimensional

representations are simpler to produce but their adherence to reality might not be easily assessed. Most of this bias can be solved passing to the third dimension
Three dimensional models are also used to perform predictions. This is probably the most important aspect: the ability of predicting and possibly testing a conceptual model plays a fundamental role in scientific investigation.

The acquisition, processing and visualisation of three-dimensional data received great attention also in the field of geological sciences. The interpretation of geological units and their geometrical relationship which has been historically represented in two dimensional maps finds its most advanced expression in the construction of fully three-dimensional geological models, which are used to represents a variety of features of interest (faults and folds, geologic contacts, compositions, ore grades etc.). Thanks to advanced geostatistical methods and conceptual models of the geological behaviour of processes and materials they can even provide probabilistic prediction of the property of the investigated geological system.

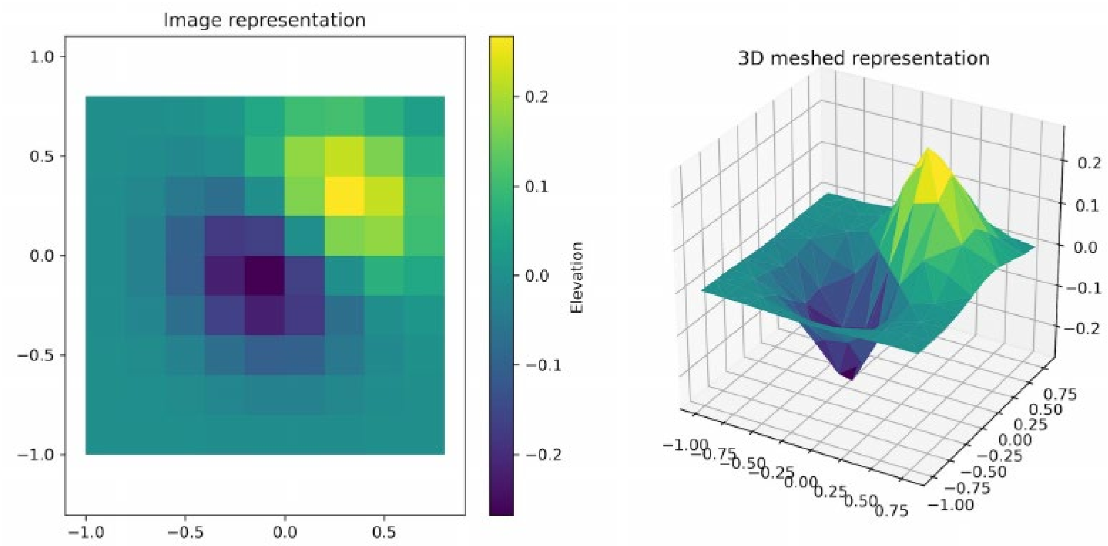
In this document we will provide insights on the basics of three-dimensional data and their representation in computers, which are fundamental to understanding how dedicated software can create and process this kind of data. We will then provide an overview of 3D modelling technologies applied to the geological domain also relevant for planetary science.

2D and 3D data types

The most common and well-known data types used in planetary sciences are probably images: these can be used to represent optical information, multiband spectral observations, and in general any scalar information that can be discretized in the form of a matrix of "pixels" whose value contain various types of information.

This same model has been historically employed also to represent elevation data in the context of geographical information systems, to produce digital terrain (or elevation) models (DTM or DEM). Such data models are often referred to as 2.5D, being half-way between a truly three-dimensional dataset (usually a raster) and a flat 2D image.

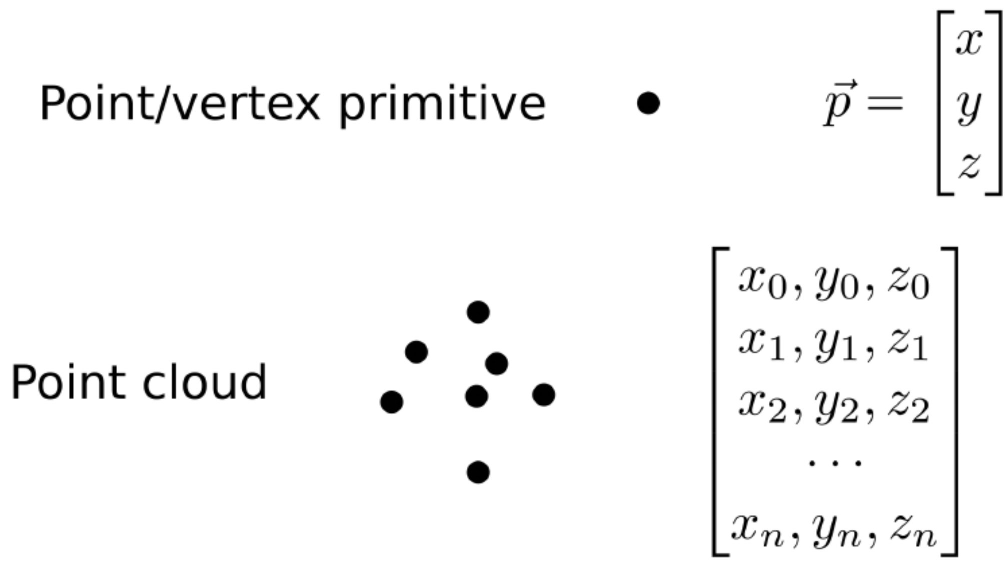
Figure 1: image representation as a matrix of pixels containing specific values. In the left case a 2d image with pixels containing a height value represents an elevation model (either DEM or DTM). On the right panel the 3D representation using the third dimension contained in the pixel values (i.e. the z value, or the height)



This kind of data products are quite common both for Earth observation and planetary missions, but they do have several limitations. Specifically, they can only represent one single elevation value for each pixel: meaning only one smooth surface (e.g. the topographic surface), without overhangs can be represented. Neither volumes nor closed bodies can be represented with such type of data. Additionally these representations are tied to specific map-projections (a 3D object is still represented as a flat image) and the elevation value itself is dependent on some kind of reference elevation standard (e.g. mean sea level, or the planetary spheroid/shape model). These limitations, which might work well for satellite observations on Earth might not be as well suited for planetary datasets, especially on small bodies, like asteroids or comets, where the body geometry might differ substantially from a spherical or ellipsoidal object for which map projections were developed. To overcome these limitations other data-formats can be employed. Here we will just draw the basics of three-dimensional data representations, but more details can be found also in GMAP Deliverable D9.4 (Stereo-DTM and Digital Outcrop Model pipelines/guideline).

The primitive of any three-dimensional representation is a point in space, whose position is characterized by a triplet of coordinates x,y, and z. An unordered set of points is known as a point-cloud.

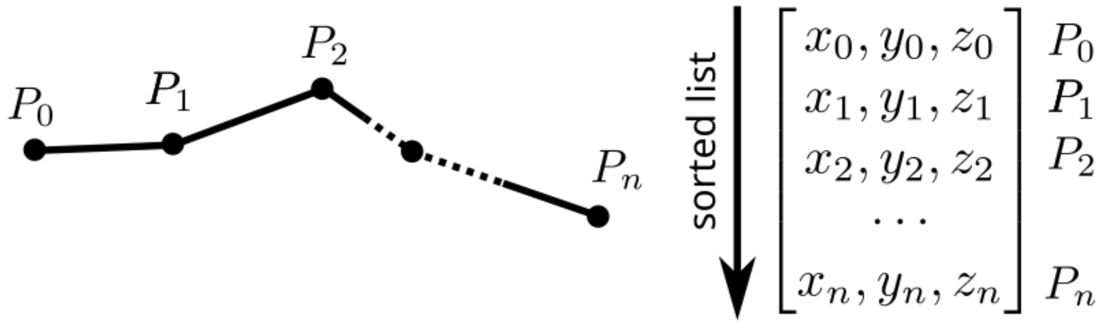
Figure 2: representation of a single point in 3D space with its x, y, z coordinates and a point cloud as a random set of points with x, y, z coordinates in the same 3D space.



Point clouds are possibly the simpler kind of 3D dataset that can be encountered. However, they have the disadvantage of being "unstructured", meaning there is no general ordering and relationships between the points. This means, for example, that even the simpler operation of finding the neighbours of a given point becomes computationally demanding on large point-clouds and requires specialized algorithms, making this format an inconvenient option for complex types of operations. Point clouds can naturally result from a variety of acquisition processes, for example laser-based scanning devices (i.e. Light Detection And Ranging - LIDARs) produces most of the times large sets of single observations, that are often represented as point-clouds. Photogrammetry and structure-from-motion algorithms as well produces point clouds made up of homologous points among the set of photographs used for reconstruction (for more details see Caravaca et al., 2020).

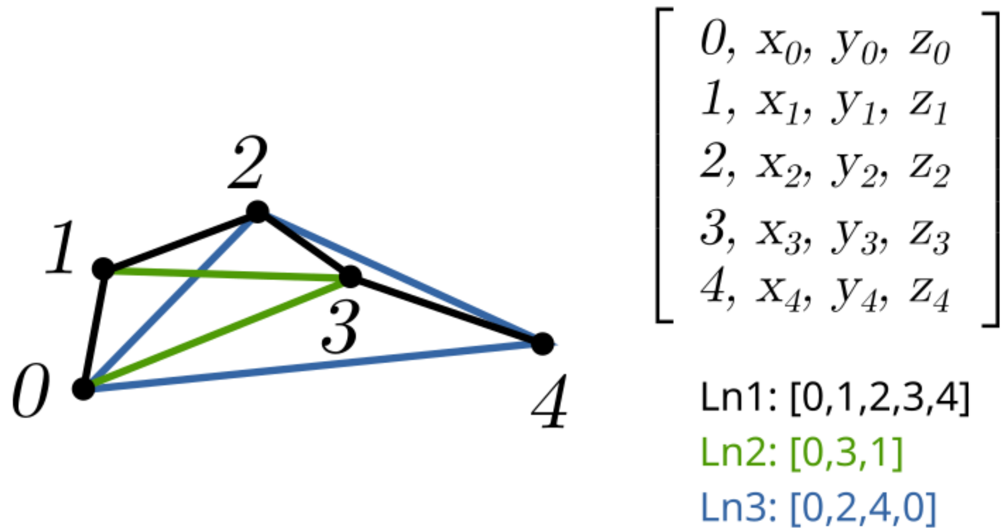
More interestingly, 3D data representations can be instead obtained whenever additional topological information is provided as a complement to the set of points. For example, a simple way to represent a line in space is to provide both a list of points and some additional information, which tells how points should be ordered and connected to form a continuous line. This could be done by providing the list of points already correctly sorted, and as additional information, that the list represents each subsequent point to be connected in a line (see Figure 3).

Figure 3: sorted list of points that can be used to represent a polyline in 3D space. The points represent connected nodes of the line



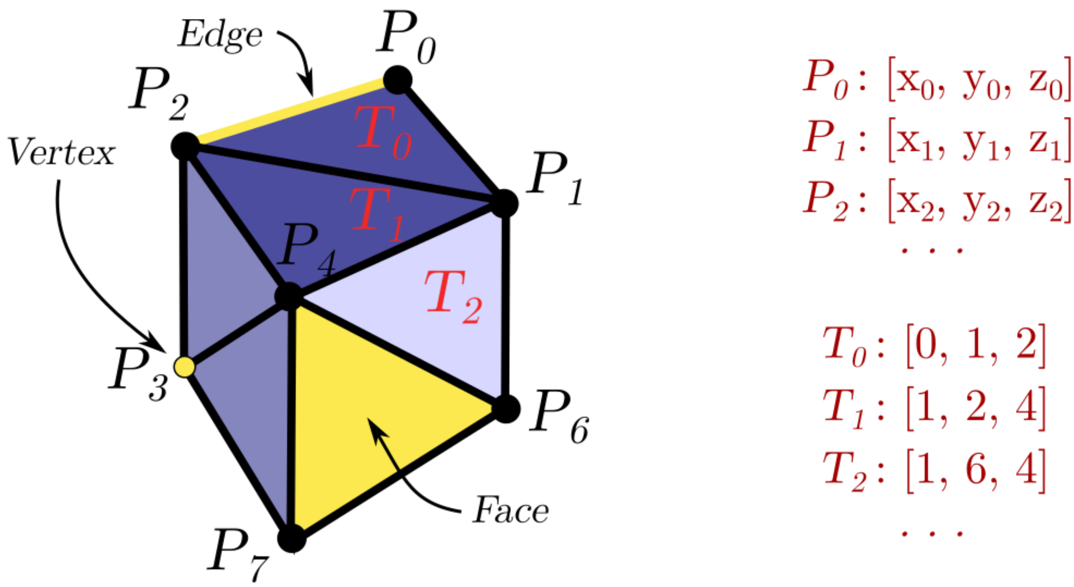
A better approach is represented by providing the list of points in any random order and then explicating that the points composing a specific line are referred to their indexed position in the list (see Figure 4). In this way we can represent any number of lines with just one set of points, and points can be even reused in different lines.

Figure 4: representation of a set of lines by the same point dataset by using indexed positions on the points list.



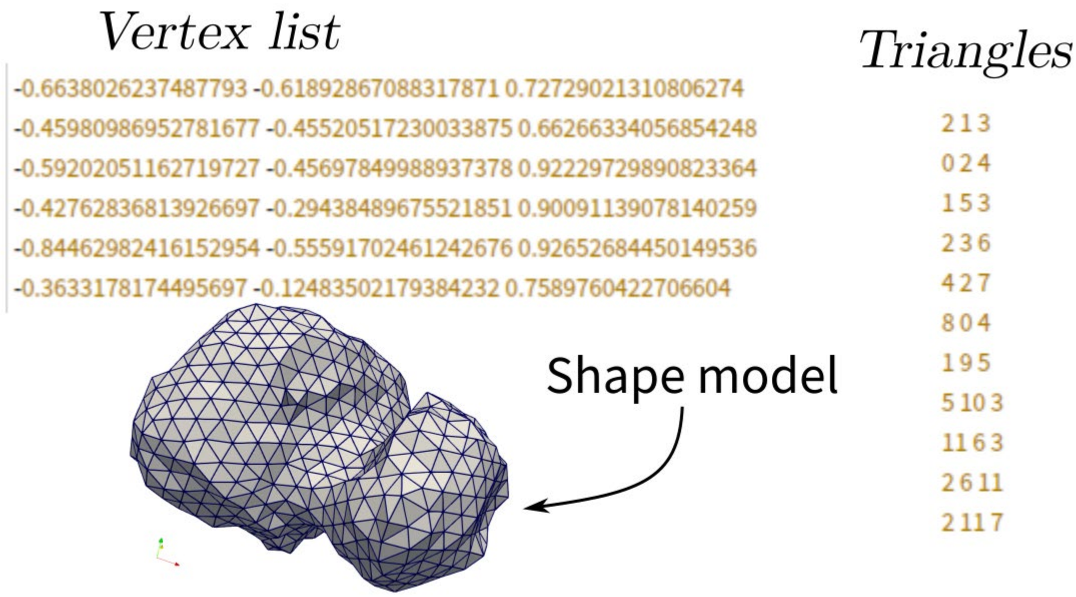
This type of data representation is more flexible and gives a rough idea of how many of these are actually achieved in three-dimensions with the same set of information (i.e. an indexed list of points). Indeed, depending on the context similar approaches can be also used to represent complex datasets. Take for example the commonly used triangulated surfaces that are more and more often used to represent 3D objects: in this case a set of triangles can be created by providing triplets of indices, saying which points should be connected together to form a single triangle (Figure 5).

Figure 5: a three-dimensional mesh is stored as a list of vertices and a list of triplets representing each triangle that compose the mesh. The integer numbers represent the corresponding vertices that should be connected together for generating the triangle.



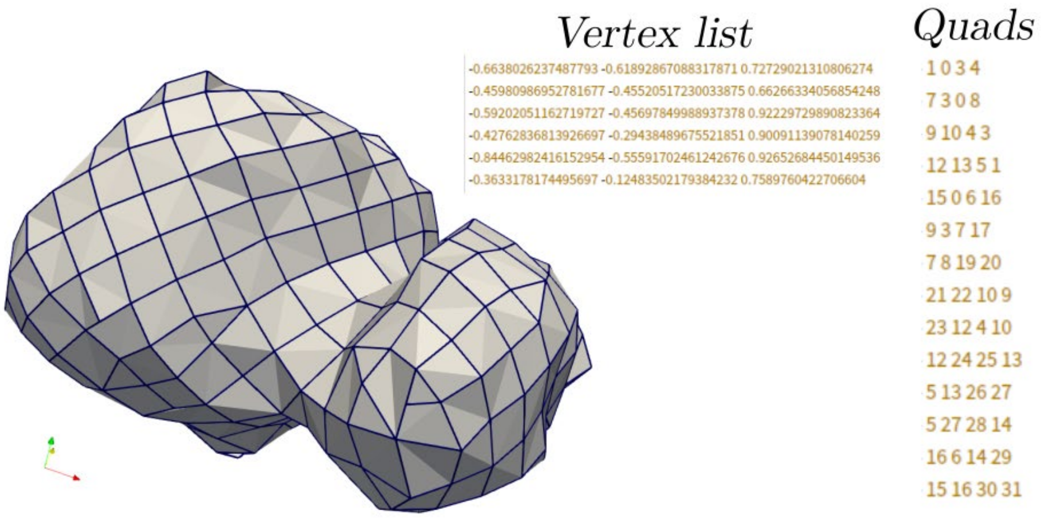
In practice, having a good understanding of these aspects is fundamental to grasp how the data is internally managed by computers and how file-formats are designed. Consider as an example the simplified model of the surface of comet 67P shown in Figure 6. The complete 3D model is entirely specified by two numerical arrays, the first one containing the list of the vertices and a second one (of integers) with the definitions of each triangle. Graphic cards and computer programs are then optimized to handle and display this kind of information in 3D.

Figure 6: real example of the dataset defining a low-resolution shape model of comet 67P. The vertex list represents the coordinates of each vertex in km and the triangles are defined by subsequent triplets of integer indices.



It must be also noted that there is no limit in the kind of base elements (or cells) that can be used to build a model, and that are not restricted to triangles. For example "quads" can also be used, as shown in Figure 7. However, the most common representations are normally triangle-based as not all the software can easily handle other types of cells such as quads.

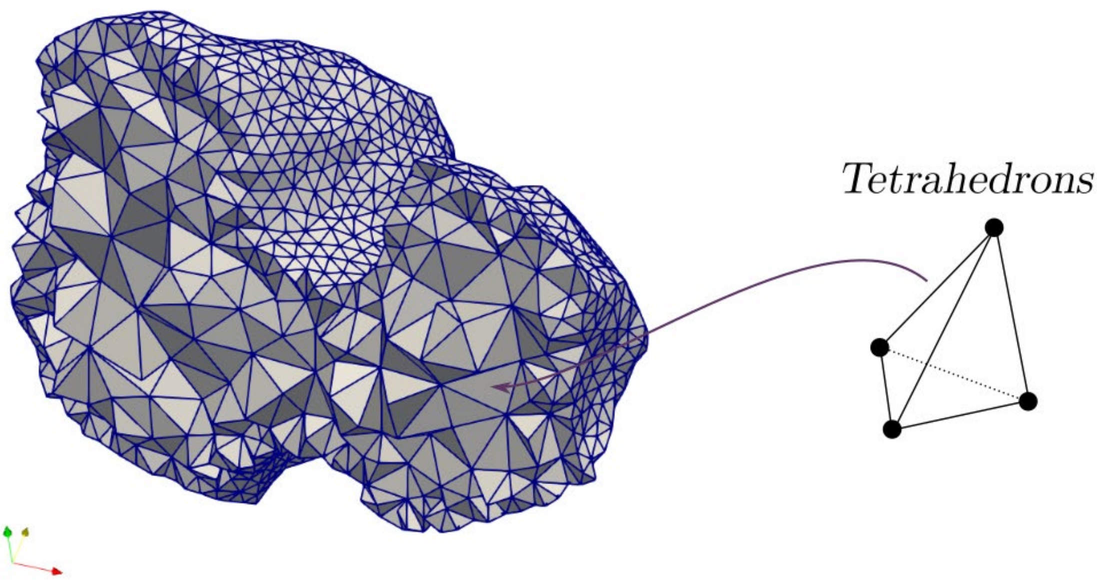
Figure 7: quads can be used instead of triangles. Not all software can correctly handle this kind of mesh.



Volumetric meshes

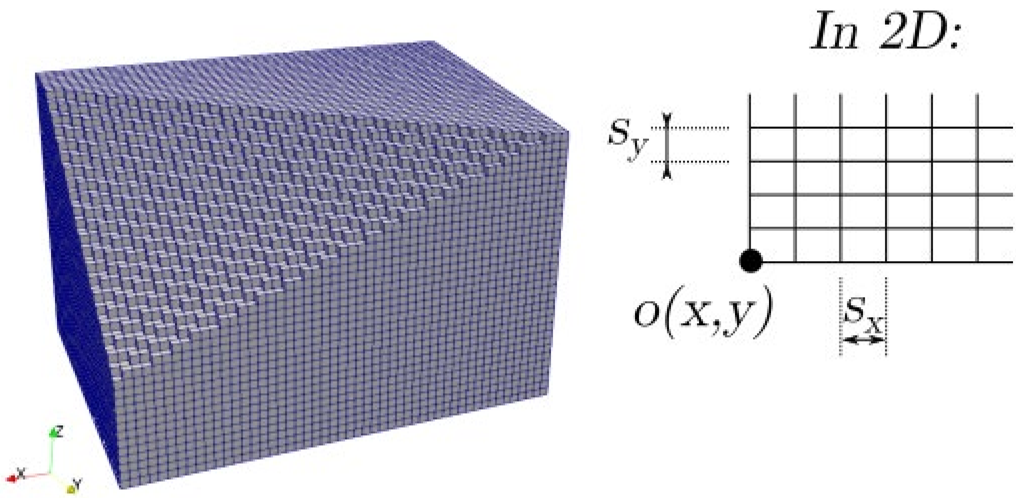
The same approach described in the previous section can be used to represent volumes. In such a case an exterior surface is filled by a series of small tetrahedrons, each representing a portion of the volume (also called tetra-volume in some geological modelling software). Also in this case the data is fully defined by the set of points and a list of the vertex-indices composing each tetrahedron (and possibly some additional rules on how the tetrahedrons should be assembled).

Figure 8: Example of volumetric mesh composed by tetrahedrons as base elements.



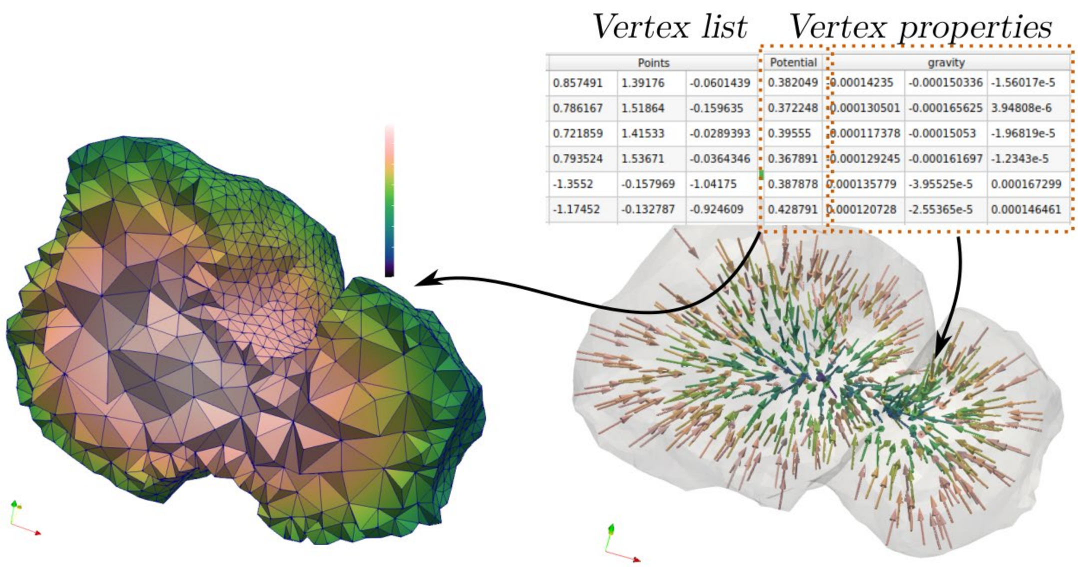
In some cases it is preferable to have a more regular base element (e.g. a cube), to apply some numerical methods (e.g. finite differences). In such a cases we do not even need to explicitly provide the list of vertices, but some basic information on the extension and the size of the base element is enough (see Figure 9) to fully represent such a dataset. Also notice that this case, when considered in two dimensions, fully corresponds to the case of images (raster data), with the only difference that some value is associated to each pixel.

Figure 9: implicitly-defined square voxels are especially suited for representing regularly sampled volumes. The two-dimensional equivalent is an image composed of pixels.



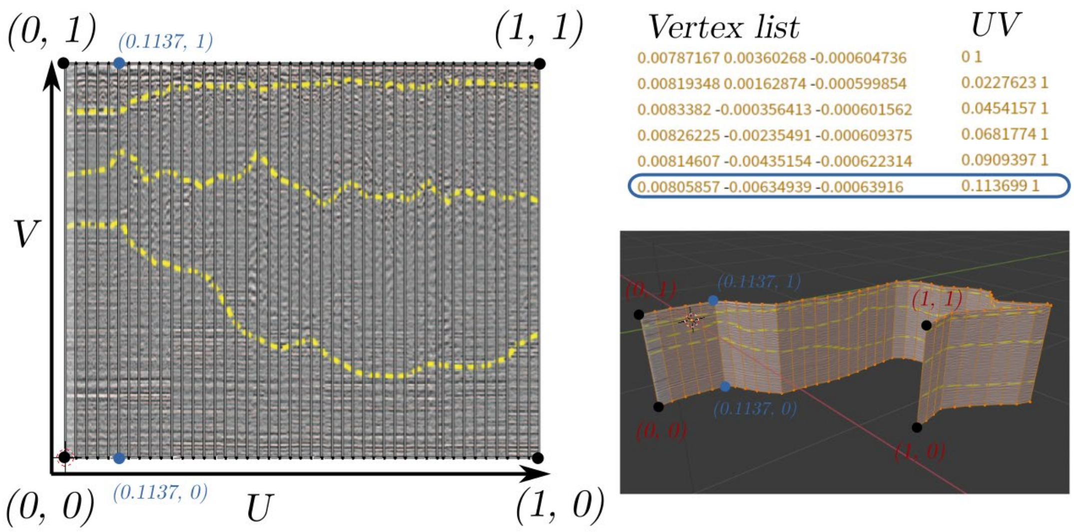
To associate scalar values (e.g. RGB colours, elevations, or any other measurable property) to this kind of 3D objects there are indeed two possibilities: the data can be attached to each vertex composing the object or to each base element (e.g. the triangle or the tetrahedron). The data that can be associated is not necessarily of scalar type, but depending on the software implementation, also vectors or tensors could be associated. The next figure shows an example.

Figure 10: a volumetric mesh composed of tetrahedra. for each vertex a value of gravitation potential and the gravity vector is also present making it possible to generate color-coded visualizations.



Although this approach also allows adding colours to triangular meshes (e.g. by rgb values attached to the points), a better more efficient approach was developed, and it is now a standard in most software and file formats. Texture mapping makes it possible to map high-resolution imagery (e.g. photographs or any 2D raster image) to meshes characterized by lower resolution than the pixel resolution of the image (i.e. the pixel size). It is indeed quite common that the resolution provided (or actually needed) by the three dimensional mesh is lower in respect to the texture-mapped images, or, anyway, to have a different resolution between the two. This is accomplished by providing additional two-dimensional coordinates to the vertex list of the mesh, each representing a location in the image to be mapped. These are called UV coordinates. In this way each face of the mesh (or quads in Figure 11) can be straightforwardly mapped to a specific region of the image, which is then displayed on top of the mesh itself, in its full resolution.

Figure 11: representation of UV mapping a raster image texture (left) on a 3D mesh (right). The vertices in the list are associated with U and V coordinates on the raster making it possible to wrap this around the mesh.



This technique is used to wrap full-resolution imagery onto 3D dimensional data, even when the 3D model has much lower resolution. This should be considered with extreme caution, especially when the data is then used to perform geometric interpretations (e.g. geologic interpretations): having such high resolution in the imagery might create the wrong impression that also the geometry is equally well represented.

Creating 3D geological models

Three-dimensional dataset suitable for scientific investigation are rarely the direct output of instruments or experiments, but rather, they result from a more complex processing, often starting with some other different data types.

There are several techniques that can be used to produce three-dimensional data and can be differentiated between active and passive methods. Active methods, as the ones based on scanning laser or other types of electromagnetic radiation, probing the surface of an object, and exploiting the return signal to later build a three-dimensional representation. In this category falls LIDARs or laser altimeters mounted on spacecrafts, e.g. the LOLA (Lunar Orbiter Laser Altimeter) onboard the Lunar Reconnaissance Orbiter (LRO), MOLA (Mars Orbiter Laser Altimeter) onboard Mars Global Surveyor or OLA (Osiris Laser Altimeter) on OSIRIS-Rex missions. In a similar manner, radar-based probing instruments, working in different portion of the electromagnetic spectrum, can even explore the subsurface at variable depths (e.g.

SHARAD (SHallow RADAR) onboard Mars Reconnaissance Orbiter and MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) onboard Mars Express.

Passive methodologies rely instead on acquired imagery by a variety of sensors that is then processed to produce elevation maps and 3D shape models. Photogrammetry exploits multi-point views of the same object to generate depth maps that are then converted into 3D meshes. The principle is the same that makes depth perception possible thanks to binocular vision (see Caravaca et al., 2020, and references therein for planetary applications).

Methods known as shape-from-shading are also common in planetary sciences and are mostly used to refine already-existent low-resolution models, by exploiting the shadows and change in shade created by topographic expressions on just a single image. In fact, from the shadow it is possible to obtain an estimate of the local slope and thus to solve for the local elevation if the camera and illumination parameters are known. These methods work better when multiple images with different lighting directions are available.

The last approach, relevant to this discussion, is the direct creation of the 3D models by using specialized software, which is a common operation in the domain of industrial design for producing accurate models of components or parts. This kind of modelling is most of the time accomplished by using dedicated CAD (computer aided design) software. Many different approaches do exist (e.g. parametric, direct CAD modelling).

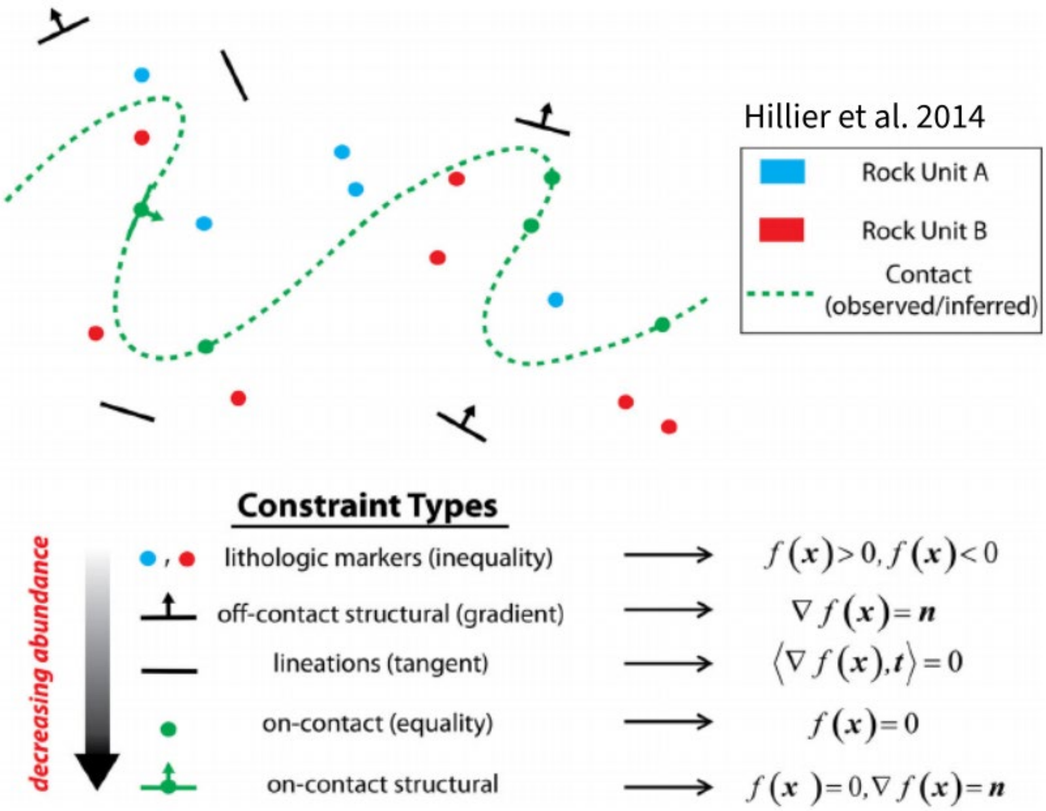
In a similar way specialized software to build geological modelling were also created, especially to support the work of oil and mining companies, which pioneered the field in many ways. Interestingly the methods developed for engineering and common CAD could not be directly applied to the geological modelling very easily, as natural systems require a more dedicated and complex approach. Therefore, specialized algorithms were developed to cope with the challenge of creating reasonable 3D representation with little data.

Historically, most of the geological maps created also present a geological cross section which has the goal of demonstrating the shape of the geological body under investigation in its third dimension at depth. For this reason, one of the simplest and more intuitive modelling approaches is represented by the creation of a multitude of geological cross sections, that can be parallel, sub-parallel or intersecting, that are then "interpolated" to fill the gaps in between generating a three-dimensional model of correlated meshed surfaces. An example of this procedure, adapted to the planetary case, can be found in (Pozzobon et al., 2020; Pozzobon & Penasa, 2021).

To overcome the limitations imposed by the quantity of the data, and to limit the human interpretation that can lead to bias, geological modelling software tries to consider all the available information on a geological system. As an example if we are going to model a marine sedimentary system made of plane-parallel layers we would like to make the model to respect some obvious constraints: for example layer parallelism and constant unit thickness. In this way, even if very little information on the geologic system is available, the modelling is performed in a sensible way, respecting the imposed constraints.

To account for this and similar constraints, a growing number of complex algorithms have been specifically designed. The methods derived from geostatistics, and interpolation theory have been fine tuned to be able to incorporate a variety of different constraints. Figure 12 summarizes how geological constraints can be measured or estimated for a geological body and are converted into mathematical expressions that need to be respected by the modelling software.

Figure 12: from Hillier et al, 2014. Several geological constraints and their mathematical formulation in the context of implicit modelling.



Numerical methods have been developed to solve the modelled geometries and to respect all the constraints in the most sensible way. These methods do not necessarily relieve the operator from making important interpretative choices, and great care must be taken to guide the software into producing meaningful results, which reflect the conceptual models based on the formation and evolution of the geological body.

Introductory papers on 3D geological modelling can be found in the suggested reading list further paragraph.

Software packages

Here we propose a selection of software we believe can be useful for the creation, analysis, and visualization of three-dimensional models. These software in most of the cases do not specifically target planetary datasets but are general-purpose software.

Open Source

LoopStructural

https://github.com/Loop3D/LoopStructural

Python library for 3D modelling of geological bodies providing an implementation of several interpolation methods (implicit modelling), suitable for modelling stratigraphy, unconformities, fault, and folds. It also wraps the Surfe interpolator based on Radial Basis Functions (https://github.com/MichaelHillier/surfe). Requires python experience and it is not provided with a GUI. Development supported by the Loop platform (https://loop3d.github.io/) and Monash University.

GemPy

https://www.gempy.org/

Is a rapidly evolving python project supported by Aachen University. It is similar in approach to LoopStructural and requires a good amount of programming practice in Python. It can handle faults/folds and unconformities by using an implicit modelling approach based on a kriging interpolator. It also features dedicated methods for uncertainty estimation of geological surfaces, based on the PyMC3 framework.

PZero

https://github.com/andrea-bistacchi/PZero

Provides an interface (GUI) for LoopStructural modelling package. 3D visualization is provided by VTK library.

OpenDTect

https://dgbes.com/

Open source packaged for Seismic data interpretation, with limited 3D modelling capabilities (can interpolate surfaces). Can be useful for the interpretation of GPR or other radar (e.g. SHARAD) imagery on planetary bodies. Plugins providing advanced tools are subject to a license fee, but standard tools for tracing horizons on sections can be used successfully on most datasets.

Pro3D

https://pro3d.space/

Is an open source 3D viewer specifically targeting planetary explorations. Written in F#, It features dip and strike estimation and other useful 3D annotations.

Cosmoscout VR

https://github.com/cosmoscout/cosmoscout-vr

Developed by German Aerospace Center (DLR) to provide a complete simulation of the Solar System coupled with high resolution map data for the planetary bodies from internet-provided Web-Map-Services (WMS). Ephemerids and spacecrafts positions are provided by SPICE. It features a plugin system that simplify extension of the toolkit. It is written in C++.

Cesium

https://cesium.com/blog/2020/07/06/camptocamp-underground-visualization-with-cesium/

https://cesium.com/blog/2020/06/16/visualizing-underground/

Provide web-oriented 3D data visualization oriented to the geospatial world. It features a JS library to create 3D-based web applications. It has been used to generate the browsable 3D geological map and model of Switzerland (https://viewer.swissgeol.ch).

Other interesting tools:

Paraview: for general-purpose scientific visualization and processing - https://www.paraview.org/

MICMAC: open source photogrammetry toolkit - https://micmac.ensg.eu/

Meshlab: general purpose 3D data processing with many filters - https://www.meshlab.net/

CloudCompare: point-cloud processing and visualization - https://www.cloudcompare.org/

Proprietary

VRGS

https://www.vrgeoscience.com

The software has a more than affordable cost for academic licences with a particular attention to PhDs projects. It allows managing DOMs and retrieving geological measurements such as fault/joint, strata and lineation attitudes as well as stratigraphic logs. It allows also a very effective 3D geological drawing with limited capacities of 3D geometrical modelling of geological volumes. Virtual environment is also implemented.

Petex MOVE

https://www.petex.com/products/move-suite/

This software is an explicit modelling software used for oil and gas exploration. It is devoted to structural analysis and has the peculiar capability to perform forward and backwards modelling of structural settings. It essentially works on cross-section interpretation and interpolation and is suitable for seismic and radargram analyses. It is able to provide comprehensive geo-structural models, basin analysis, digital fracture networks creation and geo-cellular models exploitation. Academic licensing is possible upon acceptance of conditions of PETEX. The main software works on Windows platforms.

Move provides companion apps for field activity such as FieldMove for tablets (iOS, Android and Windows) and FieldMove Clino for smartphones. Both software is available for free. It is able to record field measurements, geotagged photos, dip and strike measurements and directly sync them with the main MOVE software.

LeapFrog

https://www.seequent.com/products-solutions/leapfrog-geo/

Leapfrog is a geomodelling suite that uses implicit modelling techniques. It is user-friendly and widely used especially for mining exploration and exploitation , hydrocarbon reservoir exploration, civil engineering, and environmental analysis.

It is essentially based on DEM and borehole interpolation, which provides a best-fit solution. The final models produce geologic bodies in the form of full-volumes that can be sliced with ad hoc tools. It is used to work on medium to large-scale settings.

It works on Windows platforms, provides possibility of academic licensing, and offers training materials and dedicated support.

GoCAD

https://www.pdgm.com/products/GOCAD

SKUA-GOCAD is a software suite that provides a wide variety of subsurface geological modeling modules. Its core is based on implicit geologic modeling, nonetheless it is possible to do fault analysis, geomechanics, reservoir modeling, well correlation, flow numerical models seismic velocity modeling, and all those required by oil/gas and mining exploration. It's a wide suite of tools that are also provided with academic license upon request.

LIME

https://virtualoutcrop.com/lime

LIME is a software developed mostly for DOM and outcrop-scale analysis and visualization. It is developed by Virtual Outcrop Geology Group, NORCE Norwegian Research Centre, Bergen, Norway. It is able to import both DEMs, textured meshes and point clouds, digitize polylines, and interpolate planes. It has also capabilities for virtual field trip implementations as it is able to ingest massive data models and scaling meshes on different level of details for real-time visualization.

LIME requires Windows and a subscription. It has the possibility to get Commercial and Academic licensing and the possibility of 30 day trial.

Geomodeller

https://www.intrepid-geophysics.com/product/geomodeller/

Developed by the Australian company Intrepid Geophysics, it is an implicit modeling software working on Windows platform. As for Leapfrog it works on DEMs, geologic contacts and drill holes in order to provide best-fitting solutions by means of 3D interpolators.
it has also the capability of modeling faults and groundwater flows. Academic and education licenses are available upon application form.

AeroBrowser
https://areobrowser.com/#/
Is a 3D terrain browser for Mars data developed by Matt Brealey (https://mattbrealey.com). It features an extended collection of textured surface models and other imagery navigable from the browser.

Conclusions

In this document we presented a concise review of the basic topics needed to understand three-dimensional data and their use in planetary sciences. Modeling approaches are discussed along with their advantages and disadvantages and ad-hoc literature is provided.

The review section of existing open source and commercial software suitable for geological modeling or data processing will allow the beginner to find documentation and resources to start with.

For an up-to-date, living version of this document, please refer to the GMAP wiki at: https://wiki.europlanet-gmap.eu/bin/view/Main/Documentation/3D%20and%20geomodeling/

Suggested Readings

Geological Modeling

Wellmann, F., & Caumon, G. (2018). 3-D Structural geological models: Concepts, methods, and uncertainties. In *Advances in Geophysics* (Vol. 59, pp. 1–121). Elsevier. https://doi.org/10.1016/bs.agph.2018.09.001

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Planetary Applications

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De Toffoli, B., Mangold, N., Massironi, M., Zanella, A., Pozzobon, R., Le Mouélic, S., et al. (2020). Structural analysis of sulfate vein networks in Gale crater (Mars). *Journal of Structural Geology*, *137*, 104083. https://doi.org/10.1016/j.jsg.2020.104083

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