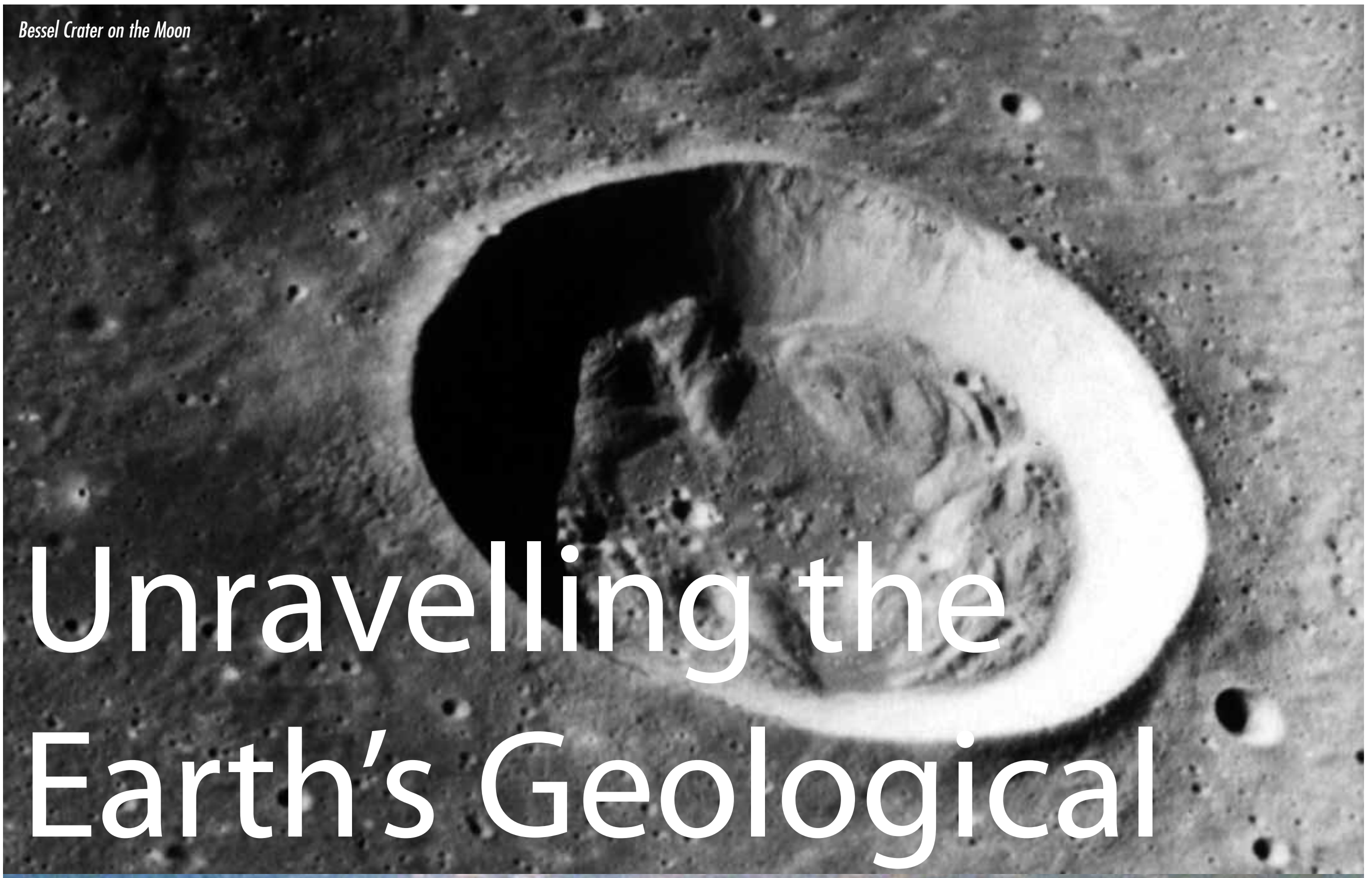

Bessel Crater on the Moon

Unravelling the Earth's Geological History from Space using Impact Craters

Barringer Meteor Crater in Arizona, USA

USGS

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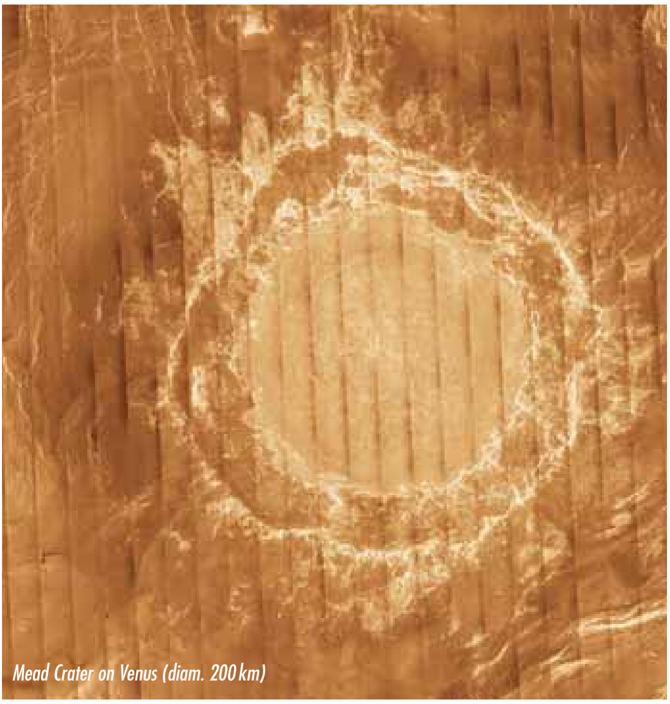


Mead Crater on Venus (diam. 200 km)

Magellan/NASA

Why are Impact Craters of Fundamental Importance?

Impact craters are ubiquitously present on the Earth, the Moon and Solar System's planets. Logically, therefore, the identification of impact craters can help us deepen our knowledge of the geology of the Earth in the context of our Solar System. The terrestrial cratering record is unique in providing a detailed picture of the history of our Solar System over the last few billion years, as well as its celestial environment. The search for the scars of ancient cosmic impacts is therefore of fundamental importance from both the astronomical and geophysical points of view. Firstly, we can obtain an estimate of the flux and size distribution of the impactors – meteoroids, asteroids, comets – that have hit Earth during the last few billion years. Secondly, the identification of impact craters can improve our detailed geological knowledge of the Earth's surface.

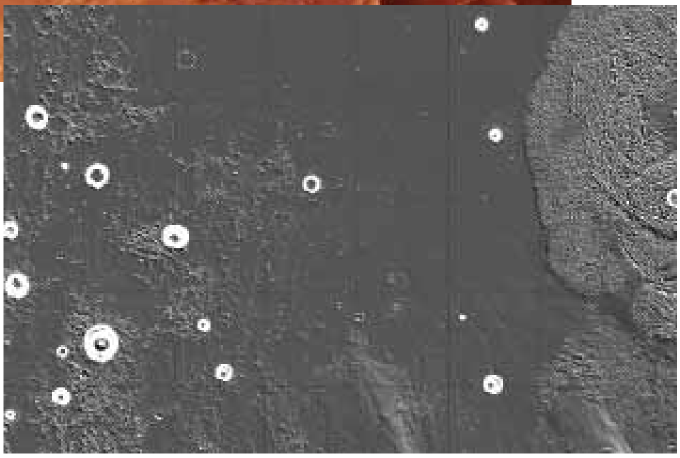
Impact Craters in the Solar System

Impact craters are the geological structures formed when a large meteoroid, asteroid or comet hits the surface of a solid planetary body. Impact cratering has marked the surfaces of all these bodies over the last 4.5 billion years and given them their most characteristic features. During this period, the Earth has been hit by countless asteroids, comets and meteoroids. Study of the resulting impact craters is an important field of space-science research, as they constitute an important link between planetary studies and geoscience (geology, geophysics, geochemistry) investigations of our own planet.

Impact craters occur throughout the Solar System and they hold precious information about the impacting body, about the surface conditions of the impacted body at the time of the collision, and also about the body's interior if the crater is sufficiently deep. Rather than being just passive remnants of planetary collisions, impact events have driven the geological evolution of many solid planetary bodies, especially in the early days of the Solar System.

The Argyre Basin on Mars (diam. 600 km)

Viking/ NASA / Calvin J. Hamilton



Craters on the Martian surface detected with parameter resolution scaling

Following the condensation of the primitive solar nebula and the accretion of the different planetary bodies, a period of heavy bombardment followed, which lasted until about 3.9 billion years ago. The surface of the far-side of the Moon, for example, is covered with craters of all sizes, produced by a cratering rate perhaps 100 times higher than today. All of the planetary bodies have experienced bombardment, but only those having solid surfaces still show the scars of even minor body collisions throughout the lifetime of the Solar System.

However, the impression left by the first Mars fly-bys was somewhat disappointing since the images sent back were morphologically similar to those of the Moon. These observations covered the older, southern hemisphere of the planet, which is indeed dominated by impact craters. When the Mariner-9 orbiter finally provided global coverage of the planet, it revealed the majestic volcanoes and canyons that characterize the northern hemisphere. The Pioneer, Voyager and Galileo missions to the outer planets have observed enormous impact features, such as the Valhalla basin on Jupiter's moon Callisto. At the other end of the Solar System, Mercury was revealed as a near twin of our Moon, its surface being pock-marked with craters of all sizes. More recently, close-range observations of asteroids have shown craters with sizes larger than 60% of the diameter of the body.

Other observations have shown that several planetary bodies have much lower impact-crater densities. This is certainly the case for Venus, Io, Europa and icy satellites such as Enceladus (a satellite of Saturn) or Miranda (a satellite of Uranus). The example of the Earth suggests that this situation arises when resurfacing processes have erased all but the latest impact craters, i.e. when the surface is younger than some hundreds of millions of years.

Years ago impacts by extraterrestrial bodies were regarded as an interesting but certainly not an important phenomenon in the spectrum of geological processes affecting the dynamic evolution of the Earth. However, the perceived relevance of these processes has changed radically as planetary exploration has progressed. It is now clear that impact cratering was the dominant geological process during the growth of the planetary bodies of the Solar System. Consequently, the role of impacts in the Earth's evolution is now receiving much greater attention. The space exploration programmes of the last four decades have changed our perception of planetary bodies in our Solar System from 'astronomical' to essentially 'geological' objects. This 'extension' of knowledge has provided new insights into the nature and the importance of impact cratering in planetary evolution.

The Moon, for example, which has experienced limited internally driven geological activity and lacks an atmosphere and hydrosphere, exhibits striking evidence of impacts. The scale of this process is extremely variable, from more than 1000 km-sized impact basins, dating back more than 4 billion years, down to micron-sized impact pits on rocks and minerals. By contrast, the Jovian satellite Io, exhibiting a high rate of resurfacing due to the constant volcanic activity driven by tidal forces induced by Jupiter's presence, has no apparent impact craters whatsoever.

Impact Cratering and Space Science

Impact cratering is increasingly being recognized not as the passive record of marginal events in the early history of the Solar System, but as one of the driving mechanisms of planetary geological evolution even on our own planet. The following are some of the most striking examples where impact cratering has helped to explain major scientific phenomena:

- The early heavy bombardment of the Moon, resulting in the excavation of large impact basins subsequently filled by lava flows, accounts for the asymmetry between the near and far sides of the Moon.
- Stresses induced by the formation of the Caloris impact basin on Mercury resulted in a major global compressive tectonics episode unlike its subsequent history.
- The dichotomy on Mars between the northern plains and the southern highlands is possibly explained in terms of several major impacts early in its history.
- On Earth, the heat generated by impacts is believed to have led to outgassing and dehydration of its volatile-rich early crust, thus contributing to its primordial atmosphere and hydrosphere.
- Major impacts may have guided the break-up of the Earth's crust, thus contributing to the opening of oceanic rift zones and possibly the formation of anomalous continental crust, as in the case of Iceland.
- The rims and central uplifts of several impact structures in sedimentary deposits have provided oil and gas reservoirs suitable for economic exploitation, and the extensive copper-nickel deposits of the Sudbury Basin in Canada are related to a huge Precambrian impact (1850 million years ago).
- A number of animal and plant extinctions throughout the Earth's history, such as that of the early Triassic (250 million years ago) and in particular that of the late Cretaceous (65 million years ago), when the dinosaurs became extinct, are linked to global effects resulting from major impacts. In the latter case, this was the impact that produced the Chicxulub crater in Yucatan, Mexico.

Apollo-11/NASA

This image, taken by the Apollo-11 astronauts in 1969, shows a portion of the Moon's heavily cratered far side

Mariner-10 / NASA / Calvin J. Hamilton

The Caloris Basin on Mercury (diam. 1300 km)

The Morphology of Impact Craters

Studies of the Moon have demonstrated that the morphology of its impact craters changes systematically with crater diameter, which in turn depends largely on projectile size, type, velocity and trajectory. Small lunar craters (about 15 km in diameter or less) display a simple bowl-shaped cavity. Above 15 km in diameter, the complexity increases to include terraced walls and then a flat floor and a central peak in the range of several tens of km to more than 100 km in diameter. The next incremental step above 175 km in diameter is to get a ring-shaped uplift, which develops into a full size concentric ring, thus becoming a multi-ring impact basin, typically between 300 and over 1000 km in diameter. The largest lunar basins have often been filled by volcanic lavas well after the impact occurred.

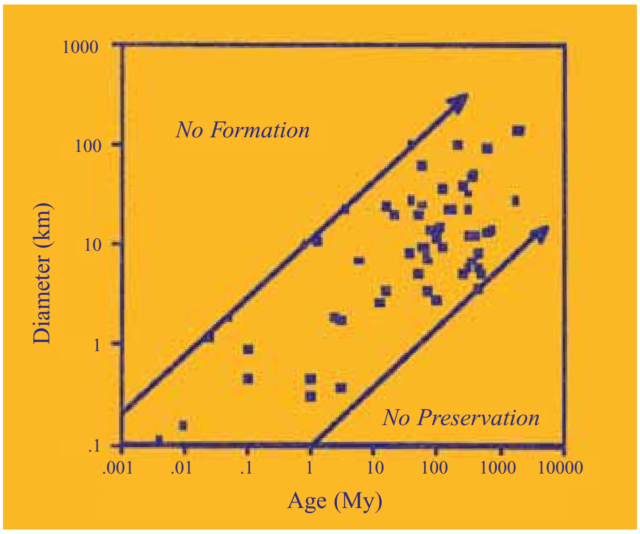
The different gravity fields on other bodies, however, lead to different diameter ranges for each morphological type of crater. On Earth, the higher gravitational acceleration produces smaller versions (compared to the Moon) of the three main types of crater: 'simple', 'complex' and 'multi-ring basins'. Also, the crater morphology reflects certain characteristics of the target planet at the time of the impact, such as the fluidized ejecta craters on Mars indicating that water or ice-rich materials were excavated, or the pancake-shaped craters on Venus bearing witness to the high atmospheric pressure of the planet, which concentrates the ejecta blanket close to the crater rim.

Impact Craters on the Earth

The dynamic processes occurring on Earth ‘hide’ most of the collision records. Erosion, sedimentation and volcanism quickly remove impact structures: approximately 30% of the known terrestrial craters are buried beneath post-impact sediments. The detection of these impact craters is therefore more challenging and complex. Luckily, however, Earth-observation satellites provide an extremely rich variety of images that can be used in the search.

There are currently about 160 known impact craters on our planet, with diameters ranging from a few hundred metres to several hundred kilometres. This low number is due to the relatively young age and the dynamic nature of the terrestrial geosphere. We also have to take into account the fact that two-thirds of the Earth’s surface is covered by oceans, and that the tectonic movements of continental plates, as well as erosion, volcanism and sedimentation processes, have erased and/or hidden most of the original morphological effects of impact-cratering. On the Moon there are over 300 000 impact craters, with sizes greater than or equal to that of Meteor Crater in Arizona, which is approximately 1 km across. If we assume a similar flux of asteroids and comets for our own planet, the total number of impact events that have affected the Earth is estimated to be about twenty times greater. If no surface renewal and reworking had occurred, the Earth’s surface should appear at least as scarred as the Moon’s, and so the relatively small number of known structures represent a small sample of a much larger population.

The known impact craters on Earth are concentrated in the Pre-Cambrian shields of North America, Europe and Australia (see accompanying figure), for perhaps two reasons. These areas have been relatively stable for quite long periods in geological terms and may be considered the most reliable surfaces for preserving impact craters. They are also regions where past scientific activity has been concentrated. The ‘scarcity’ of known craters in other areas such as Africa and



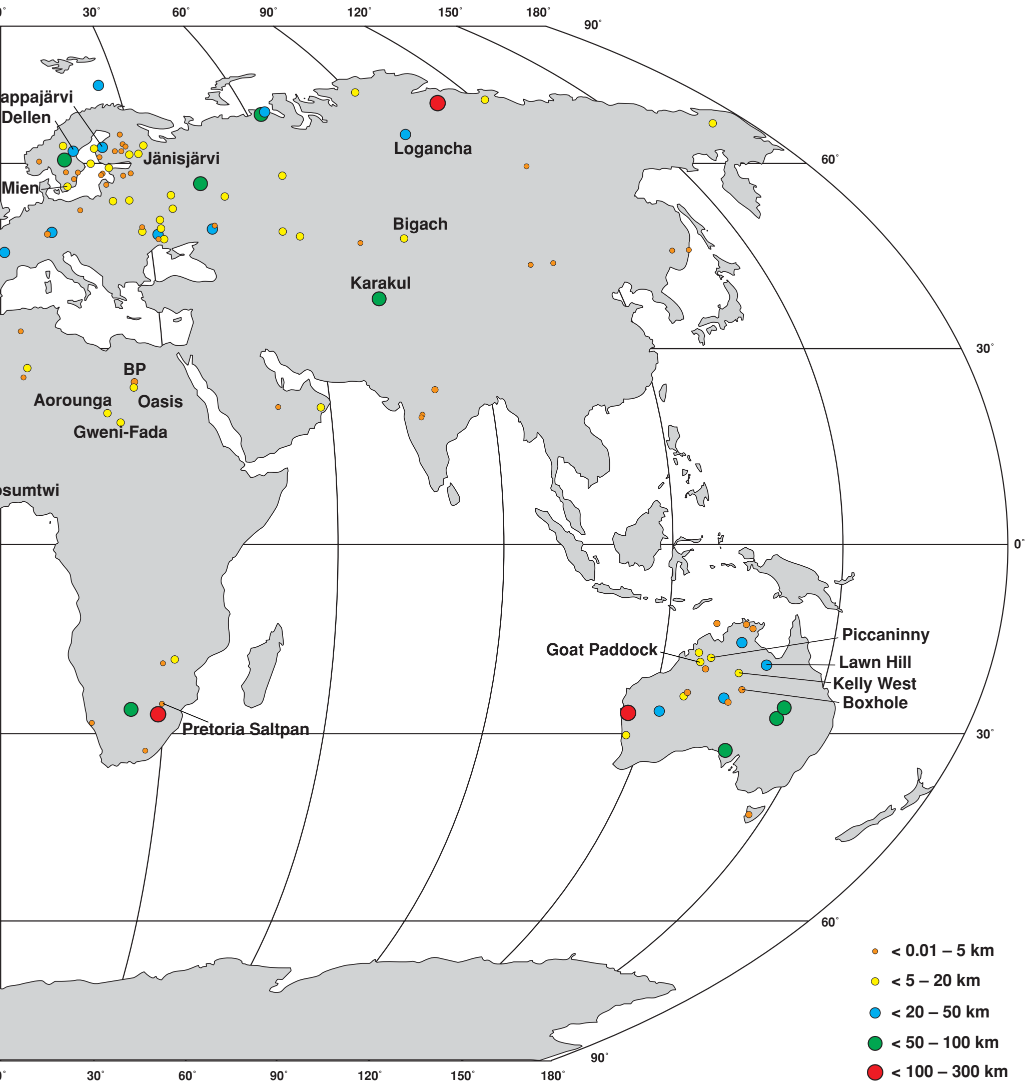
The relationship between the diameters and the ages of the Earth’s impact craters

The locations of the largest impact structures on the Earth

South America seems to be due to the lack of geological information as well as the absence of active systematic search programmes.

Terrestrial geological processes also introduce a number of biases into the known terrestrial impact record. Firstly, it is temporally biased, with over 60% of the known terrestrial impact structures being younger than 200 million years. This reflects the greater probability of removal of impact craters by terrestrial processes. In addition, there is a deficit of known craters having diameters smaller than about 20 km. This deficit increases with decreasing diameters and reflects the greater efficiency of terrestrial processes in removing smaller craters. There is also an atmospheric shielding effect at work in the rare formation of terrestrial impact craters with diameters of less than about 1 km.

With a few exceptions like Mjölnir in Norway and Montagnais in Canada, located in relatively shallow waters, all known impact structures on Earth are completely or partially on land. No impact structures are known from the true ocean basins, partly reflecting their relative youth, but also our lack of detailed knowledge of the ocean floors. Progress can be made here also with the help of space technology, by analysing gravimetric and radar data collected by satellites.



The Earth's known impact craters range in age from recent craters, formed during the last century, like Sikhote Alin in Eastern Siberia, to the highly eroded billion-year-old ancient structures like that at Acraman in Australia. In dimensions, they range from a few metres in diameter like the Kaalijarvi (Estonia) and Henbury (Australia) crater complexes, to a few hundred kilometres, like the Vredefort (South Africa), Sudbury (Canada), and Chicxulub (Mexico) impact structures. Those that remain have been preserved either because of their young age, large size, occurrence in a geologically stable region (Precambrian shields), or through rapid burial by younger sediments subsequently removed by erosion. The smaller and more recent craters (less than a few million years old) are best preserved in the desert areas of the World. In any case, orbital satellite imaging at radar and visible-infrared wavelengths, and satellite radar altimetry, are ideal tools with which to find and explore impact craters.

How Best to Recognise the Craters on Earth?

Impact craters have an approximately circular shape (possibly elongated), although the remnants may have become so irregular that it is hard to see a circle. Therefore, to define a model that represents a crater, the circular shape, being the feature most relevant, is certainly a good candidate and, for particular recognition techniques (optical and radar), can be effective. The adoption of such a simplified model has the obvious advantage of allowing recognition under a variety of circumstances (although the number of false identifications will increase), while a more complex model would allow more refined recognition, but needs to be modified for different cases.

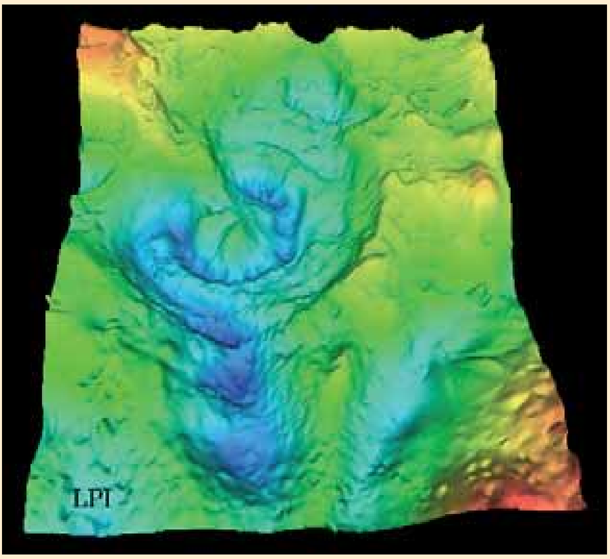
Having analyzed various techniques that did not need to consider separately different image types or different crater morphologies but would still deliver robust results, an algorithm based on the so-called 'Hough transform' was developed. The Hough algorithm exploits a geometric model of the crater's shape and allows the

NASA/JPL

Aorounga Crater in Chad, Africa (diam. 17 km)

NASA/LPI

Manicouagan Crater, Quebec, Canada (diam. 70 km)



NASA/LPI

Chicxulub Crater, Yucatan Peninsula, Mexico (diam. 170 km)

detection of craters in images from different types of sensors - a Martian crater in an optical image can be very different from a crater on Earth seen by a synthetic-aperture radar (SAR). While on planets like Mars impact craters can be well-preserved, on Earth they can be highly modified by erosional and tectonic processes and thus representation by a complex model is often impossible.

The use of the Hough transform in circular-shape identification and in crater-detection algorithms is not new, but the development of an algorithm robust enough to cope with multi-sensor images (optical and radar) is far from trivial. The natural digitization of the image and the quantification of the parameter space can introduce a loss of precision, so it is necessary to use special techniques to cope with the irregularities in crater shape due to erosion and other factors.

The results of tests on Martian surface images running the Hough algorithm indicate that craters with a wide range of radii are clearly detected. The Hough transform algorithm can also be improved by introducing an adjustment in order to be able to detect highly degraded craters, sometimes called 'ghost craters'. It certainly improved the detection of such craters on Mars, and can also be used for the Earth. While for the surfaces of Mars and the Moon, a simple classification with a few patterns covers all types of craters, the situation on Earth is more complex, because of the degradation due to tectonic processes and erosion of old impact structures. Study of ERS SAR, MODIS and Landsat images has shown that degradation, as well as vegetation coverage, can make crater recognition a challenge even for an expert image analyst.

The work done so far has focused on automatic recognition of clearly visible craters, which is the 'classical' recognition approach. However, this has shown clearly that the detection of craters not revealed by simple visual inspection can be further pursued only by exploiting data from multiple sensors, i.e. optical, multi-spectral, radar, altimetry, magnetic and gravity data. The contribution from space-based remote sensing is becoming more

The Hough Transform

The Hough transform allows the detection of simple geometric objects of known parametric form, like lines, circles and ellipses. The main idea is to build a parameter space in which the detection is computationally easier. The coordinates of the parameter space are the parameters that define the sought curve in the image space.

The fundamental algorithm consists of three basic steps:
- Each pixel of the image space is transformed into a curve (or surface, depending on the number of parameters) in the parameter space. The curve in the parameter space is defined by the same equation that defines the sought curve in the image space, by considering the parameters as variables.
- The space of parameters is divided into cells. Each pixel of the image contributes one vote to the cells lying on the transformed curve.
- The cell with maximum number of votes is selected and its coordinates in the parameter space are used to identify the curve to be found in the image space.

In the case of crater recognition, the parameter space has three dimensions - the parameters are the two coordinates of the centre and the radius of the crater - and its size depends on the image size. To improve efficiency and allow the processing of large images, techniques for speeding up the recognition process and for reducing the memory requirements are needed. A decisive saving in computational time can be obtained by exploiting the knowledge of the direction of the gradient at each point of the image. Moreover, statistical techniques (e.g. Monte Carlo simulation) can be applied to improve the computational efficiency.

Preliminary test results showed a dependency on the size of the craters. Large craters tend to have more irregular rims than smaller ones. In addition, the rims of the smaller craters are ‘smoothed’ by the limited resolution of the image. Consequently, when uniformly sampling the parameter space, the algorithm works well only for a small range of radius values. The algorithm can therefore be improved by scaling the resolution of the parameter space with the radius value. A shape is recognized as a circle when it fits a perfect circle within a certain tolerance. In particular, this error can be quantified as an increasing function of the radius, thereby allowing larger circular structures a higher radius error than small circles. A similar mathematical argument can be made for the position of the crater’s centre.

and more important due to the vast amount of data and computational power now available.

A remote-sensing-based catalogue of the features of all known terrestrial impact craters (about 160) still does not exist. Previous compilations (by Grieve in 1988 and Hodge in 1994) are now incomplete, because 30% of the craters known today have been discovered in the last 15 years, thanks in part to the increased availability of remote-sensing data. The availability of multi-sensor data from ESA’s latest Envisat satellite should provide the necessary material for such a comprehensive cataloguing activity.

Concluding Remarks

The work done so far shows that, by their nature, impact-crater studies call for a very interactive research process, requiring a multidisciplinary team effort, which in turn necessitates perseverance and a global approach to local problems. However, terrestrial impact-crater research is a broad scientific topic with far-reaching implications in such diverse fields as meteorite and asteroid research, Solar System evolution and even the search for life beyond our planet. Comparison of the cratering records and crater morphologies on different planets represents a fruitful field of investigation for reconstructing the history of our Solar System. Moreover, the algorithms developed for impact-crater recognition from space may well provide the methodologies that will make it possible to respond successfully to the challenge of automatically recognizing even more complex structures on our fragile planet in the future.

Acknowledgements

The work reported here is the result of the continuation of a specific collaboration between ESA’s Science and Earth-Observation Directorates, which began a few years ago when detailed studies and the compilation of a new catalogue of our home planet’s craters were initiated, using data from ESA’s ERS-1 and 2 satellites.