EXECUTIVE SUMMARY

Telespazio-EO Doc.No. 190.193-SPA-ES-001 – Issue 1.0

CRATERS

Document prepared by:

telespazio spa — **Earth Observation Dep.t**

in collaboration with:

Planetological Group

ESRIN/Contract No. 15711/01/I-SB

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European Space Agency Contract Report

Rome, 22th July 2002

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INTERNAL REFERENCE

Doc. nr:	190.193-SPA-ES-001
Issue:	1.0
Date:	2002, July 22

DOCUMENT CHANGE RECORD

Issue	Date	Reason(s) for change
1.0	2002, July 22	First issue

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1 INTRODUCTION

1.1 PURPOSE AND SCOPE

In this document a summary is given of the work performed in the framework of CRATERS Project. In this study, first the projects on crater recognition in the world were identified. Then, the main techniques used for automatic recognition of shapes and features in images were considered. Particular interest was posed to the analysis of the problem of localization and recognition of impact craters. After a critical study of the different techniques and an analysis of their effectiveness, we started designing an algorithm for the specific purpose of crater recognition. A prototype software implementing this algorithm was developed in order to check the effectiveness of the method under study and to perform different tests. The obtained results are very promising and suggest that an effective algorithm for crater detection, and in general for a wide range of recognition applications, can be developed starting from the results of the performed study. For a complete description of the performed work, and for further references, see [AD-03], [AD-04] and [AD-05].

This technical note is a deliverable of the ESRIN/Contract No. 15711/01/I-SB “CRATERS – Survey of Algorithms for Automatic Recognition of Impact Craters” [AD-01], as specified in the relevant SOW [AD-02]. The work has been performed by Telespazio S.p.A. – Earth Observation Dept – in collaboration with the Observatory of Turin – Planetological Group.

1.2 ACRONYMS

AD	Applicable Document
JPL	Jet Propulsion Laboratory
MODIS	MODerate-resolution Imaging Spectroradiometer
OATO-GP	Osservatorio Astronomico di Torino – Gruppo di Planetologia
PCA	Principal Component Analysis
SAR	Syntetic Aperture Radar
SoW	Statement of Work
TPZ-EO	Telespazio - Earth Observation Dep.t

1.3 APPLICABLE DOCUMENTS

[AD-01]	ESRIN Contract No. 15711/01/I-SB “CRATERS – Survey of Algorithms for Automatic Recognition of Impact Craters”	ESA Ref. IMT-CR/8394/01/SB/rr8B Frascati, 21 November 2001
[AD-02]	Statement of Work “Survey of Algorithms for Automatic Recognition of Impact Craters”	ESA Ref. AG-SOW(2001)00002-EOAD Issue 1.2 Date of issue 19 June 2001
[AD-03]	Technical Note “Crater Detection Activities”	TPZ-EO Ref. 190.193-PA-TN-001 Issue 1.0 – 2002, February 22
[AD-04]	Technical Note “State of the Art in Automatic Pattern Recognition”	TPZ-EO Ref. 190.193-PA-TN-002 Issue 1.0 – 2002, February 22
[AD-05]	Technical Note “Selected Algorithms and Test Results	TPZ-EO Ref. 190.193-SPA-TN-003 Issue 1.0 – 2002, July 8
[AD-06]	“Quality System Manual”	Document Nr.: MQ-001 – Edition: 1.0 – Date: 09-03-2001

2 MOTIVATION

Traditional interpretation of Earth Observation (EO) images and products requires to large extent the exploitation of experts' knowledge in each application area. Through visual inspection, they extract the information embedded in images and classify it through the manual association to terms. The image (product) interpretation process takes time and is expensive. For cost reasons it cannot be used for the systematic processing and classification of large data volumes. Therefore there is the need to identify methods for automated feature recognition and classification to enable the replacement of this manual interpretation activity with an automated pattern recognition process. This need will become more and more important in the near future, with the launch of new satellites, like for example Envisat.

Despite the increased computational capabilities, the retrieval of the data is still based on a few parameters like sensor, time and location. Content based retrieval systems are of no or very little use, given the peculiar meaning of (false) colors and gray scales in remote sensing images and products. Future systems should instead permit searches applied to indexes based on image information content, derived from automatic interpretation and classification processes. The way forward to those systems requires the development of a set of techniques and algorithms for automated pattern recognition of features from remote sensing images.

A simple “feature” present on the Earth, the moon and solar system’s planets is the crater. The identification of impact craters can contribute to the deepening the knowledge of the geology of the Earth in the context of our solar system. The terrestrial cratering record is in fact unique in providing a detailed picture of the history of our solar system in the last 600 million years, as well as its celestial environment. The forthcoming planetary missions like Mars Express and Cassini-Huyghens will collect huge amount of data where possible results of this study may be applied. Other applications may be in crater detection for autonomous landing on asteroids.

The search of the scares of ancient cosmic impact is of fundamental importance from the astronomical and geophysical point of views. In the first case we could obtain an estimate of the flux and size distribution of the impactors that have hit Earth during the last billion of years. In the second one, the identification of impact craters can contribute to deepen the geological knowledge of the Earth surface and to start "in loco" investigations of the discovered structures to correlate them with signatures which are present in coeval sedimentary layers.

The detection of impact craters on the Earth or planet surface provides a possible test case for the use of automatic recognition procedures. This is because of the simplicity of the forms to be detected and recognized, which facilitates the development of an automatic procedure, tough keeping significant difficulties, due to the partial erasure of the traces to be detected. The algorithms developed for impact crater recognition may provide the basis for methodologies that will make it possible to successfully respond to the challenge of automatically recognizing even more complex structures. Furthermore these algorithms may provide the foundations for tools able to support an exhaustive overview of the distribution of impact craters on earth as well as studies of comparative planetology.

3 IMPACT CRATERS ON EARTH AND IN THE SOLAR SYSTEM

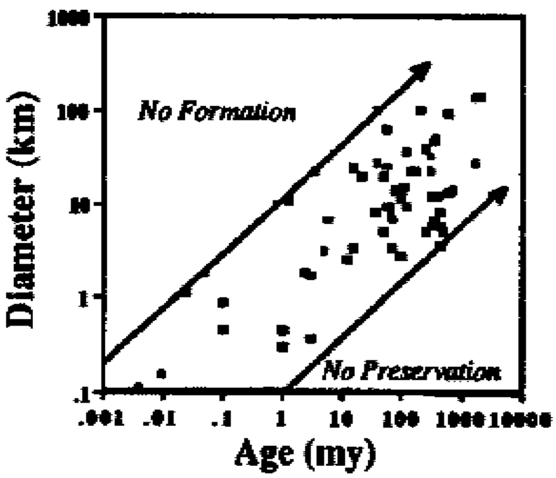
Impact craters are geologic structures formed when a large meteoroid, asteroid or comet hit the surface of a planetary solid body (planets, satellites, asteroids). Impact craterization is a process, which has marked the surfaces of all these bodies with their most characteristic features over the 4.5 billion years of the Solar System. During this lapse of time, the Earth has been hit countless times by asteroids, comets and meteorites.

During the last decades, planetary exploration has demonstrated the ubiquitous character of impact cratering in the Solar System. Indeed, the first impression given by the first Mars fly-bys was that it was, somewhat disappointingly since it gave images 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 obtained a global coverage of the planet, it revealed the majestic volcanoes and canyons, which characterize the northern hemisphere. The *Pioneer, Voyager* and *Galileo* missions to the systems of outer planets have observed enormous impact features, such has the Valhalla basin on the Jupiter moon Callisto. At the other end of the Solar System, Mercury was revealed as a near twin to our Moon, its surface being pocked with craters of all sizes. More recently, close-range observations of asteroids showed craters with sizes larger than 60% of the diameter of the body.

Several observations carried on by planetary missions have also shown that several planetary bodies exhibit much smaller densities of impact craters. This is the case for Venus, Io, Europa and icy satellites such as Enceladus (satellite of Saturn) or Miranda (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 hundred million years

Until recently, 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 relevance of these processes changed radically due to planetary exploration, since all planetary surfaces are cratered from the impact of interplanetary bodies. It is now clear that impact cratering was a dominant geological process during the growth of the planetary bodies of the Solar System. Therefore, the role of impacts in the evolution of the Earth is now receiving a radically improved consideration. For instance, large-scale impact events may are thought to be involved in modelling of the surface of the Moon as well as certain mass extinctions in the biologic record.

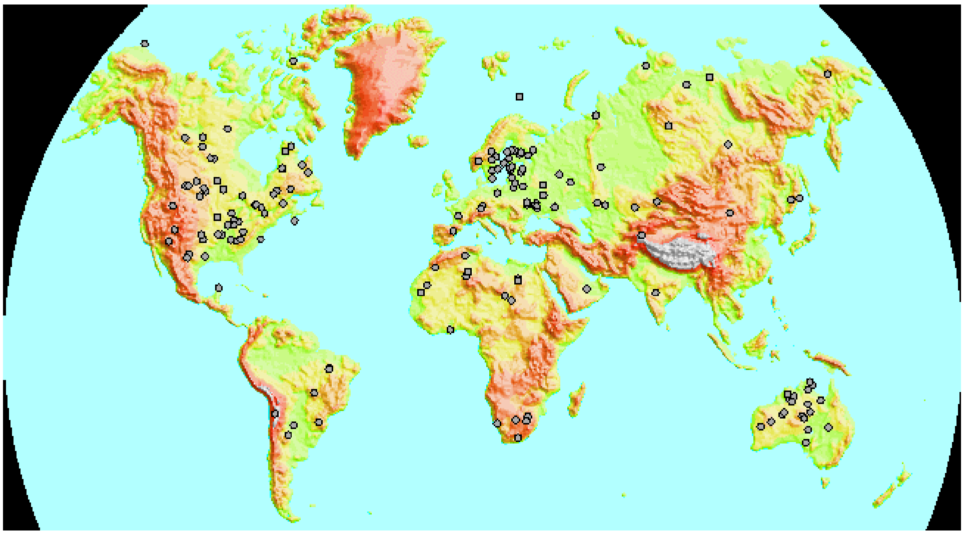
Over the last four decades, the space exploration programs have extended our view of planetary bodies in the Solar System from "astronomical" to essentially "geological objects". This "extension" of knowledge provided new insights on the nature and the importance of impact cratering and planetary evolution. The rate for such events is inversely proportional to the rate at which the surface of planetary bodies rejuvenates. For example, the Moon, which has had limited internally driven geologic activity, and lacks an atmosphere and hydrosphere, exhibits a striking evidence of impacts. The scale of this process is extremely variable, with more than 1,000 km-sized impact basins (which date more than 4 billion years) and micron-sized impact pits on rocks and minerals. On the contrary, the Jovian satellite Io (exhibiting a high rate of resurfacing), due to extensive and constant volcanic activity driven by tidal forces induced by Jupiter has no apparent impact craters.



Relation of terrestrial impact crater diameters and ages.

The dynamic processes occurring on Earth "hide" most of the collision records. Erosion, sedimentation and volcanism quickly remove original impact structures: approximately 30% of the known terrestrial craters are buried beneath post-impact sediments. Thus, detection of impact craters is more challenging and complex. Luckily, satellites for the observation of the Earth provided an extremely rich variety of images which can be analyzed.

The morphological effects of these impacts are found worldwide, and are very few when compared to the real number of the impacts that affected our planet. Currently, known impact craters, with diameters of more than a few hundreds of meters, reach the approximate number of 160. This is due to the relative young age and the dynamic nature of the terrestrial geosphere. We have to take into account that 2/3 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.



Location of the largest impact structures on the Earth.

The Moon surface (where none of these secondary phenomena are effective) is an excellent recorder of the cosmic bombardment the Earth-Moon system since its earliest times. On the Moon there are over 300,000 impact craters, with sizes greater than (or nearly equal to) the Meteor Crater of Arizona, which shows a diameter of approximately 1 km. If we assume a similar flow of asteroids and comets, both for our planet and its satellite, the total number of impact events that affected the Earth is estimated to be about ten times greater than that affecting the Moon surface.

If it no surface renewal and reworking would have occurred, the Earth surface should appear as scarred as the Moon's. Therefore, it is evident that the importance of the terrestrial impact record is greater than the relatively small number of known structures. This shows that impact terrestrial craters simply represent a small sample of a larger population.

Currently known impact craters on Earth concentrate in North America, Europe and Australia. Two factors may be involved in the origin of this distribution:

– These areas have been relatively stable for relatively geologic times and they are the best reliable surfaces for preserving impact craters. They are also regions where past scientific activity has concentrated. The "scarcity" of known craters in other cratonic areas, such as Africa and South America, seems to be due to the lack of geologic information as well as deficiency in active systematic search programs. Therefore, these cratonic areas are potential targets for future exploration.

– Terrestrial geologic processes also introduce a number of biases into the known terrestrial impact record. The known record is temporally biased, with over 60% of the known terrestrial impact structures being younger than 200 million years. This reflects the greater probability of the 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 a greater efficiency of terrestrial processes to remove smaller craters. There is also an atmospheric effect at play in the formation of small (with diameters less than about 1 km) terrestrial impact craters due to the atmospheric crushing and retardation of small impacting bodies (essentially weaker stony ones).

With two exceptions (Mjölnir in Norway, and Montagnais in Canada), located in relatively low waters, all known terrestrial impact structures are completely or partially on land. No impact structures are known from the true ocean basins, reflecting, in part, their relatively young age. An additional limit is the lack of detailed knowledge of the ocean floors. Promising results in this field could be obtained by analysing gravimetric data collected from space.

Impact craters range in age from recent craters, formed during the last century, as at Sikhote Alin (Eastern Siberia), to the highly eroded billion-year-old ancient structures, as at Acraman (Australia). Regarding their dimensions, they range from a few meters in diameter, as Kaalijarvi (Estonia) and Henbury (Australia) crater complexes, to well over 100 km, as at Vredefort (South Africa), Sudbury (Canada), and Chicxulub (Mexico) impact structures.

Whether large or small, young or old, clear or hidden by erosion and geological sedimentation, all the impact structures are important records of how astronomical objects continued to have direct effects on the events that made up the history of the Earth and of the Solar System.

4 THE RECOGNITION PROBLEM

The recognition problem is of great importance in all situations where automatic decisions must be made without the intervention of the man. The recognition problem is one of the most studied in computer vision, and many algorithms are developed to detect a particular object in 2D images. Interesting application can be generalized to 3D o more complex data, and there are also non banal application to 1D case, e.g. in time signal analysis.

In our context, by recognition we mean identification of objects defined by a given set of features a priori known. The concept of recognition given above is common to many different areas of application, but in each one the methodologies to obtain the results can be very different. The characteristics of the data elaborated and the type of the knowledge on the object to recognize have a great importance to choose the more suitable technique. In robotic applications often the image data are characterized by low level of white additive noise and distortions due to the camera, while the object searched has sharp edges and a well-identified shape. In remote sensing applications, in addition to the fact that different types of noise or distortions corrupt the images, often the features of the object searched itself cannot be well defined, or his outlines can be known only with a large approximation.

An important step, in the recognition process, is the definition of the object to detect. A representation of this object can be made only by using an ideal model that includes the most relevant discriminating features.

Several different types of techniques have been developed for recognition of objects. Two important families are the matching algorithms and the voting techniques. Matching algorithms, in the recognition process, use a copy opportunely simplified (template including the more relevant features) of the object to detect, while in voting techniques a schematic shape model of the object is used.

5 MATCHING ALGORITHMS

Often, in recognition problems, we consider real objects with features more complex than a set of geometric points like lines or simple shapes. A representation of complex objects by means of simple mathematical formulas like the parametric curve characterizing the outline of the shape can be in many cases impracticable. In these cases, by considering a set of training data, it is possible to generate an adequate model. The model is fundamental for the accuracy and robustness in the recognition process. In particular, features like shade, illumination properties or orientation of the object, being inessential to the detection problem, must not determine in a sensitive way the result of the recognition process. A model for the object to recognize is obtained by identifying the relevant features of the object. The feature space can be represented by a vectorial subspace. Each vector in this space collects a fixed number of features (given by the dimension of the space).

Matching filtering techniques are widely applied in order to detect known signals (or objects) in a noise and corrupted images, by means of use of correlation methods. The idea is to superimpose a model of the searched object with portions of the image analyzed and calculate a measure of the confidence of the obtained matching. To this goal a useful tool is the correlation integral that uses as kernel a certain model of the object to recognize.

5.1 PRINCIPAL COMPONENT ANALYSIS

Often the feature space is too complex and consequently a recognition can be computationally inefficient. In addition, the use of a high dimension feature space (many features are employed) makes worse the results of recognition algorithms. An approach widely used to obtain a feature space with low dimension is the Principal Component Analysis (PCA) technique. By using the PCA the projections onto lower dimensional linear spaces that best represents the data in a least square sense can be obtained. Therefore, by applying the PCA it is possible to reduce considerably the dimension of this space. The less significant information present in the training data is, in this way, discarded and the most relevant information is encoded in few basis vectors. The simplified model obtained by PCA can be directly used as the kernel for the correlation integral in matching algorithms.

5.2 GENERALIZATIONS OF MATCHING FILTERING

Matching filtering works less well when the object to be detected presents a high variability. It is quite clear that, as the signal is much variable the PCA method can extract with difficulty the fundamental features of the object and the training data set is not much reduced. Moreover high dimensional filters capture a lot of noise, while useful information of the signal is small.

If the paradigm to be detected is of an object particularly variable for rotation, contraction and expansion deformation template matching or continuously scalable template matching can be used. Template matching is a general match filtering method in which image pixels arrays are rotated and otherwise transformed to match pieces of an image. This is a natural extension of the matching filter, in which the model (feature space) includes transformations like rotation and scaling. Continuously scalable template matching uses a training data set provided by scientists to generate a model (feature space) for target detection in a defined and continuos range of scales.

6 VOTING TECHNIQUES

A class of methods, widely used in many recognition applications, allows to detect shapes in an image by employing the technique of "voting" in an opportune parameter space. The most famous voting technique is the Hough transform. This transform is a particular case of the Radon transform. In the recent years the Hough and the Radon transforms have received much attention.

6.1 HOUGH TRANSFORM

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

The fundamental algorithm consist of three basic steps:

1. Each pixel of the image space is transformed into a curve (or surface, depending on the number of the parameters) in the parameter space. The curve in the parameter space is defined by the same equation that define the searched curve in the image space, by considering as variables the parameters.

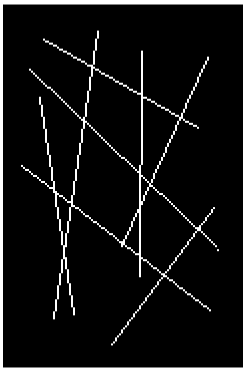
2. The space of parameters is divided in cells. Each pixel of the image give one score to the cells lying on the transformed curve.

3. The cell with maximum scores is selected and its coordinates in the parameter space are used to identify the curve to be found in the image space.

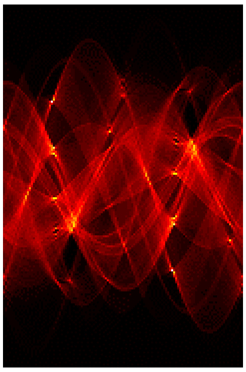
As an example, let us consider lines straight lines. Given the parametric equation of a line, we consider a work space (parameter space) where each geometrical object represented by the above formula can be characterized by only one point. Analogously, each point in the image represent a curve in the parameters space. The Hough transform performs a reversible transformation between the image space and the parameters space. This transformation is such that all points in the image space lying on a curve represented by the above analytical equation are mapped in the same point of the parameter space. After this mapping a number of points will fall in each point of the parameter space, and the coordinates of the points characterized by the highest values are the parameters of the analytical formula of the recognized objects. In Figure 1 an example of the application of Hough transform for line recognition is considered. The image (image space) and the parameter space are shown. The points with high values in the parameter identify the recognized curves in the image. The values of these points are given by the number of the intersections of the plotted curves in the parameters space. In Figure 2 a detail of the parameter space for the line hough transform is shown.

It remains to know how to find the intersections computationally. The idea is to build an array of accumulators over the parameter space. The parameter space is discretized, i.e. divided in cells or accumulators. The image space is already naturally discretized, an image being a matrix. Each cell in the parameter space takes one vote for each image point corresponding to a curve passing through the cell. The votes are summed in the accumulators. Therefore, if a cell in the accumulator has n votes, then n image points lie along the line identified by the coordinates of the cell (parameters).

The Hough algorithm can be applied for recognition of generic curves having an analytical representation. The number of the parameters gives the dimension of the parametric space.

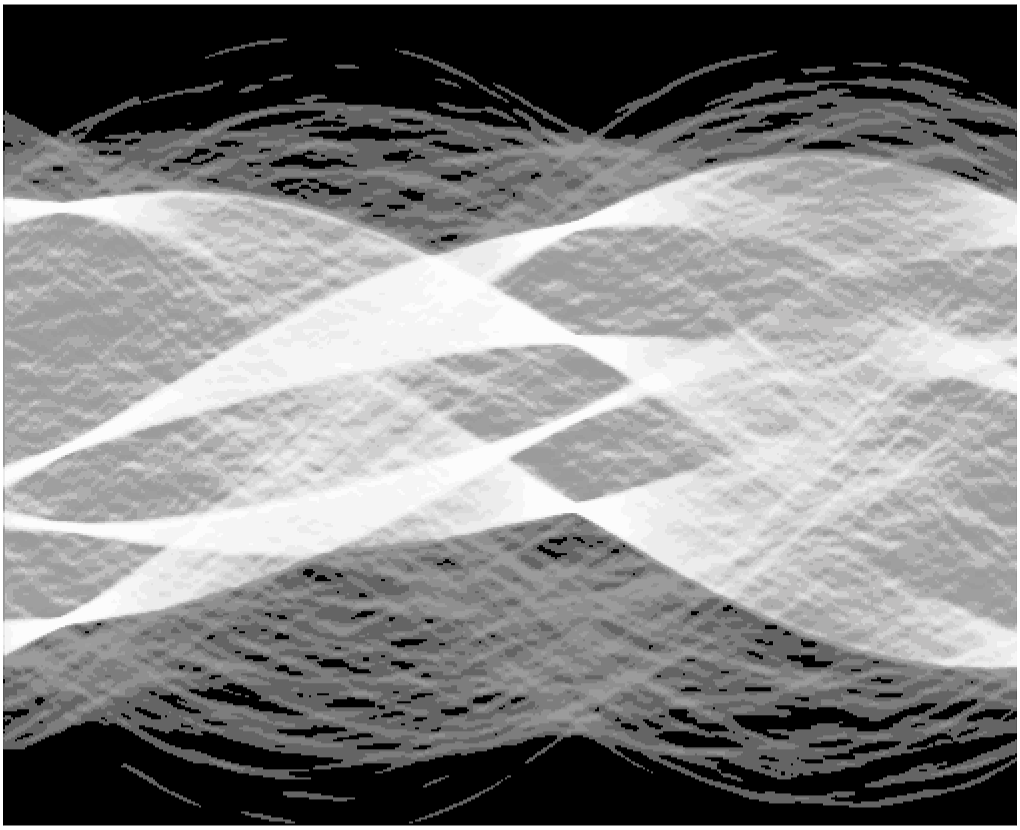


Lines in the image space.



Correspondent curves in the parameters space.

Figure 1



A typical example of parameter space after the voting process. Points of accumulation are evident.

Figure 2

7 WHICH APPROACH FOR CRATER RECOGNITION?

Impact craters have approximately a circle shape (possibly elongated), even though its outline is often so jagged that it is hard to see a circle. Therefore, to define a model that represents a crater, the circular shape, being the feature more relevant, is a good candidate. Characterizing a crater by only the circular shape is surely reductive, but it is reasonable and, for particular recognition techniques, it can be effective.

A model of the crater based on the circular shape feature is applicable to many different situations: for recognition both on Earth and extraterrestrial planets surfaces, from different optical data and SAR data. A model suitable for a large range of suitable cases necessarily captures only few features of the object to recognize, while a specialization to a particular kind of image or to a specific type of surface (Mars surface or non vegetative scene of the Earth) can allow the use of a more complex model, in which many features are considered to characterize the object to recognize. The adoption of a simplified model has the obvious advantage to allow the recognition in different circumstances, even though the number of false alarms could increase. A more complex model could allow a more refined recognition, but the model needs to be modified for each different case.

We decided to begin our study analyzing and developing a technique that did not need to consider separately different image types or different crater morphologies. In this way, we can guarantee the recognition in different situations. In order to obtain robust results, we developed an algorithm based on the Hough transform. The Hough transform exploits a geometric model of the crater shape (a circle with some tolerances). Therefore the Hough transform based algorithm allows to detect different types of craters in different types of images (a Mars crater in an optical image can be very different from a crater on the Earth seen by a SAR). Moreover, this technique not only allows to detect craters in very different cases, but also, for its generality, is suitable to be applied in a large range of different applications.

The above considerations that drove our choice of the Hough transform are particularly relevant for crater recognition on the Earth. Indeed, while on planets like Mars, impact craters are well preserved, on the Earth erosion and tectonic processes modified crater traces. Therefore, on the Earth surface many typologies of craters are present and often a representation by a complex model is impossible (features typical of different types of craters can be contrasting). In this context an algorithm that exploit a model containing only the most relevant features characterizing all craters, that is the circle shape, is convenient, and the Hough transform is the natural way to realize such an algorithm.

Approaches based on matching techniques allow to build a complex model using PCA methods. These kinds of algorithm have been applied to recognition volcanoes on Venus surface (by JPL) and rather good results have been obtained. Recently, at JPL laboratory, more sophisticate algorithms for recognition of craters on Mars has been developed. This approach used a complex representation of the model obtained by means of PCA methods and its applications are particularly suitable for recognition of objects whose characteristics (features) are only slightly variable, like volcanoes on the Venus and craters on Mars surface. The variability characterizing the craters on the Earth suggests that PCA techniques cannot be directly used.

8 A HOUGH TRANSFORM BASED ALGORITHM FOR CRATER DETECTION: PROTOTYPING, TESTS AND ALGORITHM IMPROVEMENTS

Implementation of the Hough transform algorithms must take into account different problems. The natural digitalization of the image and quantization of the parameter space introduce loss of precision; moreover the object to be recognized for its nature is not well defined (especially if we consider craters on Earth's surface).

We intend to characterize craters by means of analytical functions, in particular circular shapes. This simple model used in the Hough transform, as above explained, allows to apply the algorithm to different types of images, and to detect different crater patterns. On the other hand, the use of analytic circles makes necessary to introduce particular techniques in order to take in account the irregularities of the crater shapes (due to erosion and other factors). In remote sensing data, the outlines of craters can look very degraded and techniques to make the algorithm more robust are needed. In recognition algorithms it is also requested computational efficiency and automation.

In the following, we describe the performed implementation of Hough transform algorithm and the developed new techniques to improve robustness, efficiency and automation. Different tests on real data are shown for each case.

8.1 EXPLOITING GRADIENT DIRECTION

The computational complexity and the storage requirements of the Hough transform can be very expensive, especially when the analytical representation of the curve to be detected involves many variables. If the parameter space has several dimensions, the standard Hough algorithms become inefficient: large memory is necessary and the processing of voting is more complex. Analogue considerations hold for the dimension of the image space.

In our case (circular Hough transform) the parameter space has three dimensions (the parameters are the two coordinates of the center and the radius) and its size depends from the image size. In order to improve the efficiency and to allow the elaboration of large images, techniques for speeding up the recognition process and for decreasing memory requirements are needed.

We have obtained a decisive saving of computational time by exploiting the knowledge of the direction of the gradient in each point of the image. Theoretical considerations show that by exploiting the gradient of the image, the parameters space can be reduced to two dimensions. Moreover, statistical techniques (Monte Carlo) can be applied to improve the computational efficiency.

8.2 COARSE GRAIN PARAMETER SPACE

Each cell of the parameters space for the circle Hough transform is characterized by three coordinates that identify the position in the parameter space and by the score representing all accumulated votes. In particular, the coordinates localizing the cell represent the parameters identifying the recognized shape. For example, in our case, the parameters space coordinates are *x*, *y* and *r*, where *x* and *y* are the center coordinate of the circle in the image and *r* is its radius. If the image to be processed has size *N* x *M* and the range of radii to be considered is [r_{min}, $r_{\max}$], then the parameter space will have *N* x *M* x (r_{min} - $r_{\max}$) size. In this case the maximum tolerated error about center localization and radius is less than one pixel, that is the same resolution of the image is obtained.

In many situations it could be useful to divide the parameter space in coarser resolution cells (see Figure 3). Indeed if we assume each cell is defined by a range of values *x*, *y* and *r*, we loss resolution, but we obtain two important improvements: a decrease of storage requirements and a reduction of the algorithm sensitivity to the differences between the shape in the image and the parametric curve used for the detection. In this case each cell corresponds to several slightly different circles (different ranges and centers).

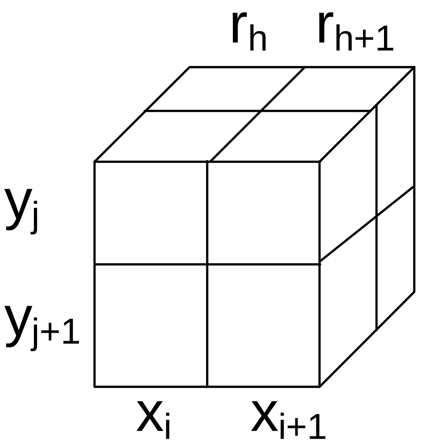


Figure 3 -- A coarse resolution cell

8.3 SCALING PARAMETER RESOLUTION

Preliminary test results showed a dependency on the size of the craters. The reason of this fact is that craters of different size have border differently jagged. Large craters have border more jagged than smaller craters. In addition, the smaller are “smoothed” by the limited resolution of the image, while the border of large craters, that can present relevant distortions, are not effectively affected by the smoothness of the resolution. It results that by uniformly sampling the parametric space, the algorithm can work well only on a small range of radius values.

In order to take into account the dependency of the results on the size of craters, we improved the algorithm by introducing the idea of scaling the resolution of the parameter space with the radius value, i.e. a non-uniform sampling of the parameter space. A shape is recognized approximately as a circle when it fits a perfect circle with an tolerable error (see Figure 4). In particular, this error can be quantified as an increasing function of the radius. By doing this, we admit that larger circular structures have a radius error higher than small circles. A similar discussion can be made for the center localization and, therefore, variable errors on x and y coordinates of the center can be introduced. Different tests suggest to scale the volume of the cells in the parameter space linearly with the radius. Figure 5 illustrates the idea of scaling the parameter space resolution.

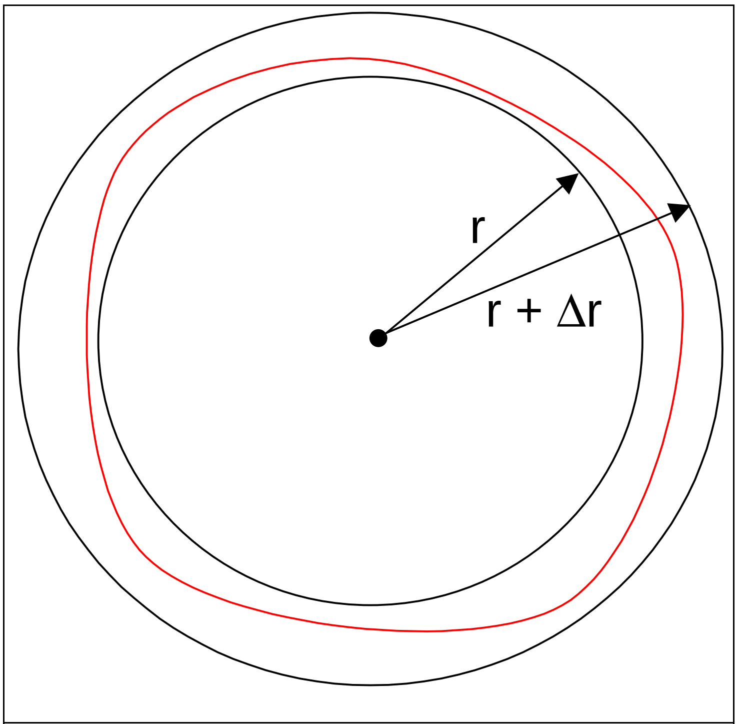


Figure 4 – Tolerated radius error

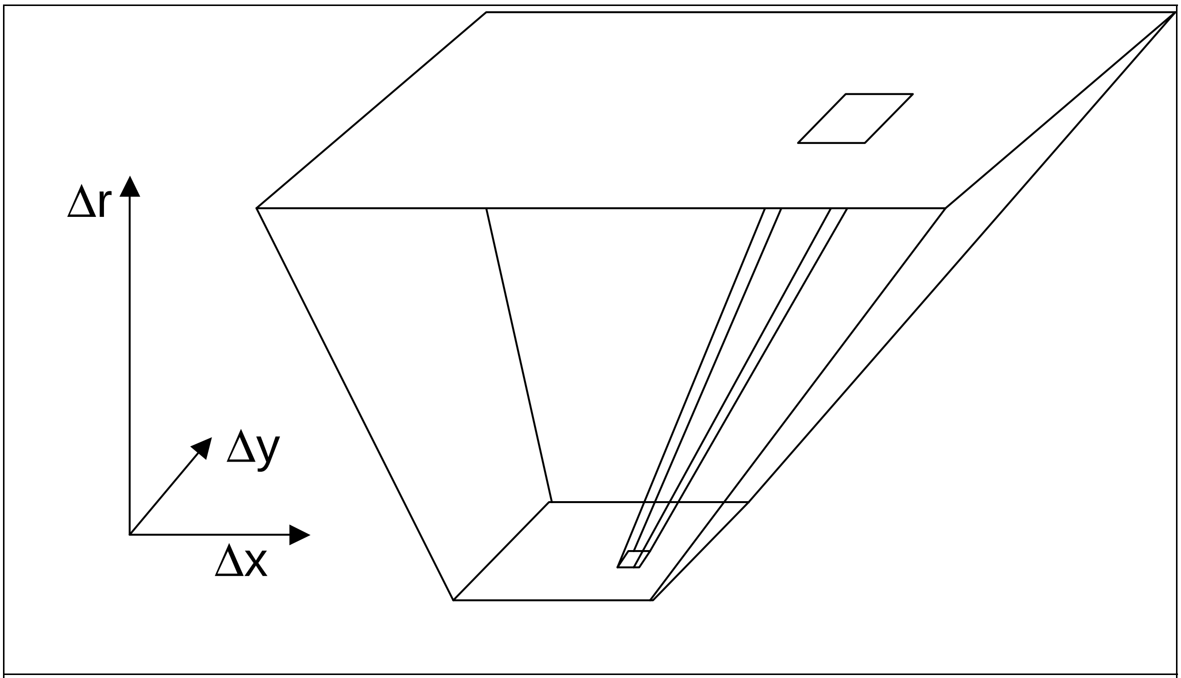


Figure 5 – Scaling of cell resolution in parameters space.

8.3.1 Tests on Mars surface images

In this section we show the result of a test obtained performing the Hough algorithm modified as described above. Figure 6 shows the image on which the test was performed. In Figure 7 the result obtained by running the algorithm is shown. Craters in a wide range of radius values are detected.

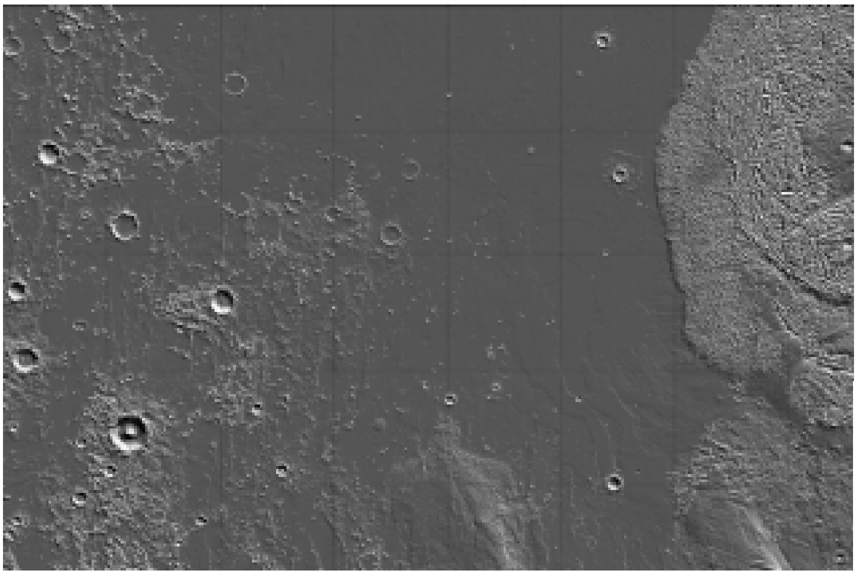


Figure 6 – Mars Surface

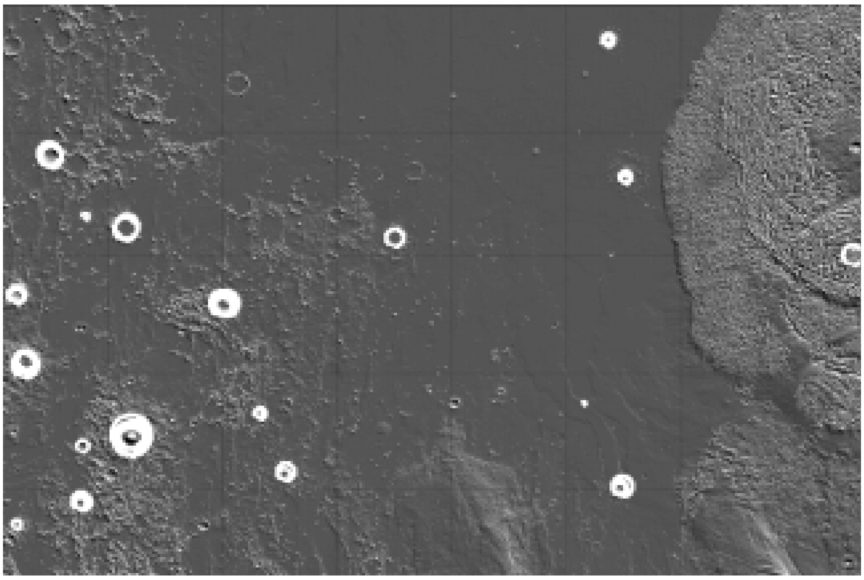
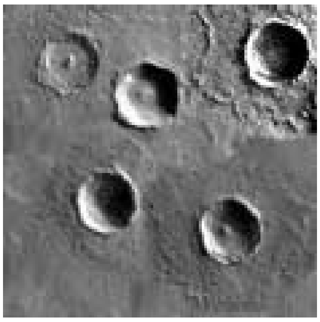


Figure 7
Craters detected with parameter resolution scaling

8.4 PENALTY AND GHOST CRATERS

Hough transform algorithm can be improved by introducing a penalty in order to detect very degraded craters. On Mars surface are visible craters particularly corrupted, characterized by weak outlines and inside areas with a very low contrast (see Figure 8), that are called ghost craters.



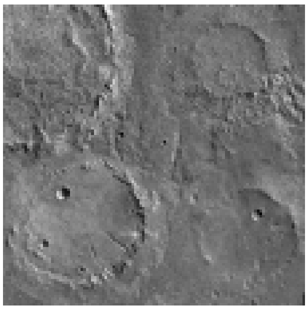


Figure 8 – Examples of young craters (left) and old craters (ghost craters - right)

The penalty is calculated by integrating the gradient absolute value over the area inside a circle. The difference between the vote and the penalty is assumed to be the new score by means of which the confidence of detection is evaluated. The penalty technique improved the detection of ghost craters on Mars (compare Figure 7 and Figure 9)., but that can be also used for craters detection on the Earth.

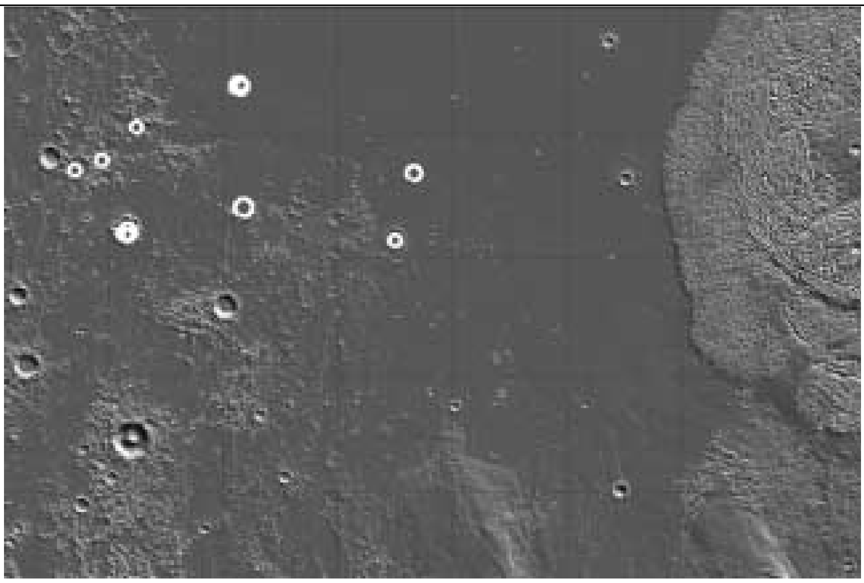


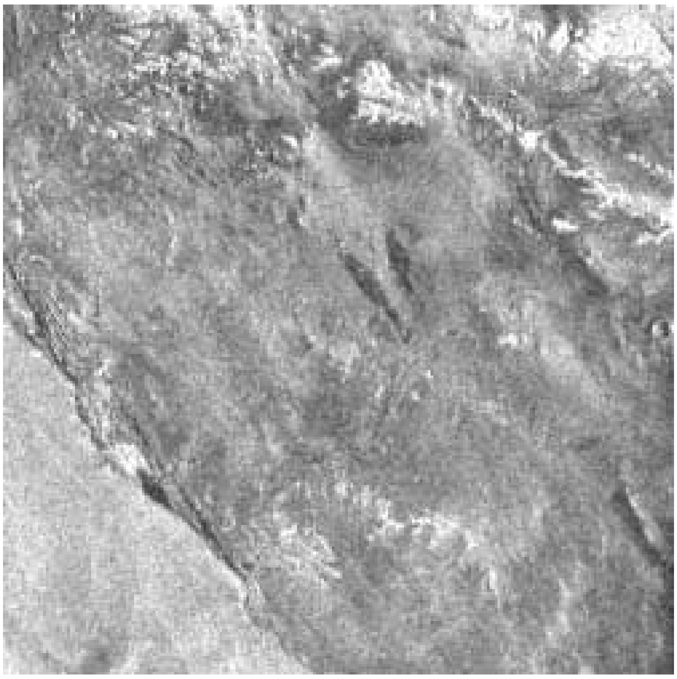
Figure 9 – First craters detected by using the penalty technique

8.5 CRATERS ON EARTH

On Earth, tectonic processes and erosion determined degradation of old impact structures. Analysis of SAR, MODIS sensor and Landsat images showed a relevant complexity characterizing impact crater structure. Often, degradation factors as atmospheric and hydro-erosion and vegetable coverage make recognition (also by human intuit) a challenge. While on the surface of Mars and the Moon a simple classification with few patterns covers all typologies of craters of the planet, on the Earth an enumeration of all possible kind of craters is more complex.

In the following, we present same results obtained by applying the developed algorithm to images of impact craters on Earth. In particular we consider:

- Roter Kamm crater, Namibia, ERS SAR image (Figure 9 and Figure 10).
- Aarounga crater, Chad, ERS SAR image (Figure 11, Figure 12 and Figure 13).
- Talemzane crater, Algeria, Landsat image (Figure 14 and Figure 15).
- Deep Bay, Canada, MODIS data.(Figure 16 and Figure 17).



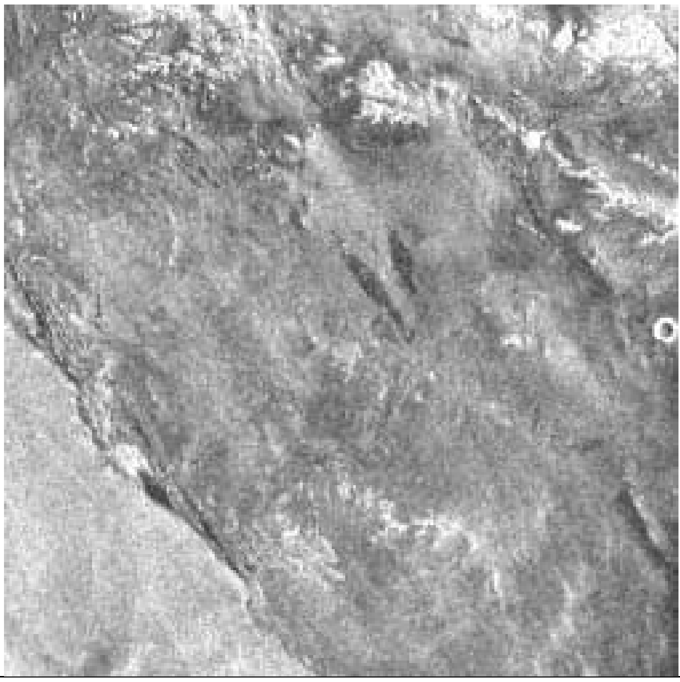


Figure 10 – The detection of Roter Kamm is highlighted by a circle

**Figure 11 –Aarounga crater, Chad.
Circular patterns can be observed.**

**Figure 12 – Aarounga crater (ERS SAR image).
The crater is visible on the top left of the image.**

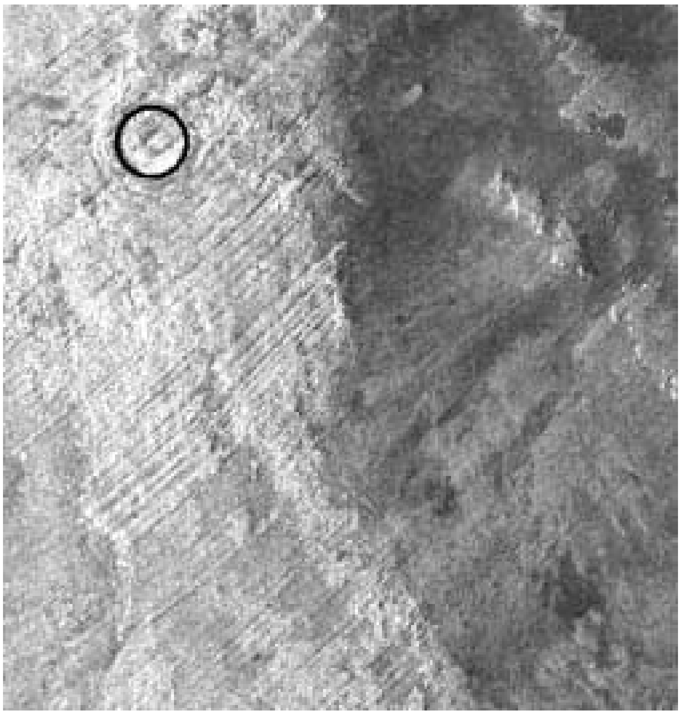


Figure 13 – The crater has been recognized without false alarms by exploiting the scaling technique.

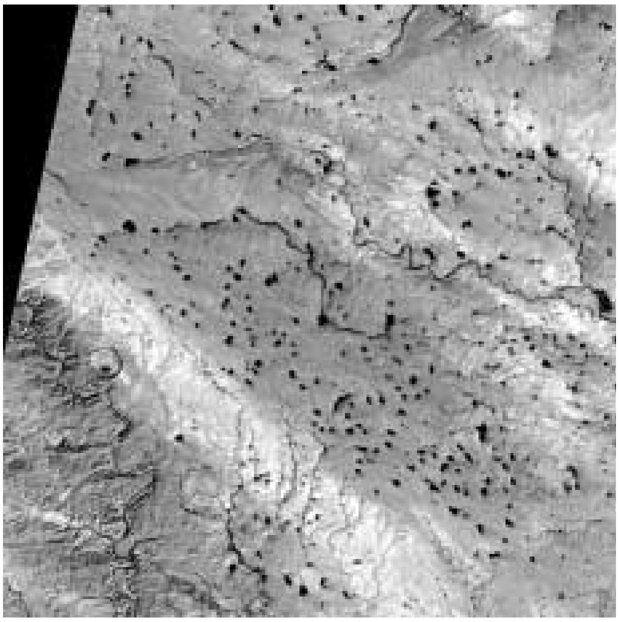


Figure 14 – Talemzane crater in Algeria (Landsat image). The crater is on the left.

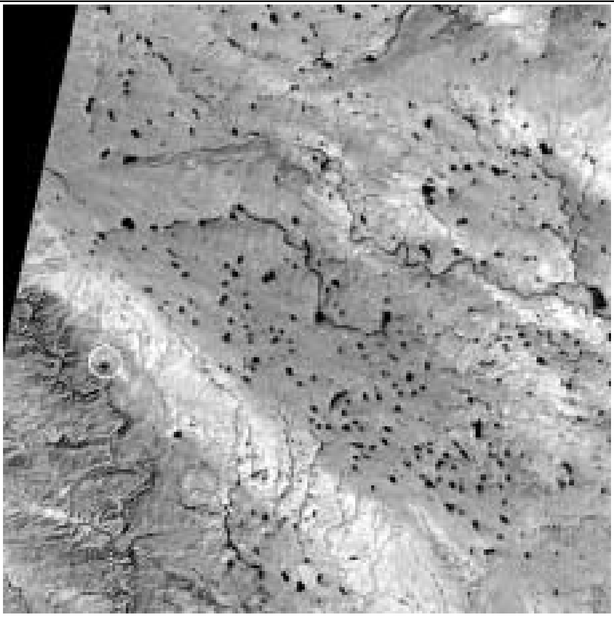


Figure 15 – The detection of the crater is highlighted by a circle

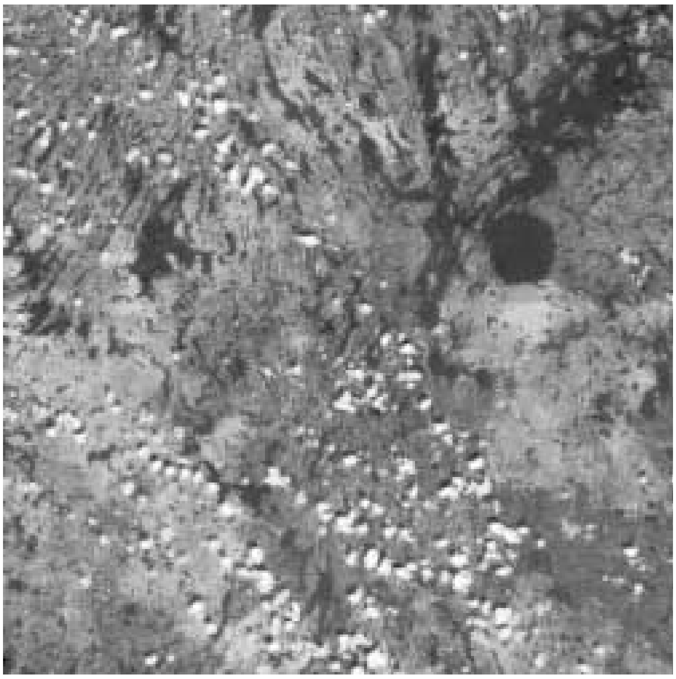


Figure 16 – Deep Bay in Canada (MODIS image). The crater on the top right of the image is now a lake.

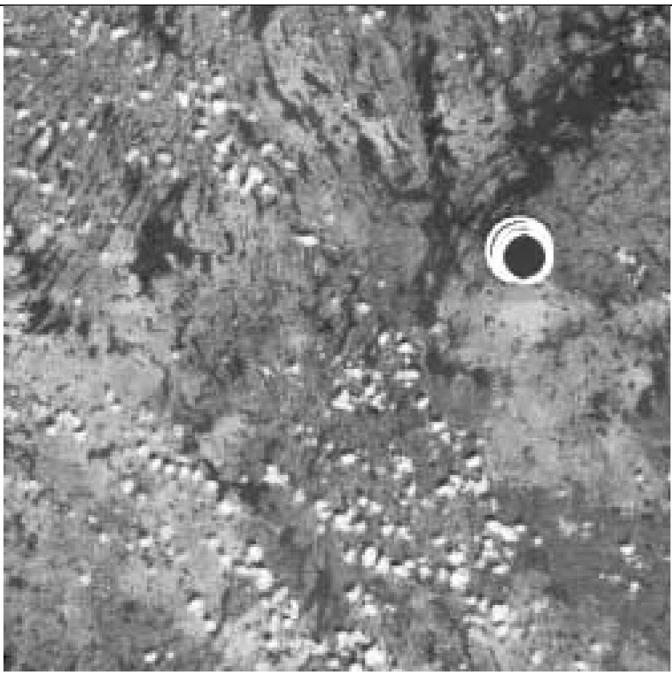


Figure 17 – The detection of the crater is highlighted by circles (multiple detection).

9 CONCLUSIONS AND POSSIBLE FUTURE WORK

The main achievements of the performed study can be summarized as follows:

- Programs and groups active in crater recognition in the world were identified.
- A critical analysis of the literature on automatic recognition techniques was performed.
- The Hough transform approach has resulted the more promising for recognition of objects like impact craters on Earth.
- A prototypal S/W implementing the Hough transform technique was implemented.
- Several tests on optical and SAR images, on Mars, the Moon and the Earth have been performed.
- Based on the tests, algorithmic improvements have been developed.
- The results are very promising, and let hope that a robust automatic recognition tool can be developed starting from the outcome of this study.

In order to outline open issues and possible further developments it is important to distinguish between two possible interpretations of a recognition tool, based on the following characteristics:

- The ability of recognizing automatically objects (craters) that are rather clearly visible: i.e., the ability of substituting an operator to examine a large amount of data.
- The ability of detecting object (craters) not revealed by a simple visual inspection.

In this study we have choosen the first interpretation, which is the "classical" one. The second interpretation of recognition, that could be better named detection, can be pursued by exploiting data from multiple sensors (data fusion), gravimetry for underwater craters, etc.

Both recognition and detection technologies are very important, and further studies should be done to develop these technologies. Recognition is the newest in remote sensing, but is becoming more and more important due to the larger and larger amount of data and computational power available. Besides scientific interest, application to craters is a good starting point for developing these technologies that can be generalized and used for other cases. In our opinion, possible short-term lines of action for future work are:

- Develop a robust crater recognition algorithm starting from the results of the performed study.
- Study possible aid for crater detection from the use of multi-source data (among which ENVISAT) and fusion techniques.

Moreover, other important possible future activities can be the following:

- Realization of a dedicated database of processed craters imaging.
- Development of algorithms and SW tools to recognize feature different from circular shapes can be considered.