QUANTITATIVE GEOMORPHOLOGIC STUDIES FROM SPACEBORNE PLATFORMS*

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Summary

The five spacecraft in the Landsat series, the first of which was launched on 23 July 1972, provided geomorphologists with their first access to a complete set of medium-resolution, multispectral images of most of the land and shallow-sea areas of the Earth. These revolutionary new data about our planet provide a valuable source of information on landforms and geomorphic processes to those scientists involved in comparative geomorphic studies of landforms on a global basis. One of the first geologists to take advantage of this new data source was Ed McKee and his colleagues in U.S. Geological Survey (USGS) Professional Paper 1052 (1979), entitled "A study of global sand seas." Another global study, entitled "Satellite image atlas of glaciers," in which Landsat images are the principal source of data, is in preparation by the author and more than 50 other scientists.

An important aspect of the Landsat image to geomorphologists is the fact that many areas of Earth now have multiple sets of coverage spanning a 13-year interval. For those geomorphic processes that produce areal changes resolvable on Landsat images, quantitative, two-dimensional measurements can be made. Sequential Landsat images have been used to determine the velocity of outlet glaciers, calculate changes in area of ice caps, delineate changes in areal extent of barrier beaches and islands following severe storms, determine the areal extent of new lava flows and deposits of tephra, and so on.

Although Landsat images of our planet represent a quantum improvement in the availability of a global image-data set for independent or comparative regional geomorphic studies of landforms, such images have several limitations which restrict their suitability for quantitative geomorphic investigations. The three most serious deficiencies are: (1) photogrammetric inaccuracies, (2) two-dimensional nature of the data, and (3) spatial resolution.

Landsat is not a mapping system in the strict sense, although Landsat images have been used to produce maps of many areas, either as a single image or as image-mosaic maps. Landsat image-maps significantly improve in our knowledge of poorly mapped regions. To serve as a true map, however, Landsat images must be related to the figure of the Earth, either by geometrically correcting the data or by fitting a recognized geomorphic grid to the data. Such a grid uses identifiable features on the image, whose geographic locations are known from independent geodetic surveys, for geometric and geographic control. Even with independent geodetic control, most Landsat image maps have inaccuracies in position of 100 m or more in well mapped areas and 1 km or more in poorly mapped areas. Although some geomorphological studies only require measurements of relative change, such as measurement of the fluctuation in termini of a glacier, many studies require precise geographic location (x,y or ϕ,λ).

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Most landforms have a unique three-dimensional character. However, Landsat images (and most other space images and photographs available to the scientific community) can only be used in geomorphic studies of a two-dimensional (x,y) nature, and then only in a relative sense because of a lack of precise geographic position. Future geomorphic studies of the Earth's subaerial landforms will require satellite data that can be analyzed stereoscopically. The third dimension, z, is the missing element in quantitative regional and global geomorphic studies.

The other limiting factor of Landsat images, and most other satellite images and photographs, is the inadequate spatial resolution for many types of geomorphic studies. The Landsat 1-5 multispectral scanner (MSS) and Landsat 1 and 2 return beam vidicon (RBV) images have a picture element (pixel) size of 79 m; the Landsat 3 RBV and Landsat 4 and 5 thematic mapper (TM) images have a pixel size of about 30 m. The standard photogrammetric definition of resolution is "the minimum distance between adjacent features, or the minimum size of a feature, which can be detected by remote sensing. For photography, this distance is usually expressed in lines (line pairs) per millimeter recorded on a particular film under specified conditions" (Manual of Photogrammetry, American Society of Photogrammetry, fourth edition, 1980). An approximate way to convert from pixel size to photographic resolution is to multiply the pixel dimension by 2.8; hence Landsat MSS and RBV (Landsat 1 and 2) images have a theoretical photographic resolution of 221 m; Landsat 3 RBV and Landsat 4 and 5 TM images have a resolution of 84 m. This means that only large landforms and geomorphic processes that produce significant change will be recorded on Landsat images. Unless a geomorphologist knows an area well through field work or analysis of large-scale aerial photographs s/he may not be aware, or even suspect, that important geomorphic features are present or that geomorphic processes have left their mark. Astrogeologists have a similar problem in their analysis of landforms on other planets and moons. My geomorphic studies of Icelandic volcanoes, for example, provide an insight into the problem. Of the 25 discrete types of subaerial volcanoes in Iceland, only 7 types of volcanoes can be unambiguously identified on Landsat MSS images. The other 18 are "missing", either because of the lack of stereoscopy (third dimension) or because of inadequate spatial resolution or a combination of both. Except in a gross sense, Landsat MSS images cannot be used to study Iceland's volcanoes. Although the increase in resolution of the Landsat 3 RBV image adds three more types of volcanoes, the combination of still inadequate spatial resolution and non-stereoscopic nature of the data still limits the usefulness of the Landsat image for such geomorphic studies. Ed McKee's research on sand seas was successful, because dunes or dune groups had areal and(or) linear dimensions large enough to be resolved spatially on the Landsat image. The third dimension was not that critical; the x-y geometric configuration of dunes and dune groups was more important. This is one of the reasons that we have been analyzing Landsat images of glaciers. Although the third dimension (z) is very important to glaciological studies, information on the x-y geometric configuration of ice sheets, ice caps, and tidal, valley, and outlet glaciers is also valuable. Measurements of area, changes in area, and fluctuations of glacier termini can also be determined from two-dimensional satellite images, such as Landsat.

To effectively carry out regional and global quantitative geomorphologic studies of the landforms of the Earth, it is necessary to develop specialized satellites which will carry optimum instrumentation. The two most important systems needed are: (1) an imaging instrument capable of acquiring photogrammetrically accurate stereoscopic images of the Earth's surface, with a ground resolution of $\leq$10 m per line pair, adequate for 1:50,000-scale topographic mapping (at a scale of 1:50,000), and (2) a laser altimeter capable of measuring elevation differences of ≤ 10 cm. Both satellite systems will need the type of positional accuracy achievable with the Global Positioning System (GPS) (projected to be a few meters in x, y, or z) and with accurate attitude control of the spacecraft achievable with stellar sensors. Both the stereoscopic imager and the laser altimeter need to be operated for at least 10 years to build up a basic global set of cloudfree data. After 10 years the stereoscopic imager should be operated repetitively to acquire new data sets for comparative studies of changes in landforms. The laser altimeter should also be operated after 10 years to support similar types of studies, such as studies of ground subsidence caused by groundwater withdrawal, ground subsidence or elevation caused by tectonic forces, inflation and deflation of volcanic calderas caused by intrusive and extrusive volcanic activity, changes in elevation of ice sheets and ice caps, and so on.

The new black-and-white, color, and color-infrared photographs from the Large Format Camera (LFC), which was flown in October 1984 on the Space Shuttle (STS Mission 41-G), provide superb examples to geomorphologists of the type of satellite data that can satisfy their needs. Frederick J. Doyle of the U.S. Geological Survey (written communication, 1985), stated that a stereo model of LFC photographs covers about 170 by 170 km with a ground resolution of < 10 m (high resolution black and white film) and has an internal photogrammetric precision of ≤ 5 m in x, y, and z coordinates. By orienting the stereo model to 3 or 4 ground control points (GCP's) an accuracy of about 8 m can be obtained in geographic position and terrain elevation. For comparison, the internal geometric accuracy of the thematic mapper (TM) image is 30 m, using about 20 GCP's. In future operations of the LFC with the Global Positioning System (GPS) and an electro-optical, stellar-attitude sensor, the stereo model would have the same internal accuracy, and the absolute position and elevation anywhere in the world could be determined with an accuracy of about 20 m without any GCP's. Although the LFC is capable of producing adequate image data, it is not likely to be flown on the Space Shuttle very often and also, because of orbital limitations of the Space Shuttle, coverage is not likely to be obtained on a systematic basis. What is needed is a dedicated free-flyer spacecraft, in near-polar orbit, to acquire global data on a systematic basis. Our experience with using Landsat images in glacier studies is that about 150 data sets (acquisition for about 10 years at 22 orbits per year over the same location) are necessary in some glacierized regions to obtain optimum, cloudfree images under the right seasonal conditions.

The U.S. Geological Survey has proposed a mapping satellite, Mapsat (also called the Orbital Mapping System (OMS) by the International Society for Photogrammetry and Remote Sensing, which has carefully studied and accepted the Mapsat concept), to acquire multispectral stereoscopic images of the Earth on a long term, systematic basis. With a stellar sensor for attitude control and the GPS for positional control, Mapsat or OMS would provide the needed image data. A NASA scientific panel has proposed a Laser Atmospheric Sounder and Altimeter (LASA) which would acquire the needed data on landform elevation. Unless LASA were carried on Mapsat or OMS, it, too, would need to be carried on a satellite with a good stellar sensor and use of GPS.

Both the stereoscopic images and the laser altimeter would provide important new sources of data to geomorphologists involved in landform studies. Stereoscopic images would provide the areal coverage and accurate x, y, and z geometry of landforms. The laser altimeter would provide detailed elevation information which, at $\leq$ 10 cm, would revolutionize comparative regional and global landform studies. Even our best topographic maps rarely show contours of 1 m and usually provide data ranging from 5- to 100-m contour intervals. Space data of this kind would permit not only the study of megageomorphology but would also be useful in microgeomorphological studies.