ENCYCLOPEDIA OF COMPUTER SCIENCE AND TECHNOLOGY

EXECUTIVE EDITORS

Jack Belzer Albert G. Holzman Allen Kent

VOLUME 8

Earth and Planetary Sciences to General Systems

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UNIVERSITY OF PITTSBURGH
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Earth and Planetary Sciences to General Systems

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EARTH AND PLANETARY SCIENCES

INTRODUCTION AND HISTORY

In one sense the earth and planetary sciences encompass all the fundamental sciences, i.e., mathematics, physics, chemistry, and biology. Thus computer usage in these sciences has been and is strongly linked to uses in earth and planetary sciences. The economic rewards of successfully solving many problems in this area have given a special push to extend both hardware and software to its limits. Many times this impetus exceeded that in the more fundamental fields above, because of the priorities involved. For example, the use of satellite-borne instrumentation to determine the nature of planetary surfaces and atmospheres has seen a hundredfold increase in the rate of digital encoding of analog data, its transmission, reception, and decoding here on Earth. This was a practical problem and the tremendous cost of space exploration dictated the most efficient means possible for obtaining and reporting findings from thousands or even millions of miles away. In the petroleum exploration field, great strides in signal processing were made as oil reserves became more and more difficult to find using seismic methods. Automated means of data acquisition, processing, and presentation became absolutely necessary as one considered ensembles of 500 or more channels, each channel containing several thousand data samples. In the early 1960s, special computers were designed just for this process alone as commercial hardware was not yet adequate to the task. In the 1970s, third generation computers now do much of the work, although special purpose processors remain to perform a significant fraction of the computation. Methods of factor analysis and the inversion of geophysical data require the inversion of very large matrices. These operations were impractical on first generation computers, but are now commonplace.

As the technology of data gathering increased, both men and computers were ready, and in many cases the computers themselves directly aided in increasing the technological abilities of men. Problems that were unthinkable in the 1940s are now routine. Not only are men now able to do routine jobs quickly, but new dimensions are facing them. It is now possible for computers to handle such large quantities of data that the limiting factor has become the cost of data collection. Today, in a world of finite resources, massive exploration strategies are being developed with the hope of making available a large proportion of the Earth's mineral wealth. As space flight becomes less costly, we see the development of orbiting observatories, and satellites designed to evaluate our resources. Much of the data from these sources will go through computer links, be processed by computers, and be displayed on computer-aided devices. In laboratories and in the field, small computers assist in the obtaining of data, freeing the scientist to make overall evaluations of large systematic data collections that were hitherto impractical to obtain.

As in many other fields, the explosive expansion of computer usage in earth and planetary sciences came as a result of many favorable factors coming together: technological development, a need, and the spreading of key personnel through the field. The development of radar in the early 1940s at the Massachusetts Institute of Technology's (M.I.T.) radiation laboratory brought together many of the best minds in the country for the priority implementation of a then-necessary military device. From this project came an order of magnitude increase in the capabilities of both component parts and newly invented circuitry. Although electronic computers were under development elsewhere, these new improvements in electronic technology were implemented in M.I.T.'s own computer Whirlwind (1947) as well as in others. Techniques in digital processing of radar signals were also being developed concurrently with the fundamental researches of Professor Norbert Weiner on the prediction of time series. The new technology was ready, the theory was ready; all that was necessary was someone to see its application to the earth sciences. This vision was fulfilled, with the formation of the Geophysical Analysis Group (GAG) at M.I.T. (1952) to solve problems in the digital processing of seismic data. This research was supported by a large number of petroleum companies who saw an opportunity to take advantage of the professional resources available at M.I.T. with the hope that the great strides made in radar technology might be repeated in this new field. Over its short lifetime (1952-1957), a large number of new methods and techniques were developed, but even more important was the spreading of its workers throughout the country to other universities, to industry, and to governmental research laboratories.

Concurrently with growth at M.I.T., the National Bureau of Standards Computer SWAC (1948) at the University of California at Los Angeles (UCLA) and somewhat later, the series of computers operated jointly by UCLA and IBM at the Western Data Processing Center provided resources for the newly formed Institute of Geophysics both at UCLA and at the Scripps Institute of Oceanography. At Columbia University the Watson Laboratory provided resources for scientists at the Lamont Laboratory of Geological Sciences. In England we find EDSAC associated with the geophysicists at the University of Cambridge, and in Israel, WEIZAC provided computational ability for a group of theoretical geophysicists there. As students at these centers received their Ph.D.'s they spread out, carrying the new methods and techniques with them into their new positions.

These early researches quickly saturated the time available for work that was not directly related to the primary goals of these early machines, most of which were funded to carry out a particular project. However, the results stimulated the appetites of many scientists for their own machines. The high cost of computing machines made their widespread use impractical in the early 1950s, and it is indeed fortunate that many of the early centers of digital computation were coincident with centers for the study of earth sciences. Toward the end of the 1950s, smaller machines (IBM 650, Bendix G-15) became available to research laboratories, and the larger machines (IBM 700 series) were being installed in university and industrial computation centers throughout the country. Large-scale computation was now possible at many places, and the decade of the 1960s saw the spread of the power of digital computation and the development of a large library of programs to do many tasks. Two major technological developments during this decade were the introduction of "third generation" computers of tremendous power, and of the development of a technique known as the Fast Fourier Transform (FFT) which reduced the time required for much digital data processing by one or more orders of magnitude. We shall say more about the FFT later. Likewise, during this same decade, funding received a stimulus because of the implementation of a large number of programs, particularly the International Geophysical Year, Project VELA for the detection of clandestine nuclear explosions, the Upper Mantle Project, and a suite of NASA space programs.

CURRENT USES

Signal Processing

The digital processing of signals takes up a large fraction of the computational time used in the earth and planetary sciences. Digital, rather than analog, recording of signals provides a significant improvement in dynamic range and a degree of flexibility in data treatment that is almost unlimited. Signals can be thought of as the changes in some characteristic measurement associated with the Earth itself (or some other planet), or as encoded information sent by a person or some device. In the first case, the variations in the Earth itself can give data that can be thought of as noise obscuring a smooth trend, or alternatively, a singular value may represent a departure from average values that may have economic importance. For example, material of high magnetic susceptibility is commonly found along with ore bodies, and a high magnetic reading is obtained as one passes over the body. Thus a departure from regional values of the Earth's magnetic field is often indicative of such an ore body. Another example is seen in the low values of gravity found when the surficial sedimentary rock layers are pierced by low-density salt. Such domal structures trap much of the world's supply of oil and gas. The second case is frequently encountered when one is attempting to relay measurements of a planetary surface over great distances. The weak signal is then often masked by the noise of the transmission medium and by errors in any of the measuring, encoding, transmitting, receiving, and decoding systems. The signal has to be extracted from the noise background and all errors corrected. Once decoded on Earth, the scientist may find that the data from his experiment could be improved significantly by further treatment. The aforementioned versatility of digital processing allows much experimentation in trying to get the most from the data.

Figure 1 shows some of the less complex operations that one can do on simple signals. The impulsive signal in Fig. 1(A) can represent a bit of information, or it can represent the presence of some item of geologic interest. One can see that such a pulse can be clearly differentiated from nearby similar pulses because it has a narrow width and it stands high above the background. It is thus advantageous to devise algorithms to change other commonly encountered waveforms into pulses that are as narrow as practicable. When noise is not a problem, it is possible to make an impulse from the rather broad diffuse signal as in Fig. 1(B) using a filter whose spectrum approximates the inverse of the spectrum of the diffuse signal. This deconvolution filter makes all the component frequencies in the output of equal amplitude and adjusts their phases so that they add in a narrow time interval and cancel elsewhere. These are just the spectral properties of the impulsive signal. If noise is a problem, this process must be modified somewhat, and a filter is constructed which reduces those component frequencies of the signal where the noise power is high. Again, one shifts the phases as much as possible to make the output narrow in time.

The dispersive signal of Fig. 1(C) can be treated in two ways. Such a signal is often found when seismic waves travel through the surface layers of the earth, or when electromagnetic waves travel through the ionosphere and magnetosphere. In such cases the velocity with which the component frequencies propagate gives us information about the transmitting medium, and thus we wish to determine these velocities. By passing the signal through several narrow band-pass filters covering

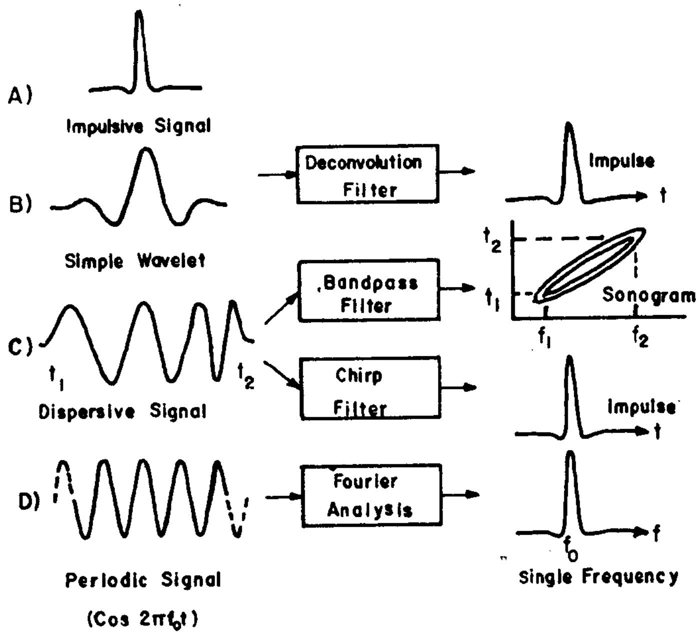

FIG. 1. Simple signals and digital processing. (A) An impulsive signal gives a maximum in resolution when it is very narrow and rises high above the noise level. (B) A broad rather diffuse pulse can be filtered in such a way as to bring all the energy together. This process is known as deconvolution. (C) A dispersive signal is one in which the component frequencies travel at different velocities. If processed through a multichannel bandpass filter, each component will show up at its appropriate time, while tracing out a figure called a sonogram. Alternatively, if the faster components are delayed by a chirp filter, the signal can be compressed into an impulse again. (D) A periodic signal has a very long duration in time composed of many cycles at its characteristic frequency f_0. Rather than compress such a signal, it can be resolved by Fourier analysis in the frequency domain where it appears as a rather sharp spectral peak.

the frequency range of interest, the time of passage of the maximum energy in each frequency band may be recorded. Drawing smooth curves through levels of equal energy as in the figure gives a sonogram presentation, or more accurately, a group velocity dispersion curve. Such curves may be compared with theoretical curves calculated from postulated models. This will be discussed in more detail later. The second way of processing a dispersive signal is again deconvolution. In this particular case the filter is relatively simple because only the phases of the signal need adjustment to collapse a signal containing many cycles into an impulse. Such a filter merely delays the more swiftly moving parts of the signal relative to the more slowly moving parts. This dispersive signal, or chirp, also has advantages in communicating information through a noisy channel. By spreading out the energy over many cycles, one can use transmitters of relatively less peak power to obtain a usable signal after deconvolution restores most of the received energy to a narrow time interval.

Carrying this idea to its limits, one can use periodic signals to spread the energy over many hundreds to many thousands of cycles. However, the compression of such a signal becomes more difficult. On the other hand, in the frequency domain this signal consists of just a single line spectrum. This impulse in the frequency domain (Fig. 1D) is just as unique as an impulse in the time domain, and may be used to extract a periodic signal from a noise level which is greater than the signal level. This is possible because the noise energy will be spread out over a band of frequencies and because the phases will be incoherent, i.e., have random values.

One sees that these simple operations, as well as more complex ones, involve the use of harmonic analysis (to get the spectral content of a time signal) and harmonic synthesis (to construct a time signal from a given spectrum). Prior to 1965 these operations were extremely costly in terms of computer usage, and many people were reluctant to treat massive amounts of digital data unless the priorities were very great. In that year, James Cooley and John Tukey [10] published a paper that brought in a new era in data processing. They gave the Fast Fourier Transform algorithm, that although known to a very few, was not in general use. This algorithm reduced the time necessary for the calculation of a harmonic analysis or synthesis from an amount proportional to N^2 (where N is the number of points in the digital representation of the signal) to an amount proportional to $N \log_2 N$. For a thousand points, this represented a savings of 100 in computation time, for larger N the savings are even greater. Despite this tremendous advantage, the scientific public had to be convinced of the algorithm's utility. In 1966, special sessions were called at several national scientific meetings to disseminate the advantages of this new algorithm. The IEEE journal Spectrum published two special articles in 1967 and 1969, while the IEEE professional group on Audio and Electroacoustics published two special issues in 1967 and 1969, all with the idea of getting this new algorithm accepted and used. In 1972 (and again in 1975), the IEEE Press (Rabiner and Rader [23], Oppenheim et al. [20]) gathered together many published papers on Digital Signal Processing for use by those concerned with the operations described above. Brigham [8] authored the first text devoted to the Fast Fourier Transform. One year later, two landmark monographs on digital signal processing were published; Oppenheim and Schafer [19] and Rabiner and Gold [22]. In many ways the decade following the introduction of the FFT algorithm is similar to the decade following 1955 when a few scientists educated the many to the tremendous power of digital computation.

Another area of signal processing is time series analysis. A description of the techniques employed is beyond the scope of this article. Standard harmonic analysis can determine the amplitude and phase of periodic signals. However, in the presence of noise, these computed values have considerable variation. The calculation of power spectra allows the computation of signal and noise properties plus statistical estimates on the variability of each. Details of harmonic analysis may be found in Melchior [17], and the techniques of power spectral methods may be found in Blackman and Tukey [6]. Applications of both methods as well as other aspects of signal processing in geophysics can be found in a monograph by Bäth [5]. A summary of terrestrial spectroscopy, the determination of the free periods of oscillation of the Earth during great earthquakes, is contained in Derr [12] where more or less conventional methods were used. A more sophisticated spectral analysis has been carried out by Mendiguren [18] who used data-enhancement techniques as well as harmonic analysis to bring out spectral peaks that could not be resolved by conventional methods.

Mapping and Data Presentation

One of the simplest and yet best labor-saving uses of computers is in the preparation of base maps for the display of data. In many cases a projection is required that is centered on some rather arbitrary spot, or standard Mercator and polar projections are not the right size, or they have distortions in the regions of interest. To prepare the proper maps takes considerable computation time, and once the new map points are calculated there follows a tremendous amount of hand labor by a draftsman. The computer and automatic graph plotters have changed all that. For example, a point-to-point world map that will give adequate resolution on a 10°× 10° area requires something like 100,000 data points stored on a magnetic tape. The data may be divided up into various subregions, continents, islands, political boundaries, etc., and all do not have to be retrieved for any given presentation. The programmer can choose his data groups, his projection point, and the type of projection. The computer will then prepare a new data tape which is subsequently plotted on a drum or flatbed plotter, in black and white or colors, with labels and coordinate lines if desired; all at the control of a few parameters in the software. If the resultant product is not correct, modifications can be made using rather reasonable amounts of computer time and a new map prepared without expending weeks or months of a draftsman's time. Such maps have been used to prepare charts of earthquake activity over various regions of the Earth's surface and to show the path of the Earth's magnetic pole over the last 500 million years. The quality of these maps is suitable for publication and yet they are relatively low in cost.

Another type of map that is largely produced by computer is a photographic map of the surface of some planetary body. The original optical image obtained by a satellite-borne television camera is scanned line by line, digitized, encoded, and sent back to a base station where it is received and processed. This process can take place over so short a distance as from an Earth-orbiting satellite or as far (in 1976) as the planet Jupiter. A special group of satellites has been designed to photograph the whole surface of the Earth at very high resolution, both in visible and in infrared light to improve our knowledge of the earth's surface. They are known as LANDSATs (formerly Earth Resources Technology Satellites—ERTS) and imagery taken by them now covers the whole United States as well as much of the world. LANDSAT imagery and information can be obtained from the EROS Data Center and auxiliary facilities at many locations in the United States. Other satellites photograph the Earth at lesser resolution to implement weather prediction and storm warning services.

Probably less useful, but far more spectacular, have been the photos of the surfaces of the Moon, Mercury, Venus, Mars, Jupiter, and a few asteroids. The computer has been invaluable in making this remote planetary imagery possible as we see in Fig. 2. This is a rather high resolution photo of the surface of Mars and has been selected to show how the use of the computer can tremendously improve the quality of the original received signal. In the upper photo, not much can be seen because of a lack of contrast. In the two lower photos, we have a stepwise improvement that shows much detail indiscernible in the upper one. Image enhancement is a large user of computer time in that each original photo is composed of tens to hundreds of thousands of dots, each of which must be processed and its intensity increased or decreased. Figure 3 shows an additional use of the computer. Once the information in each individual frame is enhanced, large numbers of them must

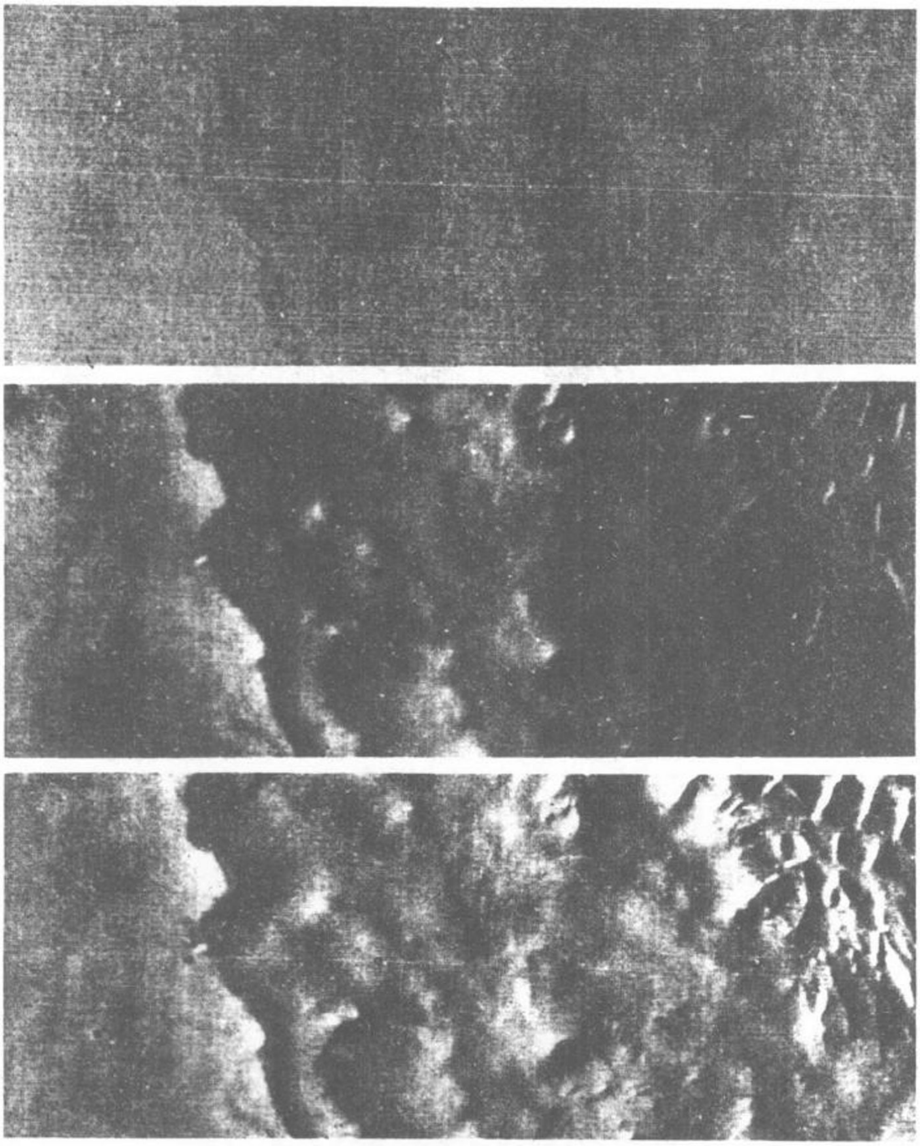

FIG. 2. Image enhancement. Each picture returned from the Mariner 9 mission to Mars was made up of 700 lines with 832 picture elements in each line. In the cropped pictures here, there are about 15,000 elements in each square marked by the calibration dots. The intensity of each element is given by a nine-bit number. In the original picture (top), few features are seen because the contrast is quite low. This is the expected "normal" picture. In the first level of processing (middle), small contrast differences are amplified. This gives a new picture with large differences in regional contrast level. In the second level of processing (bottom), the regional differences are suppressed while further amplification is made on local differences in contrast. About 5 min of computer time is required for each level of enhancement on the complete photo. The area shows a complex pattern of ridges near the Martian South Pole. The area is approximately 16 × 40 miles and was taken from an altitude of 1821 miles on February 12, 1972. (Courtesy Jet Propulsion Laboratory.)

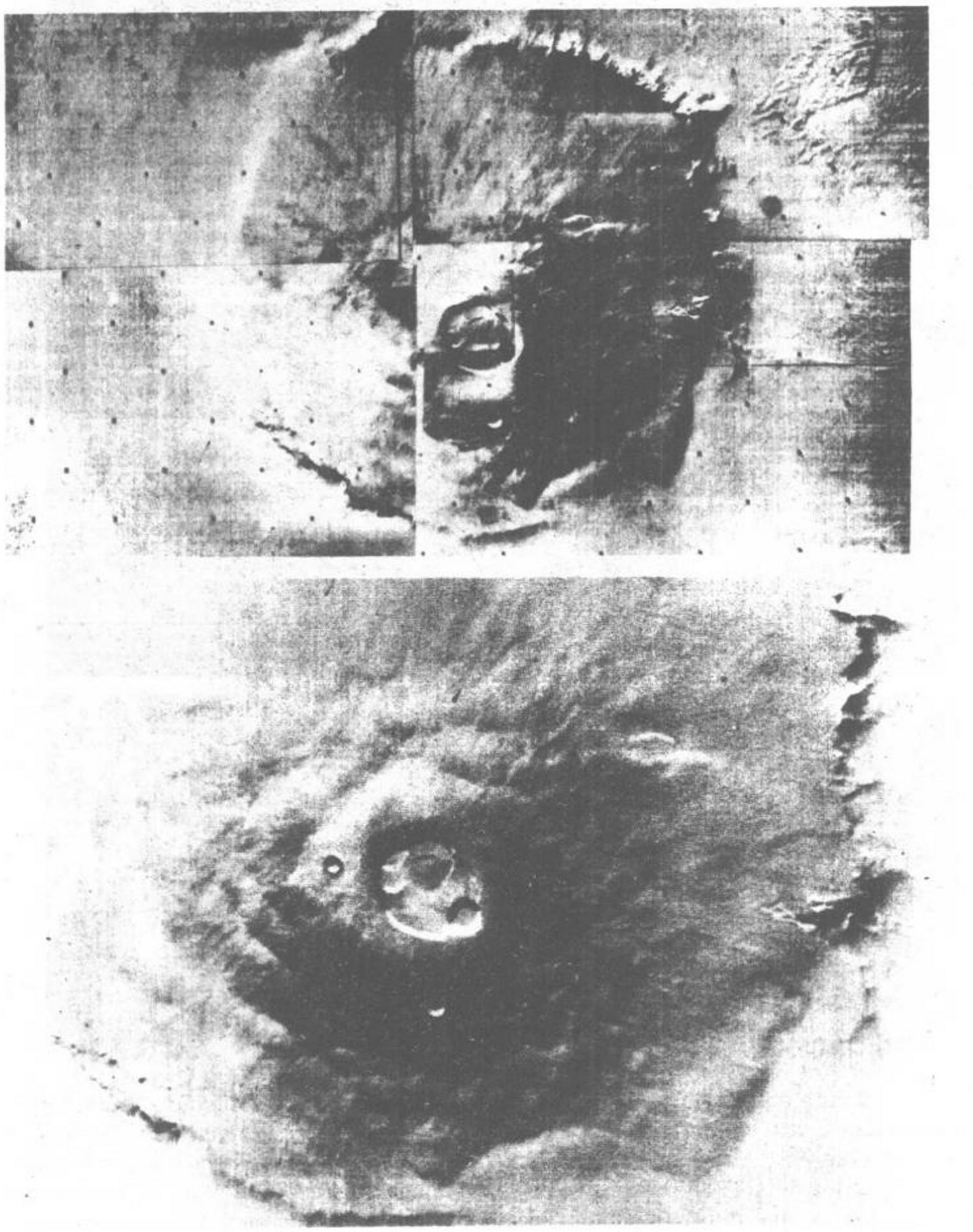

FIG. 3. Computer blending. In the upper photo, we see a mosaic image formed by five enhanced photos of portions of the Martian volcano Nix Olympica. In the lower photo, computer processing has eliminated the black calibration dots, the picture has been evenly toned, and the edges of the separate photos have been eliminated. Nix Olympica is three times as broad (372 miles) as the most massive volcanic pile on Earth. It stands 14. 2 miles above the surrounding plain. The photos were taken in late January 1972. (Courtesy Jet Propulsion Laboratory.)

be blended together to make a composite photo. Here relative difference in contrasts must be evened out, each dot of each frame must be projected into the proper position for the composite, and then the whole printed. In Fig. 3 we see the processing necessary to present the largest known volcano on the Martian surface, Nix Olympica. It is much larger than anything known on earth.

Planetary images are not restricted to visible light. Photos may be made in infrared, ultraviolet, and from Earth-based instrumentation such as radar. This latter method is very useful when clouds or dust obscure the planetary surfaces as observed in visible light. Figure 4 shows us a radar map of a portion of the southern hemisphere of the Moon. It has the resolution of earth-based photography and is not terribly different from a visible-light image. The image here has been produced from the intensity of the scattered radar signal using its Doppler frequency shifts and time delays to locate the geographic coordinates appropriate to a particular scattered signal. Alternative treatments of the data lead to elevation maps of considerable accuracy. Details may be found in Pettengill, Zisk, and Thompson [21]. Mapping of the surface of Venus is under way at the present time. This has been made necessary by the constant thick cloud cover over the planet. Figure 5 shows a surface texture much like that of the Moon, Mercury, or Mars in that it is covered with craters.

As well as imagery, satellites can map other properties of planets. Both gravity and magnetic fields have been mapped for the Moon and the Earth. An idea of the ultimate resolution can be obtained from the Earth where data are available from many tens of satellites. Marsh and Marsh [16] present a free air gravity anomaly map of order and degree 30 (corresponding to anomaly wavelengths of approximately 1000 miles). Ragan, Cain, and Davis [24] present magnetic anomaly data for the Earth between latitudes 50° north and south at a somewhat greater resolution.

Getting back to the Earth's surface, one can use high-flying aircraft to increase the resolution over small areas. High-speed aircraft can carry many instruments, such as magnetometers, infrared scanners, and gamma-ray detectors. Each flight line of the aircraft corresponds to one line of a total picture. However, where the raster lines in a television display are evenly spaced and parallel, the flight lines of the aircraft have small deviations that must be removed before the final presentation is made. This means that accurate position information must be obtained and correlated with each data point. Instrument readings and navigation data are recorded digitally every few seconds and processed later at a data processing center. Hundreds of line miles can be obtained in a few hours by modern high-speed jet aircraft. This method of data collection has replaced ground-based reconnaissance in most instances.

One instrument that has not been adapted to aircraft is the gravimeter. This instrument responds both to the force of gravity as well as to any accelerations of the platform on which it rests. Aircraft position information is presently not sufficiently accurate to remove the aircraft acceleration from the readings. Consequently most gravity readings are ground based and taken at irregularly spaced points which are easy to reach by vehicle or on foot. A regularly spaced grid is usually quite impractical because many points are quite inaccessible. This irregular grid of points requires the use of a computer to interpolate to a regularly spaced grid, which then may be used in a computerized contour plotting program to produce a gravity map such as Fig. 6. Once the regular grid of points has been calculated, additional operations may be done on the numerical data. It may be filtered in a number of different ways to smooth the data, to remove regional trends, or to

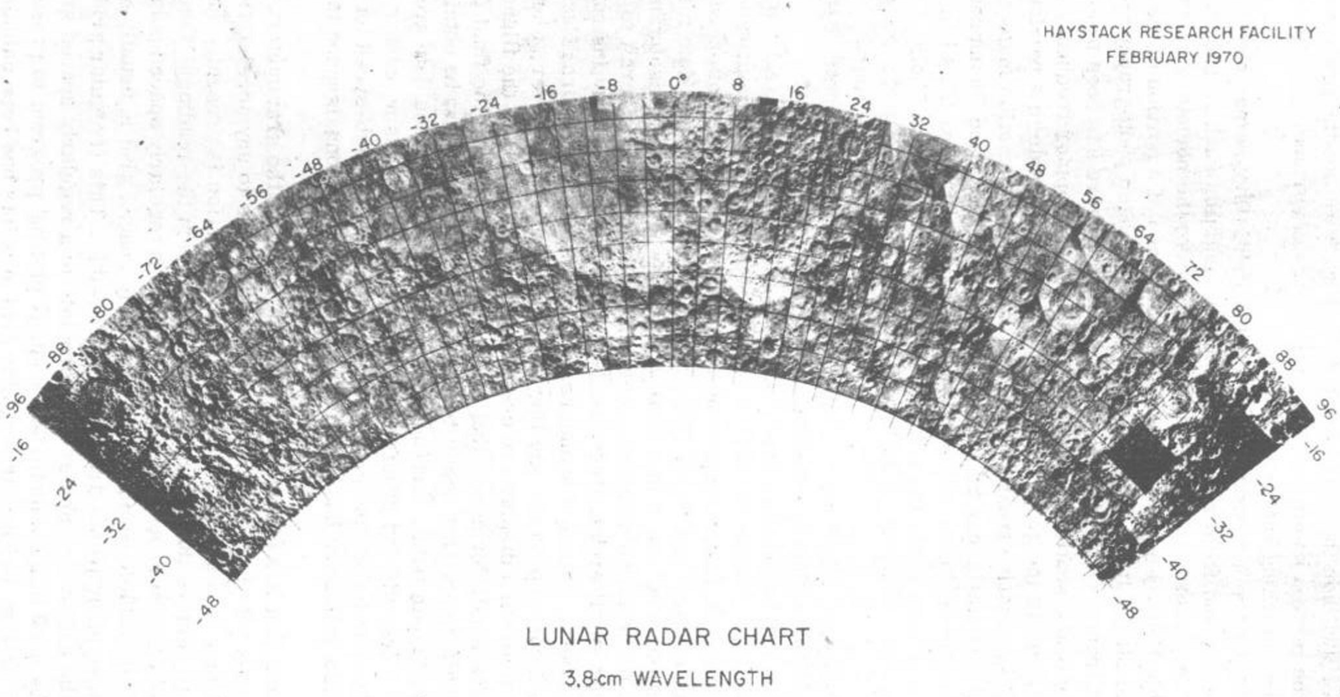

FIG. 4. Radar imagery. The map shown represents backscattered 3.8 cm radiation from the lunar surface. Using flight-time analysis for one coordinate and Doppler shift analysis for the other, this map gives almost photographic resolution (about 2 km). Note that near the edges the map is better than Earth-based photographs which have poor resolution in these regions. The concentric rings of Mare Orientale show quite clearly in the upper left portion of the figure but can be discerned only on careful inspection of visible light photos. (Courtesy Northeast Radio Observatory Corporation, Haystack Observatory.)

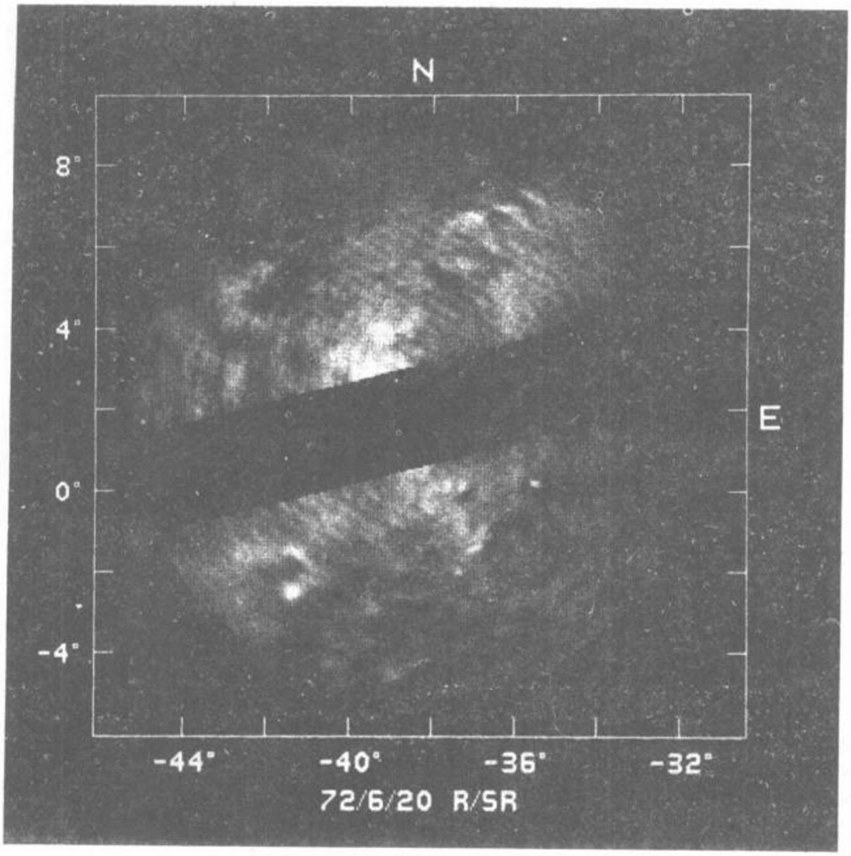

FIG. 5. Radar imagery. This photograph covers only a small portion of Venus' surface. Visible light pictures of the planet's surface are made impossible by the extremely dense clouds which cover the entire planet. Radar signals easily penetrate these clouds and are reflected back by the rocky surface of the planet. This portion of Venus, at least, is covered by craters. The largest seen is 100 miles across and 1500 ft deep; the smallest that can be resolved are about 20 miles across. The radar image was made on June 20, 1972. (Courtesy Jet Propulsion Laboratory.)