Techniques and applications of remote sensing

by

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Summary

"Remote sensing" has become a world-wide catch word for applying modern imaging techniques in traditional geo-science fields: aircraft and satellite images in the visible and more exotic portions of the electro-magnetic spectrum, computers to process these images and to employ artificial intelligence to draw conclusions automatically, and complex machinery to support the interpreting geo-scientist. The present paper will review history, present status and perspectives of remote sensing in general terms, addressing scanners, radar, satellite, image processing and some considerations of a photogrammetric nature.

Zusammenfassung

"Fernerkundung" ist heute der Inbegriff für Anwendung moderner Techniken in den traditionellen erdwissenschaften: Flugzeug- und Satellitenbilder im sichtbaren und in anderen, mehr exotischen Bereichen des elektromagnetischen Spektrums, Computer zur Bildverarbeitung und die Verwendung der Methoden der künstlichen Intelligenz zur automatischen Analyse, und schliesslich komplizierte Maschinerie zur Unterstützung des Geowissenschafters sind alle Inhalt der Fernerkundung. Die vorliegende Arbeit gibt eine Übersicht der Geschichte, des gegenwärtigen Standes und der zur erwartenden Entwicklung der Fernerkundung, wobei Abtaster, Radar, Satelliten, Bildverarbeitung und photogrammetrische Überlegungen behandelt werden.

[1/] The manuscript was prepared while the author was on leave at the Jet Propulsion Laboratory, Pasadena, USA.

1. Introduction

The term "remote sensing" was coined in the early 60's when a name had to be found for a symposium which was held in Ann Arbor, Michigan in 1962, and organized by the Willow Run Laboratories known today as the Environmental Research Institute of Michigan, or ERIM /Estes, Senger, 1974/. The symposium was held under the title "Remote Sensing of the Environment" and was designed to present to the U.S. geoscience community some of the technological advances that had been achieved during the previous decade under military sponsorship. The Ann Arbor Symposia have become an international tradition, and the words "remote sensing" went around the world /German, "Fernerkundung"; French, "Télédétéction"/. It designates, as is generally understood, the techniques of measuring properties of our environment's objects without touching them. As such, the concept includes photography, photogrammetry, imaging and non-imaging techniques. However, although one actually is interpreting the term at times as broadly as that, also one often limits the meaning of the word to describe imaging techniques essentially different from classical aerial black and white photography.

The techniques that make up remote sensing today are mostly scanning, radar and color photography, all taken from aircraft or spacecraft. The analysis of the images resulting from these techniques relies to some extent on the use of the laws of physics. However, this only holds to a limited extent. The physics used in the analysis is not very complex and is similar to that employed in interpreting black and white aerial photographs. The interaction between elctromagnetic energy and matter, although often not well-understood, does not seem to be as essential to image analysis than one may expect. Image interpretation relies very much on the same methodology as black and white photo-interpretation, i.e., on texture, lineaments, tones, and the visual and automatic location of tonal and textural anomalies. The human photo-interpreter has remained the central figure and his experience is the central asset in the use of remote sensing images.

Historically, remote sensing had its break-through with the launch of Earth-orbiting remote sensing satellites. The first such satellite was Landsat-1, launched in 1972. Previous civilian satellites with Earth observation equipment were devoted to meteorology; interestingly enough, remote sensing is often not perceived to include applications in meteorology.

The following chapters of the paper will address the main components of remote sensing; namely, scanning, radar satellites, computers, and then conclude with an outlook on the perspectives of remote sensing. References are limited to some recent developments. For extensive bibliographies one can certainly rely on works like the Manual of Remote Sensing /American Society of Photogrammetry, 1975/.

2. Scanning

2.1 Sensor:

The desire to increase the optical field of review without sacrificing image resolution, or to image at very large scales from aircraft, has led to panoramic and strip cameras /Figure 1./ Although these were scanning cameras, the term "scanning" only emerged with an imaging device capable of operating in the thermal range of the electromagnetic spectrum where photographic emulsions do not work. Instead of the emulsion one needs a detector that converts the incident radiation to electric analog signals. Since the detector produces a single output signal, an image must be composed by scanning a scene point-by-point, as shown in Figure 2.

The original purpose of the device was to create thermal images. The electric analog signals were recorded on film as seen in Figure 2b. However, one contemplated also to apply the technique in the visible range of the spectrum. Here the aim was to split light into its components and to record all components separately, not on film, but on magnetic tape /Figure 3/. This opened up entire new vistas on quantitative calibrated measurements of incident radiation in many spectral bands. It led to a break-through in automatic image analysis by subjecting the magnetic tape to rigorous computer processing. This will be further discussed in the chapter on image processing/computers. /Figure 3/

The scanning sensor images one point on the ground at a given time. By the rotation of a mirror or prism, points are sucessively integrated into a scan-line across the flight direction. Scan-lines, in turn, are integrated into a continuous image by the forward motion of the aircraft /or satellite/.

2.2 Resolution and Scale:

The resolution of scanners is often defined as spatial, spectral, intensity and temporal. Spatial resolution depends on the optics of the system which defines an instantaneous field of view /IFOV/, usually of about 1-2 milliradians from aircraft, and significantly better from spacecraft /Landsat: 0.09 milliradians/. Geometric resolution of scanners is thus not directly comparable to photographic resolution expressed in line-pairs/millimeter /lp/mm/. The IFOV of scanning defines a ground resolution element and picture element /also abbreviated to "pixel"/. This relates to line- pairs as follows: 2.8 pixels are required on the average to resolve one line-pair. This then helps to define a scale on film to present a scanner image If a film is available with n lp/mm, if "M" denotes a scale number and "d" is the diameter of a pixel on the ground in meters, we obtain:

$$M = d \cdot n \cdot 2\,800 \qquad /1/$$

A scanner image taken from a flight altitutde of 1000 m, with an IFOV of 1 mrad, produces a pixel diameter d of 1 m. With film used at a resolution of 20 lp/mm we obtain a reasonable recording scale of 1:M = 1:56 000. For the satellite Landsat scanner images, the pixel diameter is approximately d = 60 m. With film of 18 lp/mm this then leads to an image scale of 1:3,000,000. This is the scale at which Landsat images are being distributed.

Spectral resolution defines the range of spectral data that is presented on film. Technically, the amount of different spectral bands used for imaging is limited by the amount of data to be transmitted, recorded and analysed. Landsat has four bands, airborne scanners often have more -- up to 24 or so. This large number of spectral bands is available, mainly because airborne scanners are designed for experimental work and because no problems exist with the data transmission.

Intensity Resolution is defined in digital images by the number of grey levels that are recorded per spectral band. This is always 2^k, where k is 6,7 or 8 and describes the number of bits used to code the grey tones of the image pixel.

Temporal Resolution relates to the interval between imaging a given area again. With satellites this is a current notion, since in its orbit the satellite will repeat its position at regular intervals. The notion is less common with aircraft imaging.

2.3 Stereo scanning:

Images taken of one object from different positions, but with similar tones and textures, can generally be used for stereo observation and analysis. Aircraft stereo scanners have had a certain place in the minds of photogrammetrists. However, this has never played any role of significance. One concept is illustrated in Figure 4. Presently, however, the French space authorities are working to launch a satellite scanner, SPOT, with a stereo capability; and the U.S. National Aeronautics and Space Administration is contemplating a so-called Stereosat mission with stereo-scanning, whereby images are produced by looking forward and backward for stereo convergence. Height sensitivity can be as high as fractions of the pixel size: base-to-height ratios will be better than 1, and parallax differences can be measured with an error less than a pixel. Experiments are being performed at several institutions /MBB, 1979; G.D.T.A., 1979; JPL, 1979/.

2.4 Linear Detector Arrays:

Scanning was traditionally based on rotating a mirror, or prism, around an axis oriented along the flight direction. This scanning motion causes instability in a satellite, and results in very short exposure times per imaged point.

Recently, therefore, linear detector arrays have been implemented in aircraft scanners and are proposed for satellites. SPOT and StereoSat, and future Landsats will be equipped with detector arrays. This will eliminate the need for the cross-track scanning motion and increase the sensitivity of imaging considerably, because exposure times will increase /Photogrammetric Engenering, 1979/. The problem caused by different detector responses can be eliminated by appropriate calibration.

Detector arrays are presently not available for the thermal part of the electromagnetic spectrum. They will, however, become available in the future; encouraging developments are under way.

3. Radar Imaging

3.1 Sensor:

Electromagnetic distance measurements were developed between the two World Wars; from this emerged the circularly scanning Plan Position Indicator /PPI/ radar. The side-looking radar was developed during the 1950's; it operates as illustrated in Figure 5. An example of an image is shown in Figure 6.

An antenna is carried with the aircraft transmitting and receiving bursts of electro-magnetic energy. Each transmitted pulse illuminates a narrow strip of terrain to the side of the aircraft or satellite. Echoes are received and recorded via a cathode ray tube /CRT/. The echoes are resolved by the sequence in time of their arrival at the antenna. This mode of image formation is called "active sensing", or "echo-time imaging". It is called active because the terrain is illuminated much like in flash light photography.

Echo-time imaging is used because objects are resolved only if they are at different distances from the sensor so that the echoes are received at different times.

The image line produced by one pulse on the face of the CRT is integrated with many other lines to form a continuous image on film. About 2000 pulses may be transmitted and received per second in a typical aircraft operation. Recording on film is off the face of the CRT. The terrain is illuminated sequentially line after line through the forward motion of the aircraft.

3.2 Wavelength, Resolution:

The original purpose of radar imaging was to map areas through clouds and at night. The radiation used is of wavelengths of 0.8 cm up to perhaps 25 cm. These penetrate clouds, rain and fog, particularly at longer wave lengths. Longer wavelengths than 25 cm have been used, e.g., 2 meters on the Moon, but this interferes too much with radio frequencies to be usable for imaging on Earth.

The civilian applications, so far, were in cloud infested remote areas of the world, typically in all contries sharing the Amazon Basin, in Central America, Nigeria, Togo, Indonesia, Phillippines, Australia, USA, Canada, USSR and other countries.

The most common wavelengths are 0.8 cm /K-band/, 3 cm /X-band/ and 25 cm /L-band/. The band denominations are very common but are merely a relic from war when the military coded the frequencies to confuse the enemy. Today it serves electronics engineers to confuse geoscience users.

There are commonly two versions of radar sensors: real aperture radar /RAR/ and synthetic aperture radar/SAR/. With real aperture, ground resolution is defined by the shape of the transmitted pulse and deteriorates with distance of the object from the antenna. With synthetic aperture, the echoes are internally processed to form first a so-called signal-film. This is then further converted on the ground to form an image. This system provides resolution independent of distance to the object. Wether the SAR is placed in a low-flying aircraft or a satellite, the image will have the same resolution.

Radar systems have mostly ground resolutions of 10 to 30 m, some nonmilitary systems image with 3 m resolution. The theoretical limit is $\lambda/2$, where λ is wavelength, or L/2, where L is the antenna length. However, engineering constraints limit the actually achievable resolution to about $10 \cdot \lambda$, a value not achieved with most civilian radars.

A trade-off exists between resolution and swath-width: the higher the resolution the smaller is the swath covered by a system. Essentially, one can view a radar system as producing a constant number of resolution cells /at 10 m resolution, the swath may be 20 km wide, at 0.5 m the swath would reduce to 1 km/. In order to keep a wide swath one would have to increase the complexity of a radar considerably -- essentially by having multiple systems to cover adjacent swaths.

Another factor often overlooked when discussing radar resolution is the problem caused by diffraction of the highly coherent microwave pulses. As a result, synthetic aperture radar images may have a speckled appearance that creates an effect of reduced interpretability. To reduce this effect one can artificially form a new image at a lower resolution whereby neighboring pixels are grouped and averaged. This is referred to as "multiple-look" processing of SAR images. To interpret linear, man-made features, the speckle may be of lesser significance. For the study of tone and texture, however, the speckle may represent a hindrance. Speckle is not apparent in RAR images.

3.3 Satellite Radar:

Aircraft imaging radar systems are being manufactured in several countries. Satellite radar was available for geoscientists for the first time during the Apollo 17 mission of NASA to the Moon. An example of a radar image from that mission is shown in Figure 7. Since thenthere was the oceanographic satellite Seasat with a SAR system. An example of its imagery is shown in Figure 8.

Future satellite radar projects are planned with the NASA Space Shuttle /SIR-A/, with the European Spacelab, and for future free-flying satellites. An important element here is the study of arctic and antarctic ice, since cloud cover in these regions is heavy and illumination is non-existent during part of the winter.

3.4 Stereo:

With radar one can achieve stereo. Commonly one has either same-side or opposite-side stereo /Figure 9./

The same-side stereo can be more easily viewed because images are similar in tone and texture, while opposite-side radar suffers from drastically different appearances of the two images: illumination is from different directions, stereo fusion may not be possible in mountainous areas. An illustration of these problems is presented in Figure 10.

However, stereo is of great value to the geomorphological analysis of radar images and has been used in practice. A new impetus to fully exploit stereo radar may be provided through future satellite radars.

3.5 Sonar:

Underwater imaging with an analogon to radar can be achieved with a membrane made to transmit sound in water and to receive echos cast back from the ocean floor. Figure 11 shows an example of a sonar image. The membrane replaces the antenna of the radar, and sound replaces the electro-magnetic waves. The imaging geometry is identical.

4. Satellite projects

4.1 Status:

Landsat is the most widely known and used remote sensing satellite thus far. Presently there is already the third Landsat satellite in orbit. Landsat-3 originally had five spectral bands, whereas the satellites number 1 and 2 had only four /green, orange, red, near infrared/. The fifth band was a thermal channel /far infrared/; it did not, however, function properly and therefore did not have much impact.

In addition to the multi-spectral scanner there are two Return Beam Vidicon cameras /RBV/ on board of Landsat to create black and white images at a resolution of 30 m /pixel-diameter/. These data are coming slowly through the system and are not yet as widely available a Landsat-MSS images.

Another geo-science mission was Seasat which operated a SAR system and five other instruments. The imagery produced was of excellent quality: an example was presented in Figure 8. The satellite operated for several months, but became inactive due to a short-circuit unrelated to the radar system.

Thermal sensing was the purpose of NASA's Heat Capacity Mapping Mission /HCMM/, launched in 1977, to study thermal capacities of the Earth's surface by imaging it twice daily at a resolution of 500 m. The satellite is not active any more. The modelling and solution of the problem is difficult, and results are slow in coming out.

The many uses made of Landsat images have been reported in all professional geoscience journals, textbooks and special symposium proceedings. A rather significant effort was devoted to crop harvest forecasting. The large experiment to develop and test techniques was denoted as Large Area Crop Inventory Experiment, or LACIE. A final document on this partially successful effort has been compiled as a result of a LACIE symposium /LACIE, 1978/.

Apart from the free-flying unmanned satellites there are, or have been, manned missions, such as the U.S. Gemini, Apollo, Skylab, as well as the current Soviet Soyuz series; these missions mainly produced photography from space. This data has great experimental value. Coverage is however, only spotty and operational applications are thus far less common than with MSS data.

4.2 Planned Missions:

Numerous project plans exist on the drawing boards of national space agencies. Missions that are actually approved are small in number.

The main new effort in the Nasa and European Space Agency context relates to Space Shuttle and Space Lab. An approved project is SIR-A, the Space-Shuttle Imaging Radar, to fly on the second sortie of a total of six sorties of the Space Shuttle. It will be an L-band /25 cm wavelength/ SAR imaging device at look-angles less steep than those of Seasat, about 50° off-nadir. There is no other approved space imaging radar. A serious study concerns ICEX, a satellite to map sea-ice, using an X-band /3cm/ space radar. In Europe, a microwave instrument to operate alternately as scatterometer and as an imaging radar is planned for the Space Lab.

An approved project is the French SPOT satellite, to be launched in 1984, carrying an MSS sensor based on linear arrays, capable of a 10 m ground resolution /pixel size/ and of stereo. A U.S. Stereosat mission, also with linear arrays and for global stereo coverage, has not yet been approved but is seriously under consideration.

Metric camera photography will be taken in Spacelab flights by both European and U.S. groups. The approved project concerns a 30 cm focal length, 23 x 23 cm^2 format cameras without motion compensation. 60 cm focal length cameras with such compensation are being studied /G.D. T.A., 1978; Doyle, 1978/. These projects are merely experimental in nature since Space Shuttle and Spacelab missions initially are rather short. The U.S. is developing a Large Format Camera /f=30 cm, format is 23 x 46 cm^2/; its use in a particular mission seems not yet definite.

Satellite remote sensing will in the future probably develop around three concepts: the Space Shuttle and Spacelab, a Modular Multi-Mission Satellite /MMS/, and a Tracking and Data Relay System /TDRSS/, so that data go from the remote sensing satellite to a set of geostationary communications satellites from where the images are sent to Earth. This will permit much smaller and less expensive ground stations to be used.

4.3 Satellite Considerations:

Remote sensing satellites are designed in circular polar orbits to obtain global coverage under stable conditions, with an exact repetition of the orbit at every k days. The value of k for Landsat is 18. The sun angle at the time of imaging is critical for passive systems: the morning is preferred because cloud coverage may be less dense. Sun-synchronous orbits are desired since the sun angle would then be constant. These constraints have led to a satellite altitude of 900 km with an inclination of nearly 90^0. For manned missions, orbits are preferred in the vicinity of the equator and at lower altitudes. This is reflected in the choices of a 200 km altitude for the initial Space Shuttle missions. Manned missions are generally not well-suited for remote sensing: the crew has only very limited time for operation of the sensors, and missions are short in duration.

Geostationary satellites must have an altitude of about 36,000 km to have an orbit period of one day. However, although the constant position of the satellite over one point may be of interest for monitoring purposes, the altitude is too high to be of use for remote sensing.

5. Image Processing:

Image processing, particularly in digital computers, has enhanced the quantitative value of images considerably. Each pixel has a digital greyvalue: there are 8 bits per pixel and 256 levels. This is a large number of grey tones; for comparison, the eye can only discern about 10 to 30 grey levels in a chaotic mixture of image elements. Only on a grey wedge could one discern up to 1 to 2 percent grey tone differences. However, the question arises of the usefulness of a large number of grey tones. The sensor may be capable of collecting with great sensitivity, but nature often is not subtle enough to actually warrant this sensitivity.

The roots of digital processing of remote sensing images are in artificial intelligence and pattern recognition, where a tradition exists to work with grey tones and textures. In the remote sensing context two processing directions exist:

- Image pre-processing for subsequent analysis by the image interpreter;
- Image analysis, such as classification, etc.

Image processing is a topic whose extensive treatment is beyond the scope of this paper. However, for the sake of a short review, a list of image processing functions may be in order. We classify these techniques rather arbitrarily according to their application to single or multiple images:

Single Images:

Contrast manipulations /grey tone optimization/,
Image restoration /noise removal/,
Geometric and radiometric rectification,
Classification and feature extraction,
Data compression,
Data annotation.

Multiple Images:

Same techniques are applied as above to each individual image,
Image registration /match overlapping images for mosaicking or stereo/,
Data compression /make fewer images from many without losing information,
Data coding /e.g., color reproduction of MSS image/,
Image analysis /classification, change detection, pattern recognition/.

A typical example of what can be done with a single image is shown in Figure 12.

Elaborate image processing systems exist in the form of so-called black-boxes; these accept digital images on magnetic tapes and permit users to apply a multitude of image processing actions by merely pushing an appropriate button. These systems usually configured around a mini-computer /1 word has 16 bits/, color image displays and other output devices. Prices vary widely. An entire industry is developing in this area to digitize photographs, digitally process the image and read the modified picture onto film.

A more modest approach is the inclusion of several basic processing routines on a computer that is also used for other purposes, and to employ the line printer as an output device. This is sufficient where the image is not actually interpreted, but where output just codes simple results of pattern or feature recognition /Figure 13/.

6. Photogrammetric Considerations

Since they first became available, one has evaluated scanners, radar and space imagery also for their usefulness to produce maps. Radar has actually been employed for reconnaissance mapping at scale 1:200 000 or so; Landsat and space photography is being used at similar and even smaller scales where other sources of data on a region are unavailable.

Generally all mapping applications, or even studies, have relied on single images; stereo or block formation have so far not gone beyond an initial experimental exploration.

Figures 14 and 15 summarize mapping accuracies achieved with Landsat and with radar. The conclusion for Landsat can be that planimetric accuracies are in the range of one or half of a resolution element. Hight accuracies are much less: Welch /1977/ reports about several hundred meters, mainly due to the very unfavorable base-to-height ratio of Landsat. With radar, te accuracy strongly depends on density of ground control. Reasonably, aircraft radar in remote areas can lead to ±100 m planimetric mapping errors. Only in areas with rather high control density can one expect mapping errors down to about the resolution /1 point per 3 to 10 sq. km/. Similar conclusions apply to stereo radar, where experimental evidence is, however, much weaker.

Space photography has not been available in a systematic manner. The spotty coverage has been evaluated in both planimetry and height. Stereo base-to-height ratios have not been large and were in the range of 1:7 to 1:9. Height accuracies were about 0,3 to 0,4% of flight altitude, or ±180 m. Planimetric accuracy was ±40 to ±60 m with a resolution of about 60 lp/mm at scale 1:1 million. Still there were problems in identifying man-made features essential to succesful mapping /Leberl, 1978/.

7. Conclusion, Outlook

Photography is, and will remain for some time, the essential tool in remote sensing. Scales from aircraft can presently be about 1:200 000 /superwide angle camera, high flying aircraft/, where problems may only arise in the visibility and weather conditions. From space photographic scale has been 1:1 million, but will be about 1:300 000 if cameras with 60 cm focal length and at orbit altitudes of 200 km or so are available from Space Shuttle or Soyuz-type platforms. No new technologies need be developed to fully exploit space photography.

Radar will maintain a modest significance due to its all-weather, daynight capability. Radar images are presently not well understood: The extreme monochromatism of the radar sensor, the active mode of operation and the long wavelengths create image grey tones whose significance are not yet fully exploited. It is with uncalibrated images that one has to work, where emphasis is on linear elements in the image and on texture, not however on grey tone itself. Work is being done and needed to more fully appreciate look-angles, frequency, radar backscatter etc. as one expects today. Radar on satellites will be available in the future for geoscience tasks.

Multi-spectral sensing, such as with airborne or satellite scanners, is today a widely accepted tool for the study of man's natural environment. Airborne scanning essentially is a research tool, while operational use is made of satellite MSS. Its use is particularly wide-spread in developing countries and in North-America, much less in Europe, for example. The latter is the result of the coarse ground resolution of satellite MSS that makes it inappropriate for the finely structured agricultural patterns of Europe. However, resolution will drastically improve, e.g., in the French SPOT satellite, to about 10 m, and stereo will become available.

Presently, it is not clear how the scanning data, radar images and space photography will complement one another. But it seems that a particular role is available for each of these sensors, where scanning is designed to monitor rather rapidly changing area extended phenomena /agriculture, vegetation/, photography will be directed towards high resolution to monitor man's activities and to update maps, whereas radar may complement both scanning and photography, the first to add information on surface roughness and moisture, the latter to cover areas hidden by clouds or by the polar darkness.

One can safely state today that engineering has produced powerful hardware in the form of imaging devices that users are presently hard at work to learn to apply. The usefulness is immediate only there where traditional problems can be solved more easily than before. This applies essentially only in those areas of endeavor where previously no data were available at all, such as in remote areas of the world. Slowly the new tool will permit one to give answers to questions that in the past were not asked and not relevant. In the future, however, such questions will become increasingly of relevance in the effort to control man's impact on the environment and its wise exploration. It is for these new, emerging needs that remote sensing will be of greatest value.

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FIGURE CAPTIONS

Figure 1: Principle of /a/ panomaric and /b/ strip cameras.

Figure 2: /a/ Principle of scanning by platform and prism motion; /b/ Operation of the sensor; /c/ Example of a thermal scanner image of Ossiacher See, Austria. Note temperature anomalies along the path of ships on the lake surface; /d/ Color coded thermal image of Graz, Austria. The Mur river is easily identified in the image center. The dark areas are warm. The dark spot in the lower right /southeast/ corner is the Puch factory. The famous Grazer Schlossberg is the bright yellow area in the uper image center /Courtesy Asutroplan, Vienna/.

Figure 3: Principle of multispectral scanning with recording on magnetic tape.

Figure 4: Early concept for stereo scanning

Figure 5: Operation of side-looking radar

Figure 6: Example of a radar image taken of an Atlantic island with a synthetic aperture radar at 25 cm wavelength /Courtesy NASA-JPL, USA/

Figure 7: Example of a section of an Apollo 17 synthetic aperture radar image of a lunar feature. Wavelength 2 m, orbit at 116 km altitude /Courtesy NASA-JPL, USA/

Figure 8: Seasat-SAR image, 25 cm wavelength, of Los Angeles, USA. About 30 m resolution digital correlation of the signal data to form an image.

Figure 9: Typical stereo arrangements for radar

Figure 10: Example of a radar stereo model in opposite side stereo. Area in Arizona, USA /Courtesy Aero Service-Goodyear, USA/

Figure 11: Example of an underwater soun image made with sonar in the Pacific coastal waters of California /Courtesy NASA-JPL, USA/

Figure 12: Example of performing image processing steps with a single thermal image: /a/ original; /b/ noise removal; /c/ geometric rectification; /d/ radimetric rectification. Red. Mountain, Arizona, USA.

Figure 13: Line printer output of a simple image processing result: /a/ image; /b/ lake from the image. /Landsat channel 7 image of the areas around Lake Walchen, FRG/

Figure 14: Planimetric errors using Landsat MSS imagery

Figure 15: Planimetric errors using block of radar imagery

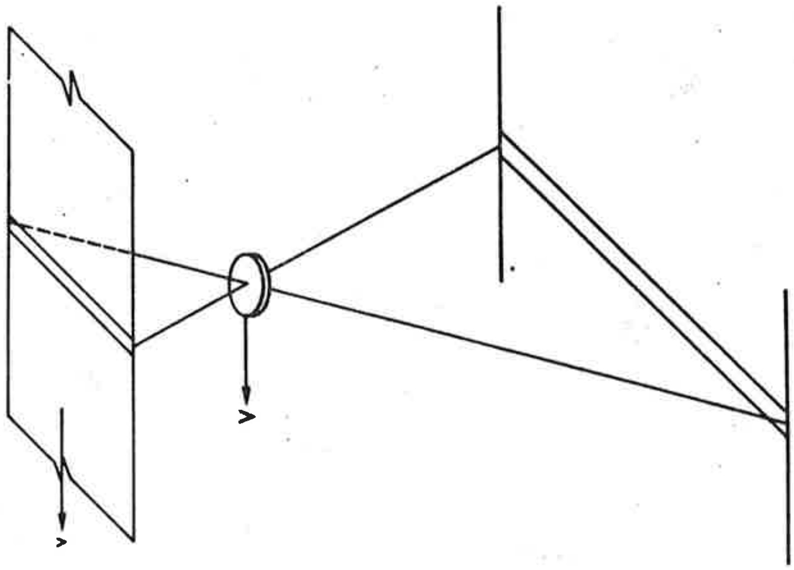


Fig. 1

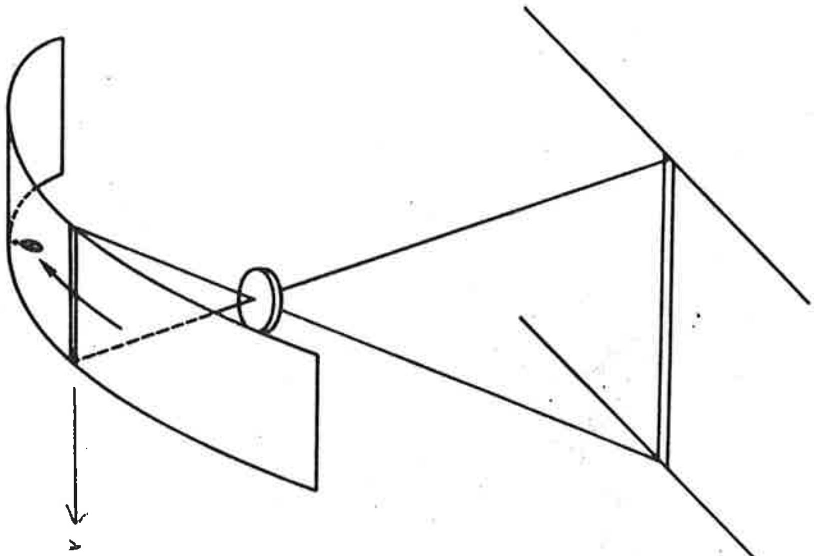


Fig. 1

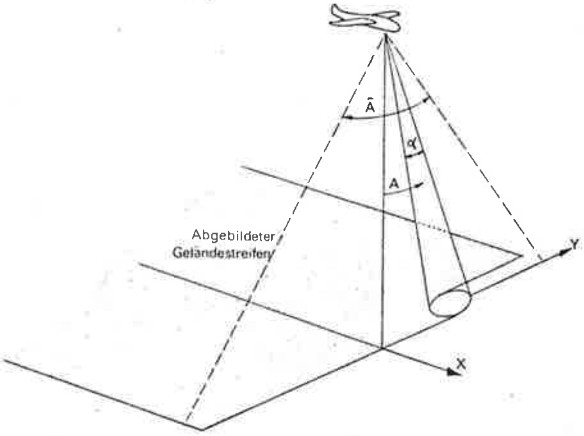


Fig. 2 /a/

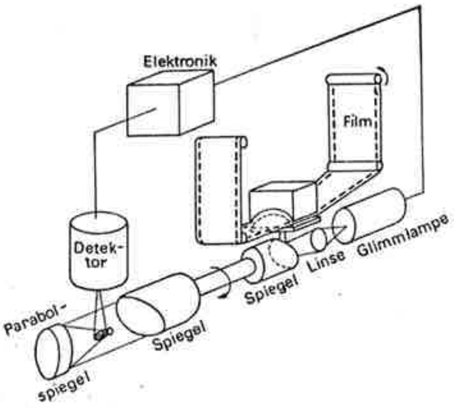
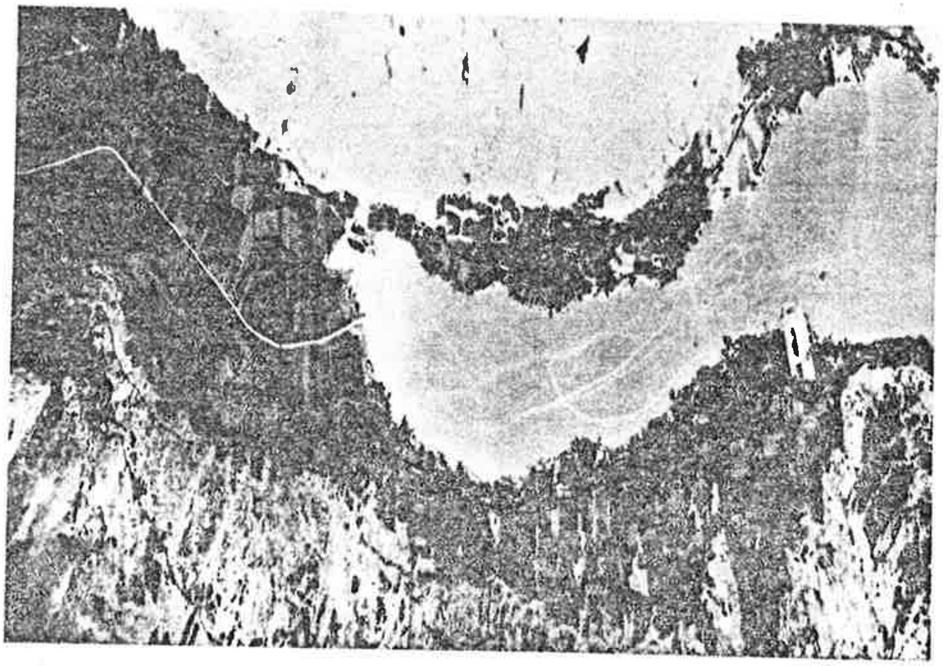


Fig. 2 /b/



←

Flight direction

Fig. 2 /c/

Flight direction /North/

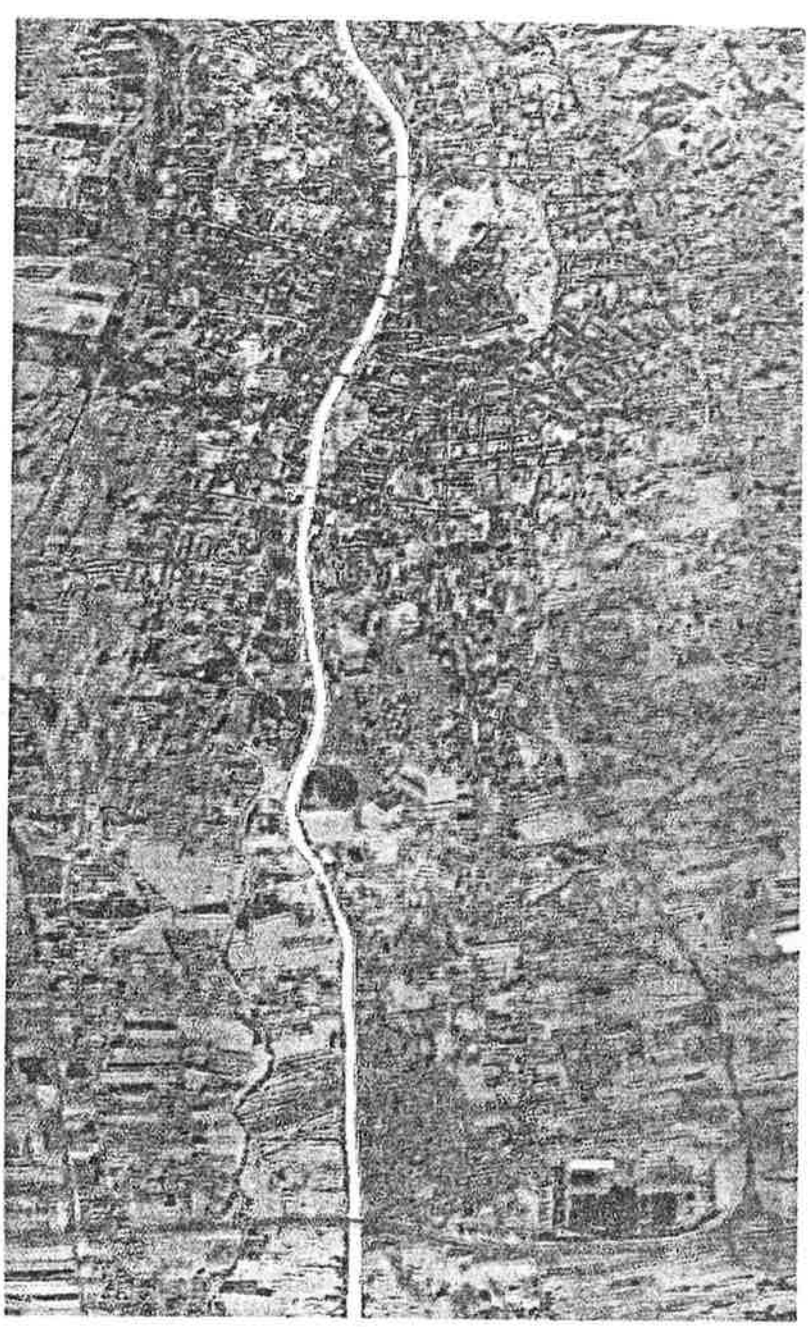


Fig. 2 /d/

South

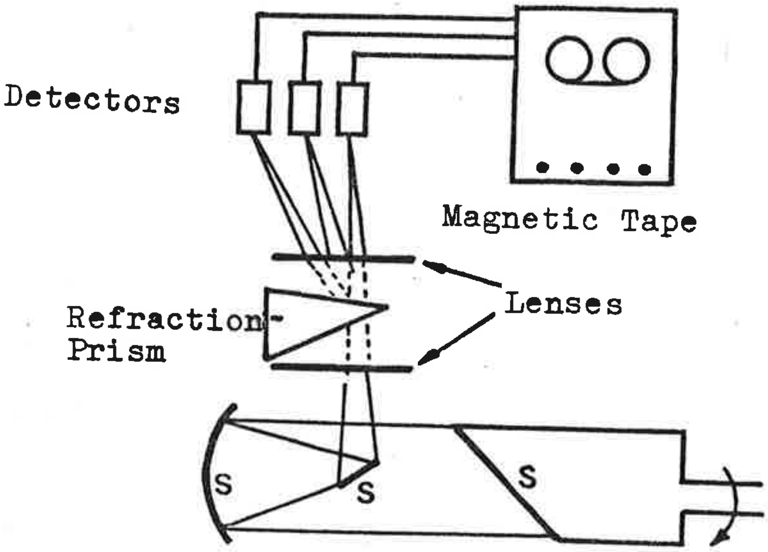


Fig. 3

s = Mirror

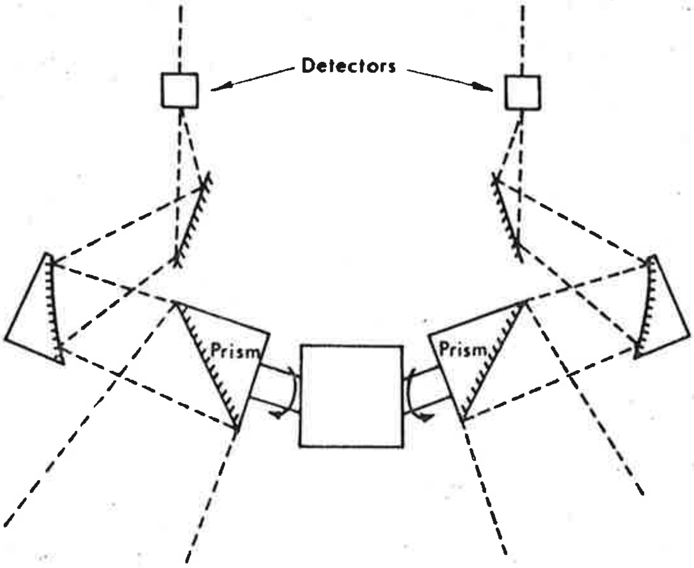


Fig. 4

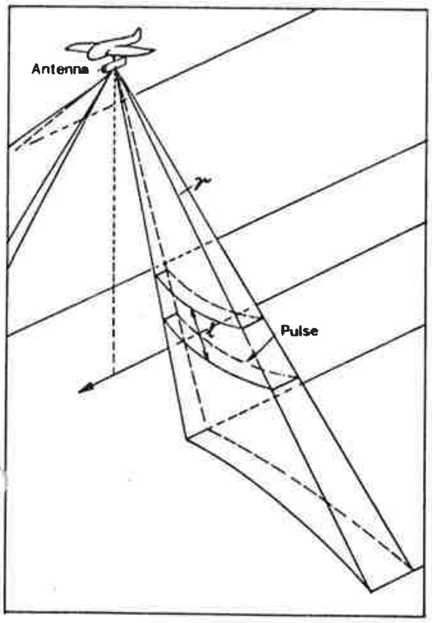

Antenna
Pulse

Fig. 5 /a/

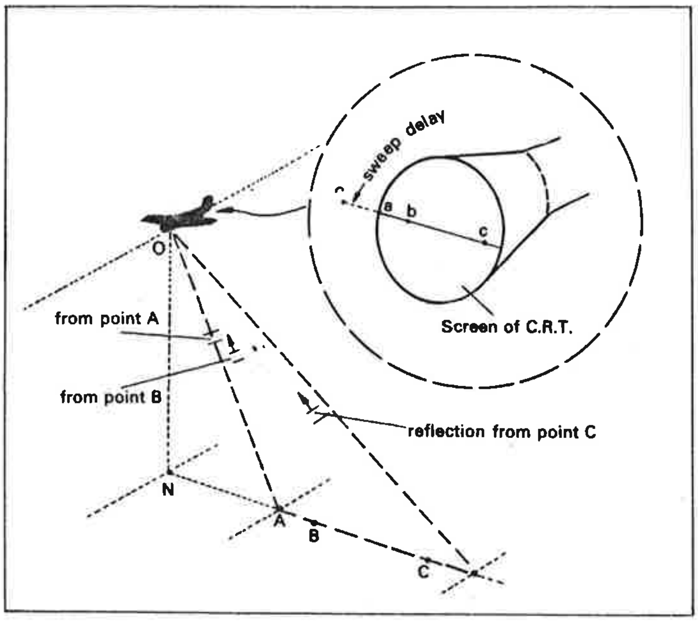
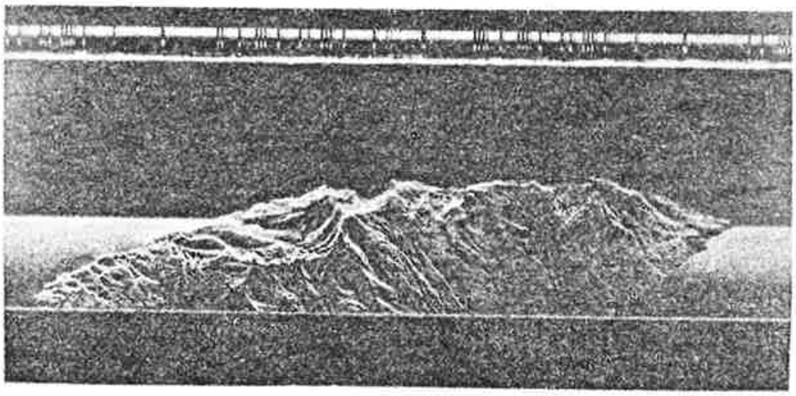
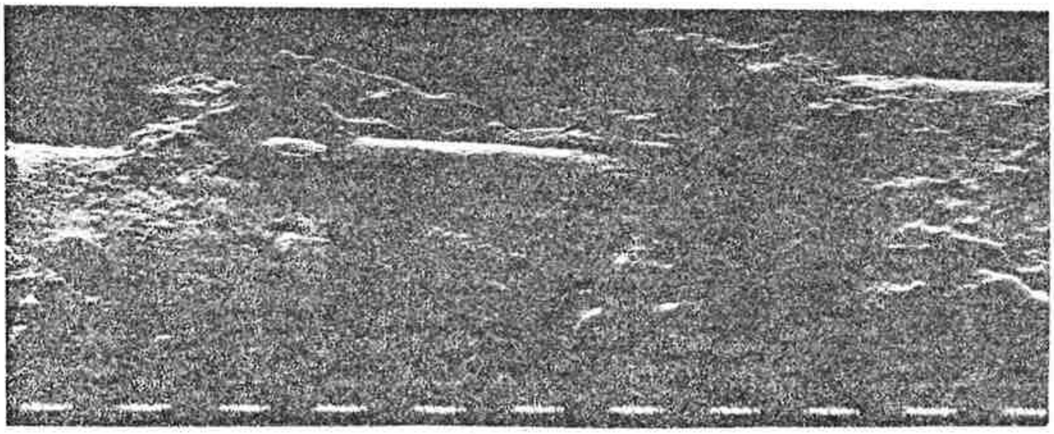

sweep delay
a
b
c
Screen of C.R.T.
O
from point A
from point B
reflection from point C
N
A
B
C

Fig. 5 /b/





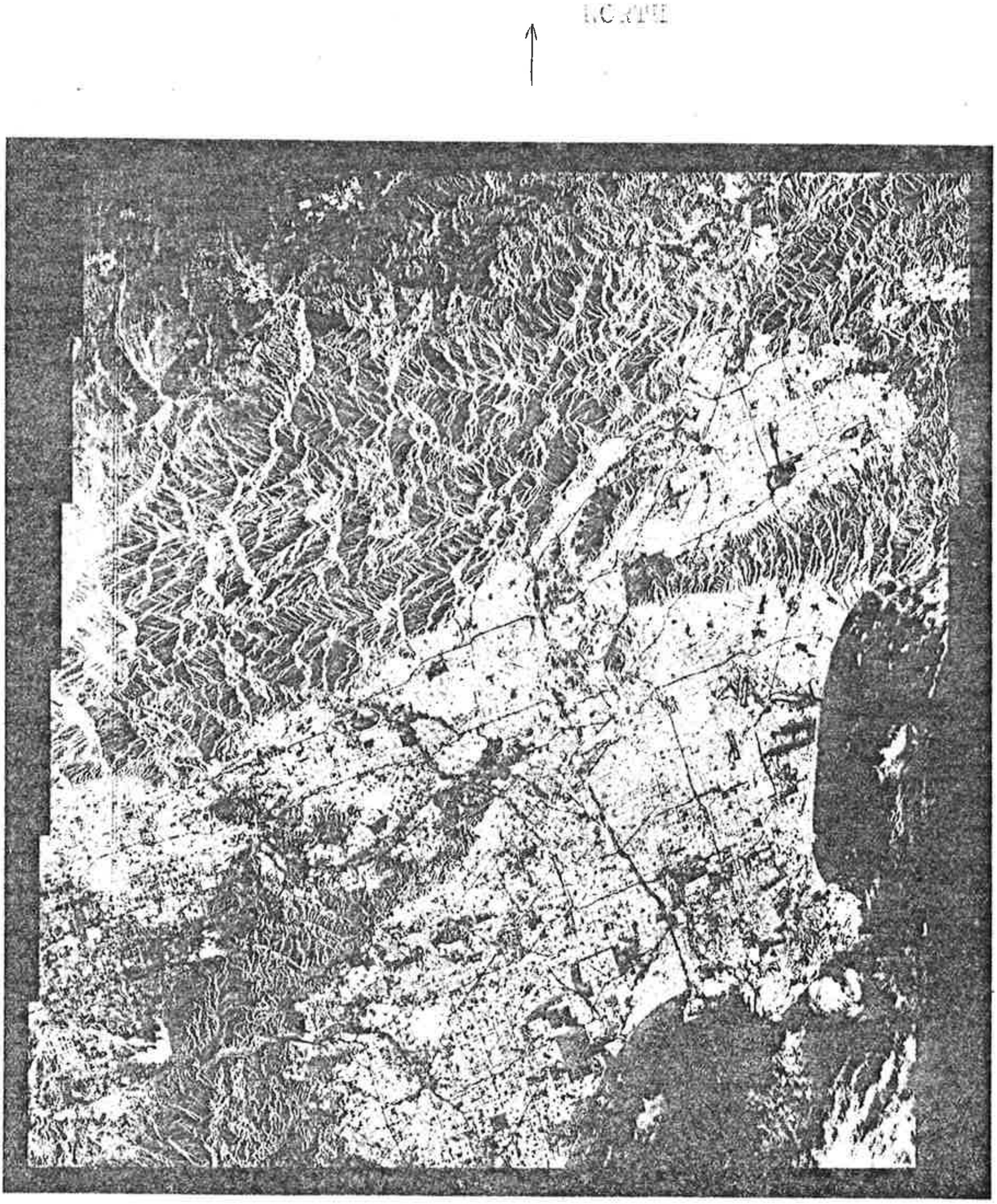
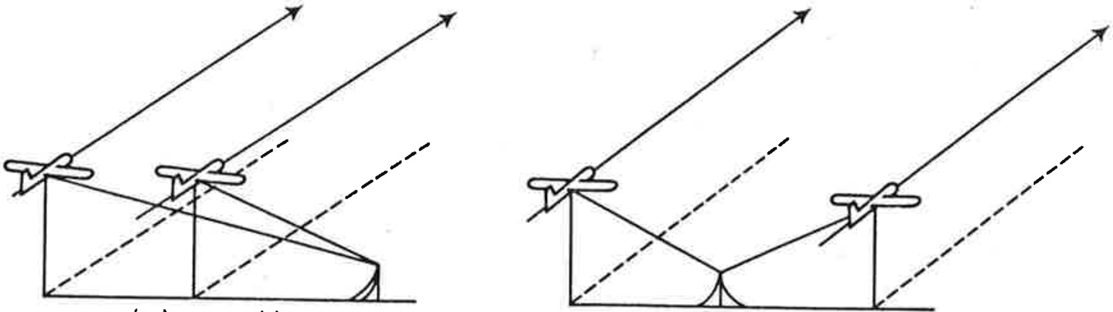


Fig.



(a) same side

(b) opposite side

Fig. 9

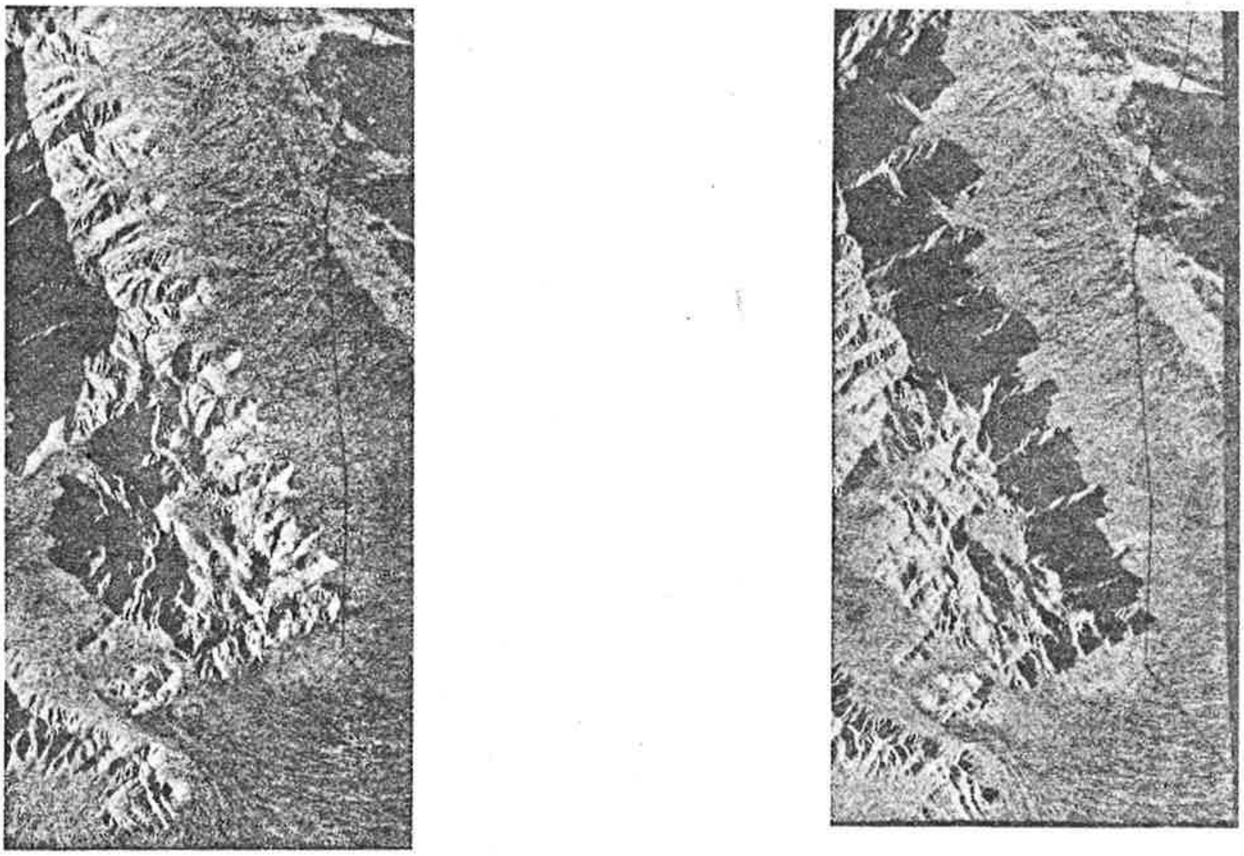


Fig. 10

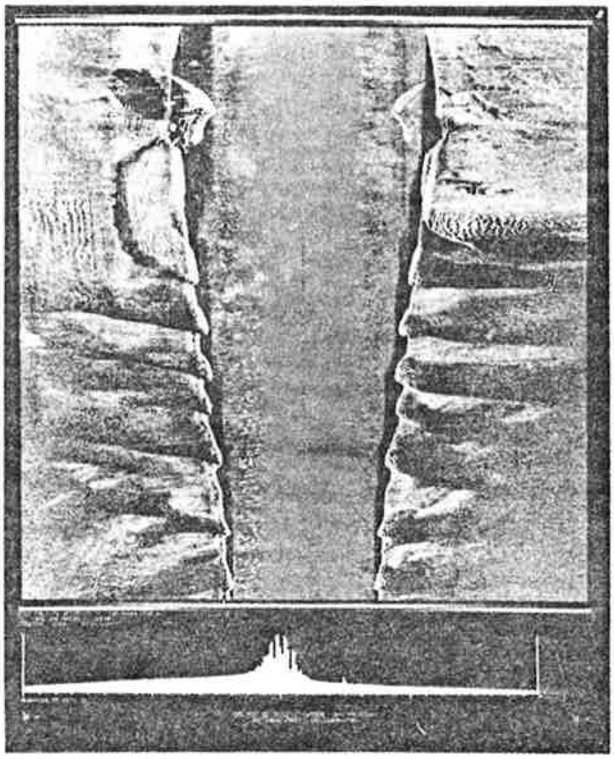


Fig. 11

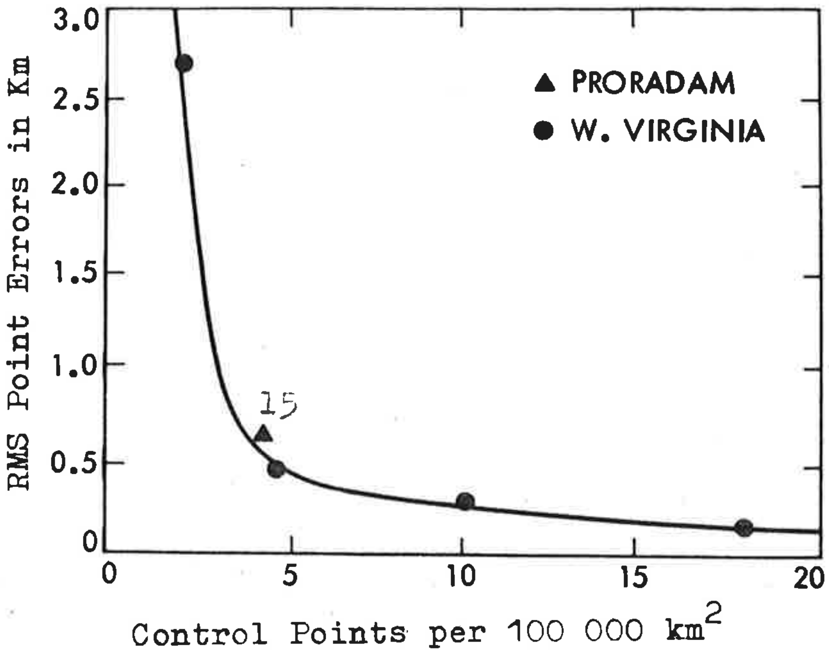

3.0
2.5
2.0
1.5
1.0
0.5
0
RMS Point Errors in Km
▲ PRORADAM
● W. VIRGINIA
15
0
5
10
15
20
Control Points per 100 000 km^2

Fig. 15