

Flight Planning and Navigation for Thermal-IR Surveys

Advance planning and the VLF navigation system solve the problems flying IR imagery mosaics at night.

INTRODUCTION

MANY REPORTS have demonstrated the application of airborne thermal-IR imagery to a wide variety of disciplines. Workers in different fields have become interested in acquiring IR imagery to evaluate its potential for their specialty. Little has been published to aid people who are not remote sensing specialists in the acquisition of suitable imagery.

Most published reports on IR imagery are based on one or two flight lines over known target areas which may be repeated at different times of the day. These reports pro-

cessing imagery have improved the capability for obtaining imagery mosaics.

The purpose of this report is to summarize our experience in planning and conducting IR surveys. It is hoped that other workers will be encouraged to improve these methods and report their results.

FLIGHT PLANNING

GENERAL

Planning an IR-imagery flight program for mosaic coverage requires decisions on time of day, flight line orientation, and altitude. These decisions will be influenced by the

ABSTRACT: Charts of image scale and lateral coverage as related to aircraft elevation practical guide for planning thermal-IR imagery mosaic flights. Examples of imagery flown at different altitudes demonstrate that spatial resolution decreases with increasing altitude, but contrast does not appear to decrease. For detection of linear geologic features, flight lines should be oriented so that scan-line direction is not parallel with these features. For most purposes imagery is flown at night when conventional navigation methods are difficult at best for mosaic patterns. Experience shows that the newly developed very low frequency (VLF) navigation system is well suited for this purpose. The VLF system should also be applicable to aerial, geophysical and photographic surveys.

vide valuable interpretation keys and a justification for employing thermal-IR imagery in reconnaissance surveys of large areas. The usual end product of reconnaissance surveys is a mosaic of parallel imagery strips with sufficient sidelap for matching adjacent strips. Planning and conduct of mosaic flights is more complex than flying single lines. Williams and Ory (1967) and Stingelin (1969) made useful recommendations for flying mosaics. Additional flying experience and the development of new navigation methods and equipment for recording and

objective of the survey. For example, the imagery requirements for a regional geothermal survey differ from those for a detailed mapping of limestone and dolomite outcrops. The flight plan elements described in the following sections should be applicable to most surveys.

TIME OF DAY

Nighttime imagery is preferable or necessary for almost all applications because the effects of differential solar heating and shadowing are eliminated. On daytime imag-

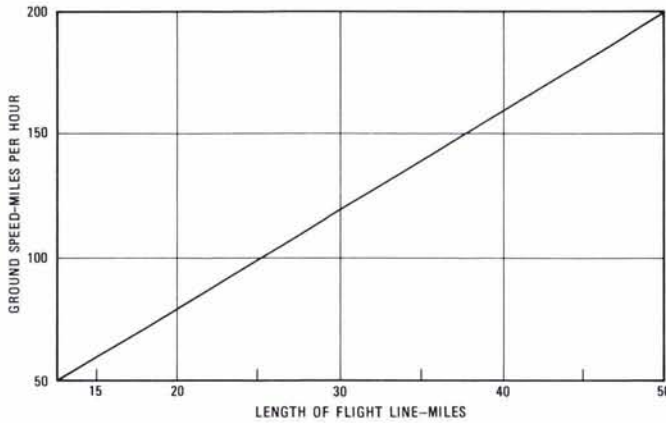


FIG. 1. Maximum flight-line lengths for standard 15-minute recording tape.

ery, topography is the dominant expression because of differential solar heating.

Imagery flown at different times of day in New York state is illustrated by Stingelin (1969, Figure 1) who concludes that nighttime imagery is superior to daytime imagery for most applications. In the Arbuckle Mountains of Oklahoma, Rowan and others (1970) conclude that predawn imagery is most useful in distinguishing rock types and for mapping fault or fracture zones. Daytime imagery of the Arbuckle Mountains displays much stratigraphic and structural detail, largely because of topographic expression. Wolfe (1971) compared day and night imagery of the Carrizo Plains, California and noted that topography dominated the daytime imagery. Differences in rock type are more apparent on the nighttime imagery, although Wolfe (1971, p. 51) emphasizes that the IR signatures are largely controlled by properties of surface debris, not bedrock.

Maximum thermal contrasts generally occur near sunset but the radiant temperatures change as the night progresses. The most stable radiant temperatures occur in the predawn hours. If a number of parallel lines are to be flown, more uniform results are obtained from predawn flights. Local weather conditions, such as early morning ground fog, must be considered in flight planning.

Flying mosaic patterns at night introduces navigation problems which are discussed in the navigation section of this report.

FLIGHT-LINE ORIENTATION

Topography and safety factors may dictate flight-line orientation, particularly for night flights at lower altitudes. Where a choice is possible, the optimum orientation may pro-

duce better results. For geologic projects the regional strike or structural grain of the area may be known in advance. If the flight lines are oriented normal to the regional strike, the scan-line pattern will be parallel with the strike and may mask linear features. It is preferable to orient the flight lines parallel with the regional strike or at an acute angle.

FLIGHT LINE LENGTH

The length of flight lines depends upon the dimensions of the survey area. Much imagery is now recorded on magnetic tape and the recording time per tape determines the maximum line length. One widely used IR-scanner system records on magnetic tape with a 15-minute recording time. Figure 1 shows the maximum line lengths as a function of aircraft ground speed. For example, at 180 mph, the maximum line length is 45 miles. The pilot, who should be involved in all flight planning, can provide an estimate of aircraft speed for the flight altitude. After allowing for possible headwinds, the line length can be estimated from Figure 1.

ALTITUDE

Flight altitude controls image scale and lateral ground coverage on either side of the flight track. Flight altitude is meaningful only where it is expressed as elevation above average terrain and this notation is used in the accompanying imagery examples and charts. The selection of a flight elevation is a tradeoff or compromise. On one hand the interpreter usually wants the highest resolution and largest scale to facilitate his work. On the other hand, budget considerations press for smaller-scale imagery in order to reduce the number of lines and hours of flying.

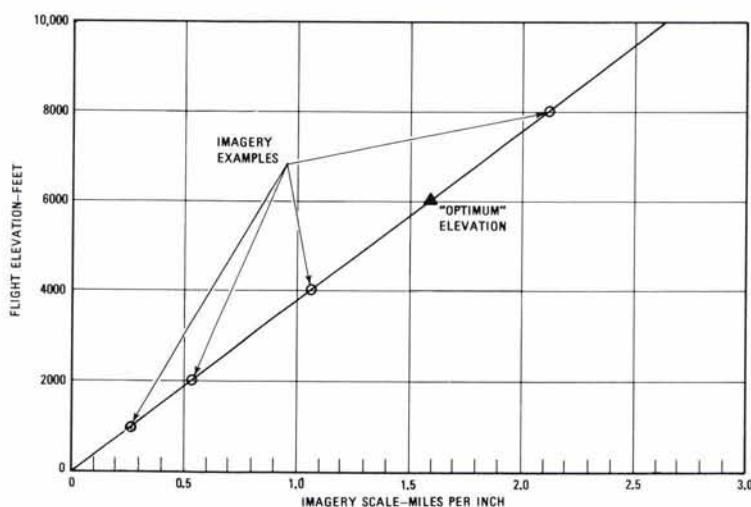


FIG. 2. Imagery scale related to flight elevation above terrain. This is for rectilinearized imagery with 120° scan-angle printed on 70-mm film. See Figure 3 for imagery examples.

IMAGE SCALE

The chart on Figure 2 shows imagery scale as a function of flight elevation above terrain. The chart applies to rectilinearized imagery with 120° scan angle printed on 70-mm film. Rectilinearized imagery has been processed to correct the marginal distortion inherent in scanner imagery. A chart similar to Figure 2 could be computed for non-rectilinearized imagery by calculating the average scale for the central 80° or 90° of scan angle. The highly compressed outer margins of non-rectilinearized imagery are not used in compiling mosaics. Figure 2 can also be adapted for scanners with narrow fields of view and for imagery printed on films other than 70-mm size.

To illustrate imagery at different scales, the same flight line was repeated at four different altitudes and samples are shown on Figure 3. The original image scales for these altitudes are shown by the circles on Figure 2. For comparison, the same ground area is outlined on each image and measures 0.5 miles wide by 2 miles long. For geologic reconnaissance we have found that imagery flown at 6,000 ft above terrain with a scale of 1 inch to 1.6 miles is generally optimum. This is not advocated as a standard elevation for all imagery, but 6,000 ft is a good trade-off among the many factors that must be considered.

Ground Coverage and Flight Line Spacing. Ground coverage at right angles to the flight path is also related to flight elevation above terrain, as shown on Figure 4

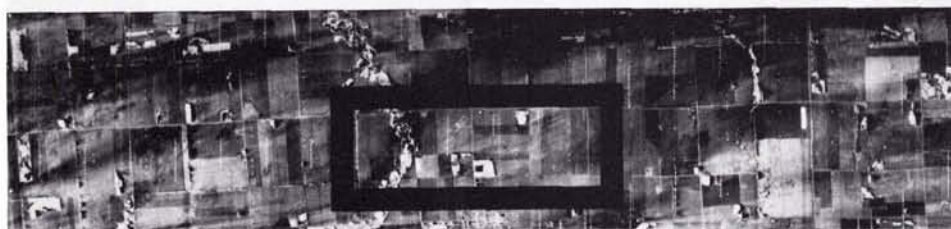
which is calculated for a 120° scan angle. Lateral coverage is the same whether or not the imagery is rectilinearized; the main difference is that with rectilinearized imagery the marginal areas are undistorted and may be used for interpretation. The examples on Figure 3 illustrate lateral coverage at different altitudes. The optimum elevation of 6,000 ft above terrain produces imagery which covers a ground swath 4 miles wide, or 2 miles on either side of the flight path. By spacing the flight lines 3 miles apart, 1 mile of sidelap is obtained for adjacent strips of imagery. This allows a margin of error for the inevitable navigation problems at night and also covers the project area without flying an excessive number of lines.

INFORMATION CONTENT

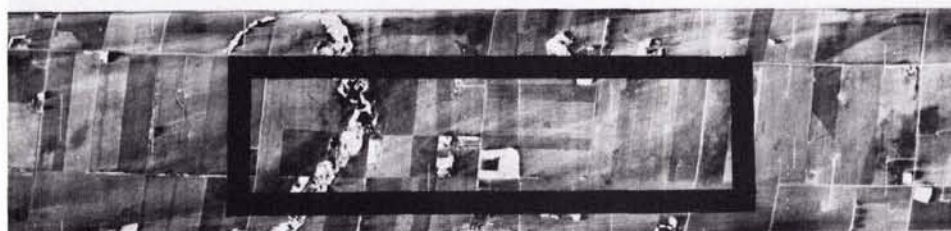
Image quality is often expressed in terms of resolution which is the minimum separation between two objects for which the images appear distinct and separate. In IR scanners resolution is determined by spot size of the detector element and typically is on the order of 3 to 5 milliradians. At a distance of 1,000 ft, one milliradian amounts to one foot of separation. For example, a 3-milliradian detector at 2,000 ft above terrain produces imagery with resolution of 6 ft along the center line. Resolution becomes lower (poorer) toward the margins of the imagery because the greater slant distance results in a larger spot size. Rosenberg (1971, p. 1255) pointed out that resolution alone is not a valid measure of the quality or



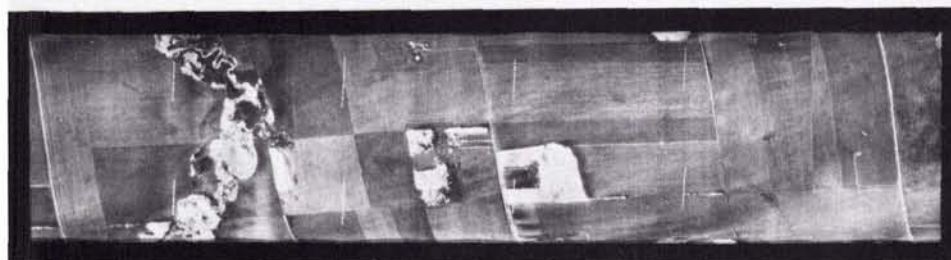
A. 8000 FT ABOVE TERRAIN



B. 4000 FT ABOVE TERRAIN



C. 2000 FT ABOVE TERRAIN



D. 1000 FT ABOVE TERRAIN

FIG. 3. Flight line repeated at four different altitudes to illustrate relationship to image scale. The same area is outlined in black on all images and is 0.5 miles wide by 2 miles long. Eight to 14 μm nighttime imagery.

useful information content of imagery and that *detectability* and *recognizability* must also be taken into account. Our experience tends to confirm this for the ability to detect a geologic anomaly is more related to imagery contrast than to spatial resolution.

Horvath and others (1970, Figure 7-f) evaluated thermal IR imagery flown at five alti-

tudes from 2,000 to 10,000 ft and noted that image contrast did not vary significantly with altitude nor is there any apparent level shift. Changes in apparent target radiance can easily be compensated for in an optical-mechanical scanner because of the electrical form of the signals (Horvath and others, 1970, p. 213). Our imagery examples of Fig-

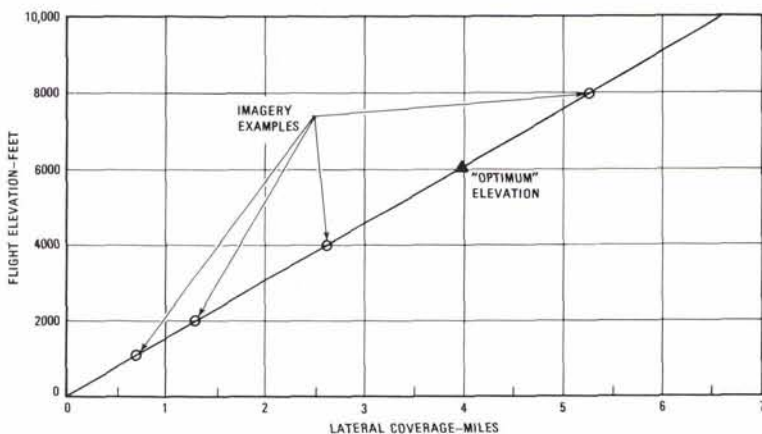


FIG. 4. Lateral coverage of imagery related to flight elevation above terrain. This is for imagery with 120° scan angle. See Figure 3 for imagery examples.

ure 3 agree with these observations because there is no significant contrast change with altitude.

Another way to evaluate image quality as a function of altitude is to reproduce the imagery at the same scale. The imagery within the black rectangle on Figure 3 was photographically enlarged or reduced to the same scale (1 inch = 0.55 miles, before reproduction) and illustrated on Figure 5. This example shows the progressive loss of detail as the resolution becomes poorer at higher altitudes. Good contrast persists to the highest altitude although the boundaries between contrasting fields are not as sharp at 8,000 ft as at lower altitudes. Imagery at 6,000 ft above terrain has ample information content for geologic reconnaissance.

OPTIMUM FLIGHT PLAN

As mentioned earlier, no single flying height is ideal for all imagery applications. For geologic reconnaissance we have found that 6,000 ft above terrain is a good tradeoff between broad coverage and adequate image information content. At lower elevations more flight lines are required to cover the same area and the information content may not be sufficiently greater to warrant the additional cost. There are several operational disadvantages to higher elevations. Extended night flying in unpressurized aircraft at altitudes greater than 10,000 ft above sea level is not recommended and produces a noticeable decrease in crew efficiency. Also flights above 10,000 ft should be conducted under instrument flying rules (IFR) which may require numerous clearances from air traffic control during the many course changes.

NAVIGATION

GENERAL

The problem of navigating a pattern of parallel flight lines in the dead of night can only be appreciated after one has actually attempted it. Even in daytime this is not a simple operation, but at night the difficulties are multiplied. The two phases of the problem are to fly from the base air strip to a starting point in the survey area and then to fly the mosaic pattern.

A typical nighttime survey at 6,000 ft above terrain requires a series of parallel lines 40–50 mi long and spaced 3 mi apart. Lateral coverage of this imagery extends for 2 mi on either side of the flight line, providing 1 mile of sidelap between adjacent strips. A number of navigation methods have been considered or used and are discussed in the following sections.

AIRWAY NAVIGATION AIDS

The existing VORTAC and other radio aids are designed for point-to-point navigation and are of little use for imagery flights. If an aid exists at the base air strip, it may be useful in navigating to the survey starting point, but will not solve the mosaic navigation.

DEAD RECKONING

Using the aircraft compass and air-speed indicator is unsatisfactory because of the unknown effects of winds aloft and the lack of visual checkpoints at night to update position location.

RECOGNITION OF GROUND FEATURES

Under suitable conditions, surprisingly good navigation can be accomplished by



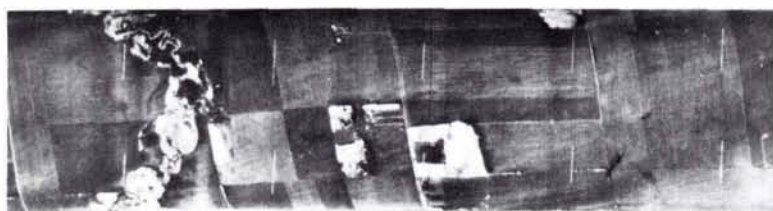
A. 8000 FT ABOVE TERRAIN. 3X ENLARGEMENT OF ORIGINAL



B. 4000 FT ABOVE TERRAIN. 2X ENLARGEMENT OF ORIGINAL



C. 2000 FT ABOVE TERRAIN. CONTACT PRINT OF ORIGINAL



D. 1000 FT ABOVE TERRAIN. 1/2X REDUCTION OF ORIGINAL

FIG. 5. Imagery flown at different elevations, but photographically enlarged or reduced to same scale (1 inch = 0.55 miles, before reproduction). Each image is 0.5 miles wide by 2 miles long and is taken from the area within the black rectangle on Figure 3. Eight to 14 μm nighttime imagery.

visual contact at night. The required conditions are: full moon, good visibility with no haze, and terrain with numerous recognizable checkpoints. In terrain with a regular network of section roads, we have flown imagery lines parallel with one set of roads and counted the crossroads for distance. The offsets were determined in the same manner. Other features, such as lakes and towns, provide checkpoints. The disadvantage of this method is that the three requirements rarely occur at the same time and

place. If they do coincide, the period of sufficient moonlight only occurs for about one week in each month.

PORTABLE LIGHT BEACONS

The traditional method of navigating night surveys employs ground personnel with spotlights to occupy positions along each flight line. Two-way radio communication is essential. A 12-volt hand spotlight that plugs into the automobile cigarette lighter socket is inexpensive and efficient, provided the

operator aims the spot directly at the aircraft and oscillates it in a distinctive vertical pattern. The major disadvantage to this method is that many areas lack the road network required for rapid movement of the ground crews from line to line. Lesser disadvantages include: topography that obstructs the view of beacons; ground crews becoming geographically disoriented (lost); expense of laying out, marking, and occupying the ground stations.

LORAN AND SHORAN

I have no personal experience with these methods which require installation and maintenance of a chain of ground transmitters. The logistics and expense are not attractive for remote-sensing surveys.

INERTIAL GUIDANCE AND DOPPLER

These systems are self-contained on board the aircraft and do not require the ground transmitters of the preceding methods. My only personal experience has been to observe a radar imagery project using doppler navigation. Both systems should be sufficiently accurate for the remote sensing surveys, but their cost, especially of the inertial guidance system, may be prohibitive.

VERY LOW-FREQUENCY RADIO NAVIGATION

A new and relatively inexpensive navigation system utilizes very low-frequency radio transmissions from existing stations to guide aircraft (Parrish, 1972). We have successfully employed this system in a number of nighttime surveys. It could also be used for photography, radar, magnetometer and radiation surveys. Because of these potential applications and the recent development of the system, some general information is given here.

Basic Principles. The U. S. Navy operates a chain of very low-frequency (12 kHz to 30 kHz) radio communication and navigation stations at worldwide locations. Because of the very low-frequency and high power, the radio waves follow the curvature of the earth and may be received at great distances. The navigation system works on the principle of fixing position in relation to intersections of hyperbolic lines formed by radio waves converging from two stations. The manufacturer of the airborne system supplies a directory of airports giving their distances in microseconds to the various transmitters. These data can also be obtained for any desired

geographic coordinates such as the corners of a survey area.

In order to set up a navigation course, two calculations are needed, one for the distance to the destination and another for the course deviation or left and right steering. For the distance calculation, the pilot selects a VLF station behind the flight origin and a station ahead of the destination. The respective values for these stations at the origin and destination are determined from the directory. By simple addition and subtraction a numerical factor is derived from this information and entered into the distance portion of the system controller. For course deviation the same procedure is followed using stations located generally to the left and right of the flight heading. This factor is entered into the left-right sector of the system controller. For technical information on principles of VLF navigation see Watt (1971).

Hardware and Operation. The four components are a system controller, course-distance indicator, remote receiver module and a small whip or blade antenna. The complete system weighs less than 13 pounds and draws about 1.5 amps. The course-distance indicator and the system controller shown on Figure 6 are mounted on the aircraft instrument panel. The system controller has nine signal lights to indicate whether the signal from each VLF station is acquired. The calculated distance factor is dialed into the upper row of thumb wheels with the stations shown on the two left-hand positions. The course deviation information is dialed into the lower set of thumb wheels.

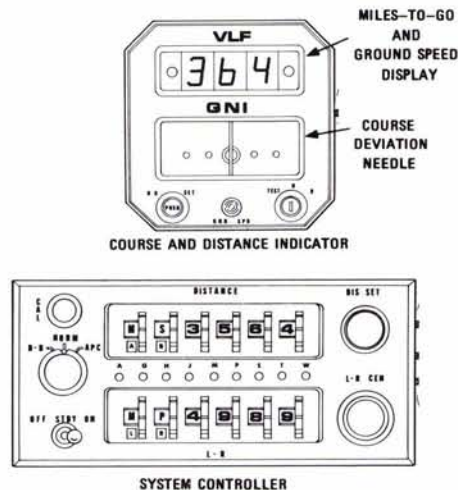


FIG. 6. Indicator and controller units for VLF navigation system.

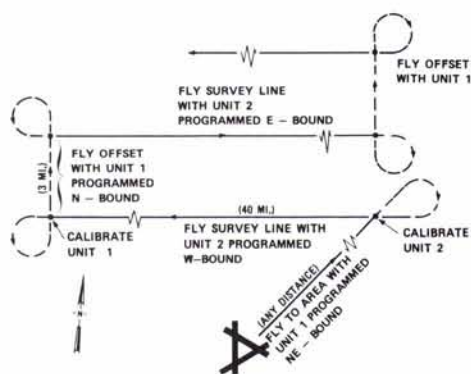


FIG. 7. Typical flight plan for imagery mosaic using VLF navigation.

Before takeoff the system is adjusted so that the course deviation needle is centered and the correct distance from origin to destination is shown on the miles-to-go display. The calibrate button (CAL) on the system controller is then pressed to designate the starting point for the trip. During flight the pilot keeps the needle centered for left-right steering and the miles-to-go display counts down to zero as the destination is approached. At three-minute intervals an updated ground speed is automatically com-

puted and can be displayed on the distance indicator by pressing a button. Additional details on the system and its operation are available from its manufacturer, Global Navigation, Inc. 24701 Crenshaw Blvd., Torrance, California.

Remote Sensing Application. A typical flight plan to produce a nighttime IR mosaic is shown on Figure 7 and requires two VLF navigation units. Unit 1 is programmed to navigate northeast from the air strip for the required distance to reach the starting point for the survey. When the distance indicator on Unit 1 reads 0 miles, the survey starting point has been reached. At this point the calibration button on Unit 2 is pressed to designate the starting point for a 40-mile westbound line that had previously been programmed on Unit 2. The pilot then makes a circle to the right and the needle on Unit 2 will align the aircraft on a westbound course heading directly over the survey starting point. The miles-to-go on Unit 2 has been accumulating to 44 or 45 miles as the turn carried the aircraft away from the programmed destination. When the miles-to-go reads 40, the aircraft is at the survey starting point and the IR scanner is actuated to obtain imagery along the westbound survey line. To navigate the offset leg

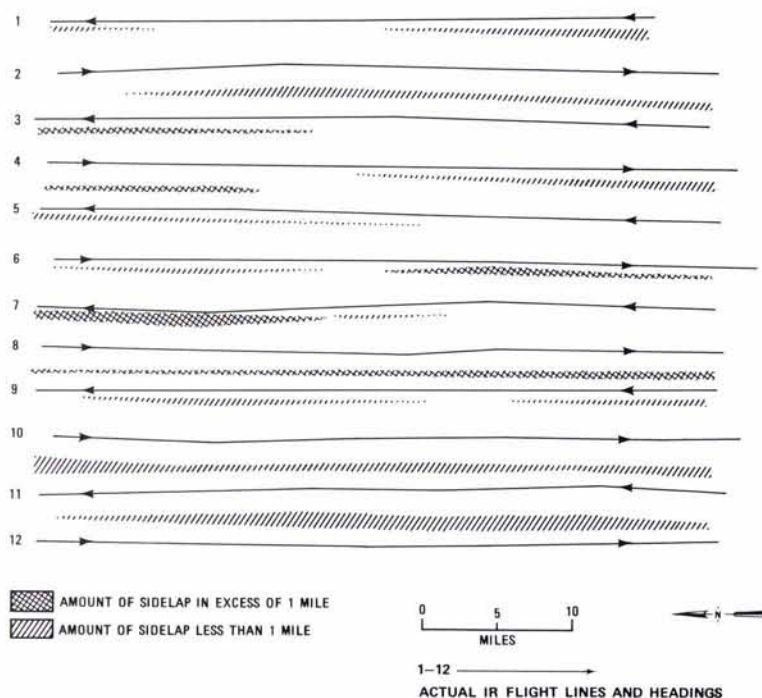


FIG. 8. Area B showing flight lines and imagery sidelap.

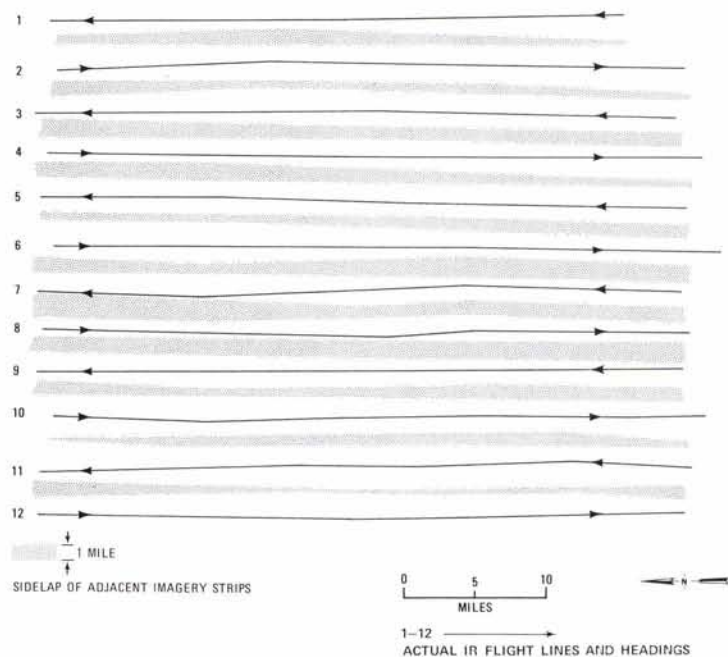


FIG. 9. Area B showing excess and deficit sidelap.

(3 miles in our example of Figure 7), Unit 1 has been programmed to fly a 3-mile northbound course and is calibrated when Unit 2 reads 0 miles indicating the end of the westbound survey line.

By throwing a switch, Unit 2 is then put in the *retrace mode* to reprogram it for a 40-mile eastbound line which is calibrated upon completion of the offset leg. The remainder of the mosaic flying is a repetition of these operations.

In practice, the navigation procedure quickly becomes routine after a few lines and offsets are completed. Our experience shows that it is advisable to make an abbreviated daytime *dry run* for each project area to check the course programs and project starting point. Some corrections can be made to obtain greater accuracy on the night flights.

Navigation Examples. In order to evaluate VLF navigation system for nighttime imagomosaics, the results from a typical project area are illustrated. The area was flown at 6,000 ft above terrain with lines 40–45 miles long spaced at 3-mile intervals to obtain approximately 1 mile of sidelap between adjacent image strips. Figure 8 shows the actual flight lines as determined by plotting the center line of each imagery strip on a

base map. Imagery sidelap is shown by the stippled pattern and ideally should be 1 mile wide.

The deviation of sidelap from the desired 1-mile standard is evaluated by plotting the amount of sidelap in excess of 1 mile and the amount less than 1 mile (Figure 9). Where the sidelap is exactly 1 mile, no pattern appears between the adjacent flight lines. This navigation accuracy is entirely satisfactory for mosaic purposes. It should be noted that some of our earlier results, although acceptable, were not as precise as this example which has the benefit of considerable experience. Most of the flight line deviations are caused by crosswind drift and subsequent slight over-correction. This could be minimized by coupling the VLF system to an autopilot which can sense and correct the deviations sooner than a human pilot.

Evaluation. The VLF system has several advantages over the other possible nighttime navigation methods. It is simple to operate and is independent of ground beacons except for the VLF stations. It is sufficiently accurate for imagery mosaics if a reasonable sidelap is provided to allow for minor course deviations. Tymczyszyn (1971) evaluates point-to-point navigation with this system.

SUMMARY

Acquiring thermal-IR imagery of large areas requires a mosaic flight pattern which must be carefully planned and navigated. Flight planning includes selection of time-of-day, flight altitude, and orientation and spacing of flight lines. Charts of image scale and lateral coverage as related to flight elevation above terrain are a practical guide to flight planning. Information content of imagery is related to contrast and spatial resolution. Resolution decreases with increasing altitude, but contrast does not seem to decrease. For many requirements an acceptable tradeoff between image quality and operation economy is provided by parallel flight lines at 6,000 ft above terrain spaced at 3-mile intervals. The resulting image scale is 1 inch equals 1.6 miles. Each image strip has a 4-mile swath width on the ground with 1 mile of sidelap on adjacent strips.

For geologic purposes, flight lines should be oriented so that scan lines are not parallel with the structural strike or grain, as this

tends to obscure linear features. To avoid the effects of differential solar heating, night is the optimum time for most image flights, introducing navigation problems. Experience has shown the limitations of conventional nighttime navigation methods. The newly developed VLF navigation system produces satisfactory guidance for nighttime mosaic flights and has advantages over other methods.

ACKNOWLEDGEMENTS

Many colleagues in the Standard of California organization made important contributions to this research. These include, but are not limited to, W. J. Anderson, R. H. Cull, S. McPhee, G. R. Porter, S. J. Reber, J. Reid and W. J. Simpson. I. A. P. Rumsey, formerly of Chevron Standard Limited, made many valuable contributions. Personnel from Daedalus Enterprises Incorporated and Global Navigation Incorporated provided training and consultation for operating their equipment.

LITERATURE CITED AND GENERAL REFERENCES

- Horvath, R., Braithwaite, J. G. and Polcyn, F. C., 1970, Effects of atmospheric path on airborne multispectral scanners: *Remote Sensing of Environment*, v. 1, p. 203-215.
- Parrish, R. L., 1972, VLF navigator challenges Vortac, Loran, Doppler and inertial: *Business and Commercial Aviation*, Feb., p. 50-52.
- Rosenberg, P., 1971, Resolution, detectability and recognizability: *Photogrammetric Engineering*, v. 37, p. 1255-1258.
- Rowan, L. C. and others, 1970, Thermal infrared investigations, Arbuckle Mountains, Oklahoma: *Geol. Soc. America Bull.*, v. 81, p. 3549-3562.
- Sabins, F. F., 1967, Infrared imagery and its application to structural mapping in Southern California: *Geol. Soc. America Bull.*, v. 80, p. 397-404.
- Sabins, F. F., 1969, Thermal infrared imagery and its application to structural mapping in Southern California: *Geol. Soc. America Bull.*, v. 80, p. 397-404.
- Stingelin, R. W., 1969, Operational airborne thermal imaging surveys: *Geophysics*, v. 34, p. 760-771.
- Tymczyszyn, J. J., 1971, Potential operational advantages of low cost VLF/Omega navigation equipment in "Proceedings of First Omega Symposium": Institute of Navigation, Washington, D. C., p. 132-137.
- Watt, J., 1971, The omega system, in Beck, G. E., Editor of *Navigation systems*: van Nostrand Reinhold, London, p. 118-133.
- Williams, R. S., and Ory, T. R., 1967, Infrared imagery mosaics for geological investigations: *Photogrammetric Engineering*, v. 33, p. 1377-1380.
- Wolfe, E. W., 1971, Thermal IR for geology: *Photogrammetric Engineering*, v. 27, p. 43-52.