See pages 55 & 56

FLOYD F. SABINS, JR.
Chevron Oil Field Research Co.
La Habra, Calif. 90631

Flight Planning and Navigation for Thermal-IR Surveys

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

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) navitation system is well suited for this purpose. The VLF system should also be applicable to aerial, geophysical and photographic surveys.*

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 provide 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 processing 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 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-

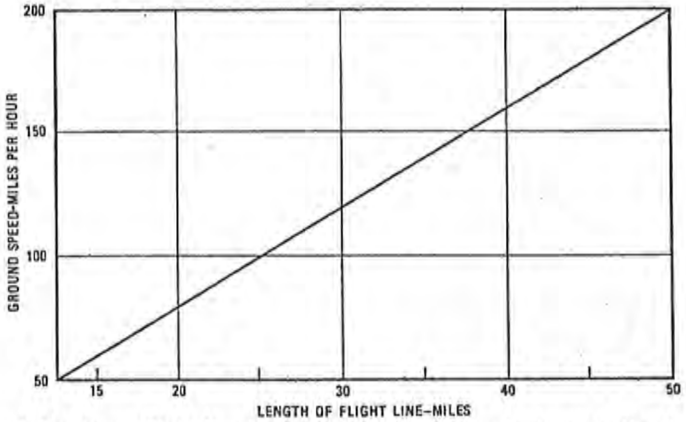


FIG. 1. Maximum flight-line lengths for standard 15-minute recording tape.

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

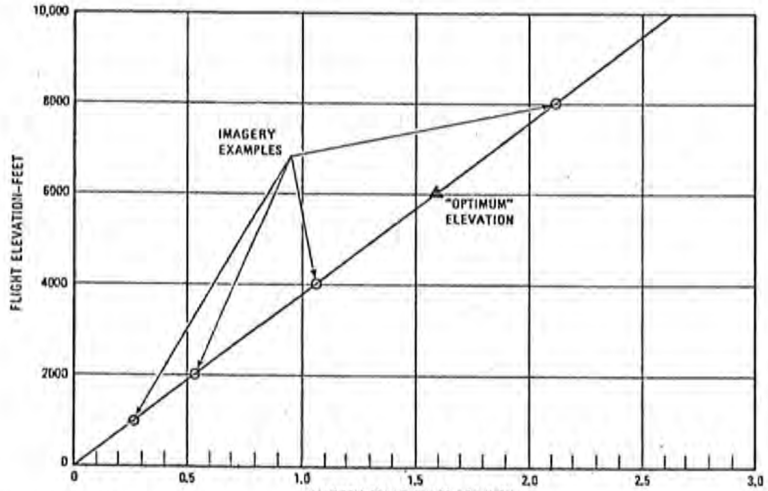
Topography and safety factors may dictate flight-line orientation, particularly for night flights at lower altitudes. Where a choice is possible, the optimum orientation may produce better results. For geologic projects the regional strike or structural grain of the area may be known in advance. If the 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.



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.

E SCALE

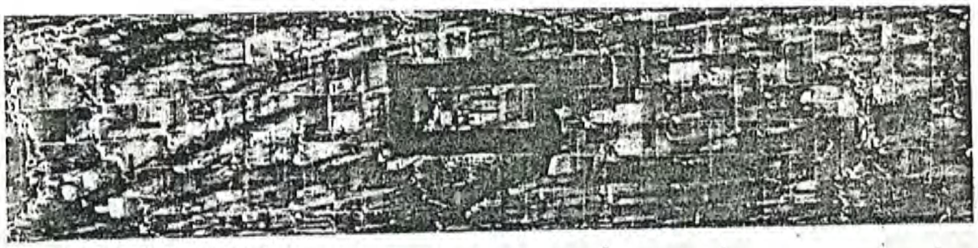
e chart on Figure 2 shows imagery scale
function of flight elevation above ter-
. The chart applies to rectilinearized
gery with 120° scan angle printed on
m film. Rectilinearized imagery has
processed to correct the marginal dis-
on inherent in scanner imagery. A chart
lar to Figure 2 could be computed for
rectilinearized imagery by calculating
average scale for the central 80° or 90° of
angle. The highly compressed outer
gins of non-rectilinearized imagery are
used in compiling mosaics. Figure 2 can
be adapted for scanners with narrow
ls of view and for imagery printed on
s other than 70-mm size.

illustrate imagery at different scales,
same flight line was repeated at four dif-
nt altitudes and samples are shown on
re 3. The original image scales for these
udes are shown by the circles on Figure
or comparison, the same ground area is
ined on each image and measures 0.5
s wide by 2 miles long. For geologic
nnaissance we have found that imagery
n at 6,000 ft above terrain with a scale of
ch to 1.6 miles is generally optimum.
is not advocated as a standard elevation
ll imagery, but 6,000 ft is a good trade-
mong the many factors that must be con-
red.

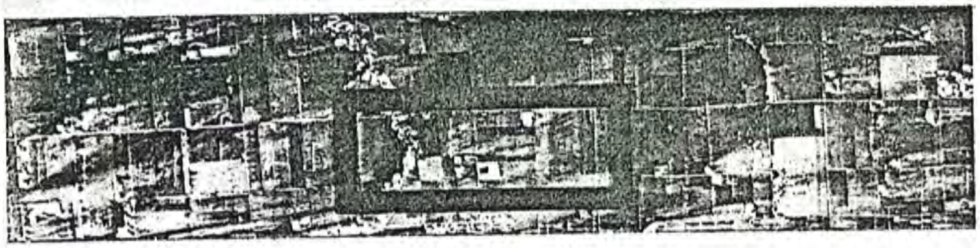
ound Coverage and Flight Line Spac-
Ground coverage at right angles to the
t path is also related to flight eleva-
above terrain, as shown on Figure 4 which is calculated for a 120° scan angle. Lateral coverage is the same whether or not the imagery is rectilinearized; the main difference is that with 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

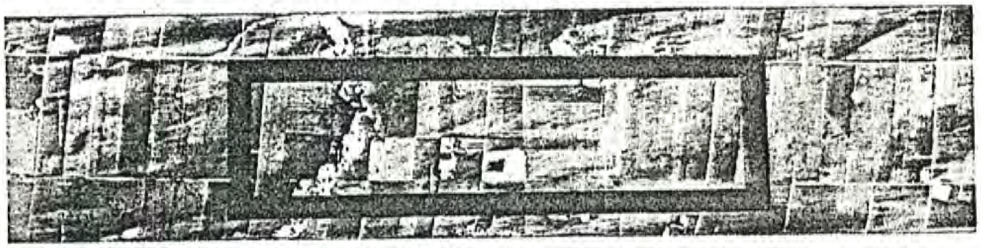
Image quality is often expressed in terms of resolution which is the minimum separation between two objects for which the images appear distinct and separate. In IR scanners resolution is determined by spot size of the detector element and typically is on the order of 3 to 5 milliradians. At a distance 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



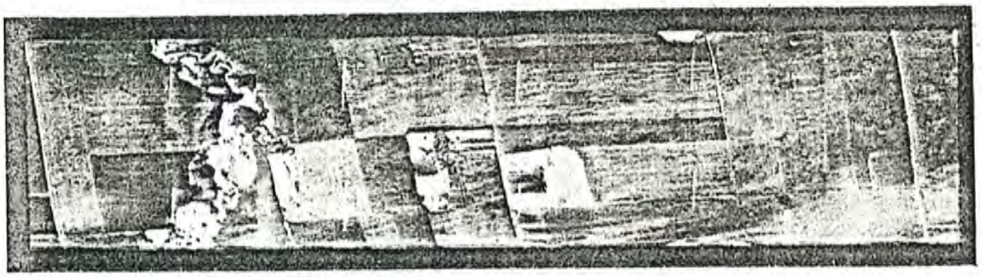
A. 8000 FT ABOVE TERRAIN



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 altitudes from 2,000 to 10,000 ft and noted th image contrast did not vary significantl with altitude nor is there any apparent lev shift. Changes in apparent target radianc can easily be compensated for in an optica mechanical scanner because of the electric form of the signals (Horvath and other 1970, p. 213). Our imagery examples of Fi

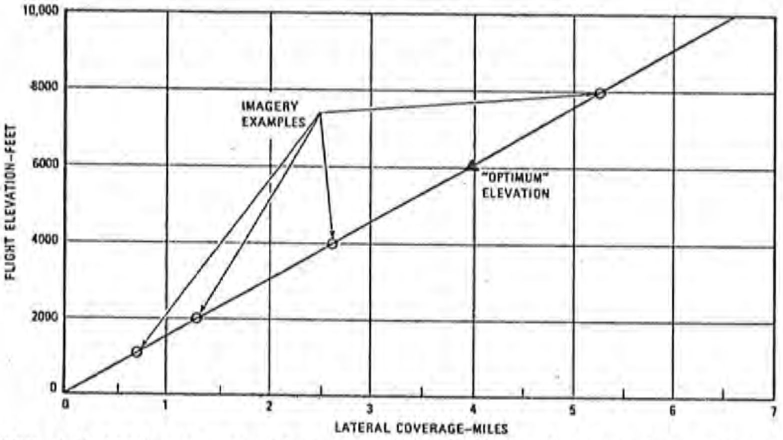


FIG. 4. Lateral coverage of imagery related to flight elevation above terrain. This is for imagery with 120° scan angle. See Figure 3 for imagery examples.

agree with these observations because
is no significant contrast change with
de.

ther way to evaluate image quality as a
ion of altitude is to reproduce the imag-
t the same scale. The imagery within
lack rectangle on Figure 3 was pho-
phically enlarged or reduced to the
scale (1 inch = 0.55 miles, before re-
ction) and illustrated on Figure 5. This
ple shows the progressive loss of detail
resolution becomes poorer at higher
des. Good contrast persists to the
st altitude although the boundaries
een contrasting fields are not as sharp at
ft as at lower altitudes. Imagery at
ft above terrain has ample information
nt for geologic reconnaissance.

UM FLIGHT PLAN

mentioned earlier, no single flying
t is ideal for all imagery applications.
eologic reconnaissance we have found
,000 ft above terrain is a good tradeoff
een broad coverage and adequate
information content. At lower eleva-
more flight lines are required to cover
ame area and the information content
ot be sufficiently greater to warrant the
ional cost. There are several opera-
disadvantages to higher elevations.
ded night flying in unpressurized air-
t altitudes greater than 10,000 ft above
vel is not recommended and produces
iceable decrease in crew efficiency.
flights above 10,000 ft should be con-
d under instrument flying rules (IFR)
may require numerous clearances
air traffic control during the many
e 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.

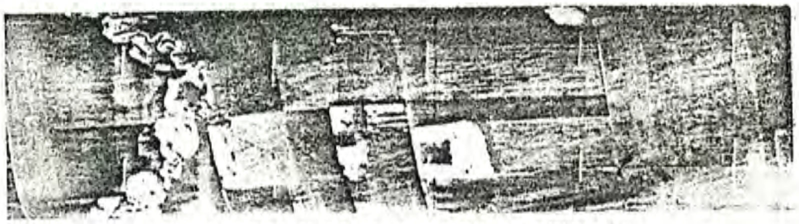
RECOGNITION OF GROUND FEATURES

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. ½X REDUCTION OF ORIGINAL

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

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 su ficient moonlight only occurs for about o week in each month.

PORTABLE LIGHT BEACONS

The traditional method of navigating nig surveys employs ground personnel wi spotlights to occupy positions along ea flight line. Two-way radio communication essential. A 12-volt hand spotlight that plu into the automobile cigarette lighter socl is inexpensive and efficient, provided t perator aims the spot directly at the aircraft nd oscillates it in a distinctive vertical pat- rn. The major disadvantage to this method that many areas lack the road network quired for rapid movement of the ground rews from line to line. Lesser disadvan- ges include: topography that obstructs the iew of beacons; ground crews becoming eographically disoriented (lost); expense of ying out, marking, and occupying the round stations.

ORAN AND SHORAN

I have no personal experience with these ethods which require installation and aintenance of a chain of ground trans- itters. The logistics and expense are not at- active for remote-sensing surveys.

ERTIAL GUIDANCE AND DOPPLER

These systems are self-contained on board e aircraft and do not require the ground ansmitters of the preceding methods. My ly personal experience has been to ob- rve a radar imagery project using doppler avigation. Both systems should be suf- ciently accurate for the remote sensing rveys, but their cost, especially of the iner- al guidance system, may be prohibitive.

ERY LOW-FREQUENCY ADIO NAVIGATION

A new and relatively inexpensive naviga- on system utilizes very low-frequency dio transmissions from existing stations to ide aircraft (Parrish, 1972). We have suc- ssfully employed this system in a number nighttime surveys. It could also be used r photography, radar, magnetometer and diation surveys. Because of these potential plications and the recent development of e system, some general information is ven here.

Basic Principles. The U. S. Navy operates a ain of very low-frequency (12 kHz to 30 Hz) radio communication and navigation ations at worldwide locations. Because of e very low-frequency and high power, the dio waves follow the curvature of the earth d may be received at great distances. The avigation system works on the principle of ing position in relation to intersections of perbolic lines formed by radio waves con- rging from two stations. The manufacturer the airborne system supplies a directory of rports giving their distances in micro- conds to the various transmitters. These ta 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.

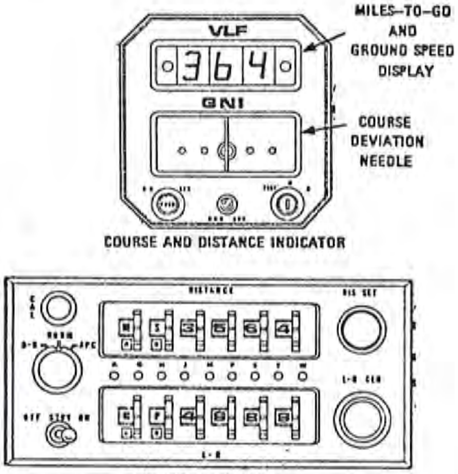


FIG. 6. Indicator and controller units for VLF navigation system.

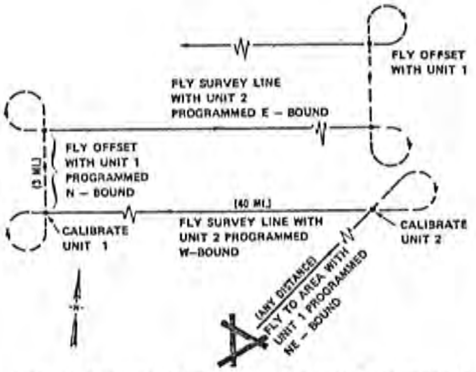


FIG. 7. Typical flight plan for imagery mosaic using VLF navigation.

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 computed 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

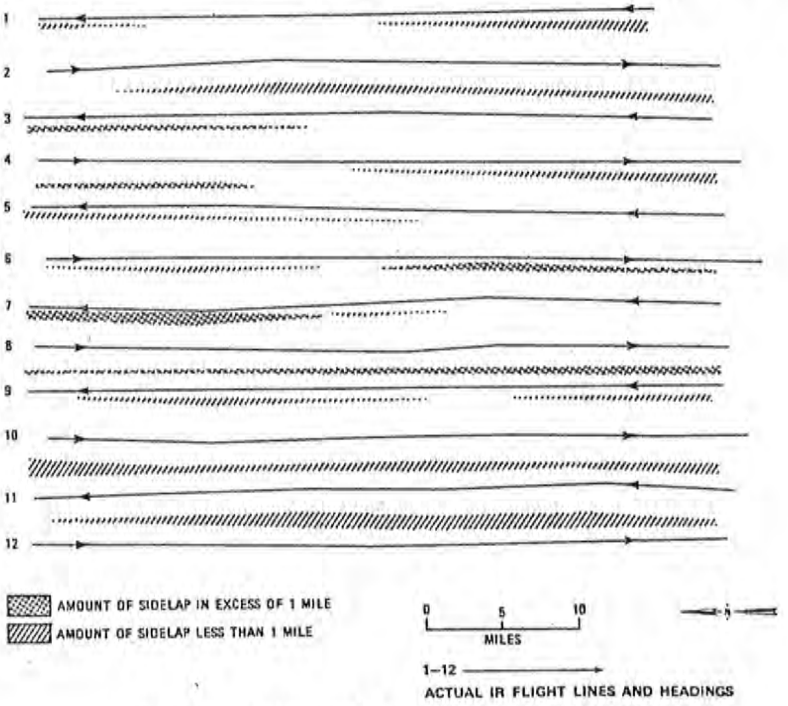


FIG. 8. Area *B* showing flight lines and imagery sidelap.

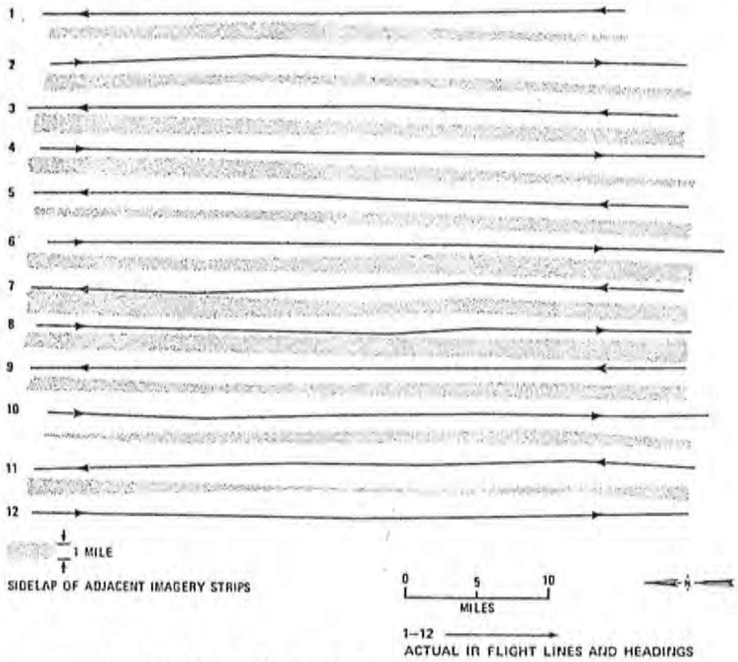


FIG. 9. Area *B* showing excess and deficit sidelap.

iles in our example of Figure 7), Unit 1
been programmed to fly a 3-mile north-
nd course and is calibrated when Unit 2
ls 0 miles indicating the end of the west-
nd survey line.

y throwing a switch, Unit 2 is then put
he *retrace mode* to reprogram it for a
nile eastbound line which is calibrated
n completion of the offset leg. The re-
nder of the mosaic flying is a repetition
ese operations.

practice, the navigation procedure
kly becomes routine after a few lines
offsets are completed. Our experience
ws that it is advisable to make an abbre-
ed daytime *dry run* for each project area
heck the course programs and project
ting point. Some corrections can be made
obtain greater accuracy on the night
nts.

avigation Examples. In order to evaluate
F navigation system for nighttime imag-
saics, the results from a typical project
a are illustrated. The area was flown at
00 ft above terrain with lines 40–45 miles
g spaced at 3-mile intervals to obtain
roximately 1 mile of sidelap between ad-
ent image strips. Figure 8 shows the
al flight lines as determined by plotting
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 avoi
the effects of differential solar heating, nigh
is the optimum time for most image flight
introducing navigation problems. Exper
ence has shown the limitations of conver
tional nighttime navigation methods. Th
newly developed VLF navigation syste
produces satisfactory guidance for nighttim
mosaic flights and has advantages over othe
methods.

ACKNOWLEDGEMENTS

Many colleagues in the Standard of Cal
fornia organization made important co
tributions to this research. These includ
but are not limited to, W. J. Anderson, R.
Cull, S. McPhee, G. R. Porter, S. J. Rebe
J. Reid and W. J. Simpson. I. A. P. Rumse
formerly of Chevron Standard Limite
made many valuable contributions. P
sonnel from Daedalus Enterprises Incorp
rated and Global Navigation Incorporat
provided training and consultation
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.*
80, p. 397–404.

Stingelin, R. W., 1969, Operational airbor
thermal imaging surveys: *Geophysics*, v. 34,
760–771.

Tymczyszyn, J. J., 1971, Potential operational
vantages of low cost VLF/Omega navigati
equipment in "Proceedings of First Om
Symposium": Institute of Navigation, Washi
ton, D. C., p. 132–137.

Watt, J., 1971, The omega system, in Beck, G.
Editor of *Navigation systems:* van Nostr
Rheinhold, London, p. 118–133.

Williams, R. S., and Ory, T. R., 1967, Infr
imagery mosaics for geological investi
tions: *Photogrammetric Engineering*, v.
p. 1377–1380.

Wolfe, E. W., 1971, Thermal IR for geology: *P*
togrammetric Engineering, v. 27, p. 43–52.