EARTH SCANNING TECHNIQUES FOR ORBITAL ROCKET VEHICLES

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Earth scanning techniques for a small orbital rocket vehicle

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Summary

Two systems of an earth scanning, minimum instrumented, orbital rocket vehicle are described. The resolving abilities of an optical-video and X-band radar system are compared, as are their weight and power requirements. The possible advantages of a human observer are stressed. It is concluded that the described radar unit would prove unsuitable for a small missile; the optical unit would have a resolving power advantage but would suffer from meteorological and general atmospheric interference.

Introduction

A practical earth scanning system would be a definite utilitarian function of an orbital or «satellite» rocket vehicle.

While is desirable to consider the eventual development of a system able to discern a maximum amount of information, it is expedient here to discuss a single type of information — an installation or plant at least 600 yds. dia. with an optical and radio frequency reflectivity appreciably different from that of the surrounding terrain. This single type of target is treated exclusively here in order to keep the paper within reasonable length. Similarly, several assumptions are made, viz:

a) The scanning units are based on existing, unclassified techniques.
b) The simplest systems are chosen.
c) A continuous source of ½ K.W. a. c. and d. c. power is available for scanning unit and telemetering transmitter.
d) The target environment is fairly flat within a radius of 250 miles and has the reflectivity and characteristics of flat, vegetation covered terrain.
e) A minimum of scanner attitude stabilization is required, with severe vehicle stabilization correctable by home-base programming.
f) Out of a total payload of 1000 lb., control and other, 250 lb. are available for the earth-scanning unit. Tentative size specifications for the satellite are: length, 25 ft.; dia., 5 ft.

A satellite is defined here as a vehicle in a constant altitude orbit, with an environment of negligible drag and relatively stable great circle orbit with negligible precession during one revolution.

The orbital velocity (v) of this vehicle is determined by the relationship

$$v = \left[g_0 \frac{R^2}{(R + h)} \right]^{1/2}$$

where

R = rad. of earth = 4000 mi.
h = altitude = 500 mi.
g = 32.2 ft./sec.^{2}

This yields a velocity of 4.3 miles/sec. or 3.7 miles/sec. ground speed. The period of this great circle orbit would then be 1.8 hours. (1)

g) Home-base contact is possible at all times (although possibly not necessary). The exact location of the vehicle is known either by Loran-type or wireless beacon contacts or wirelessed position indication obtained by astronomical reference.

Specifications

The specifications and requirements for the scanning unit may be summed up, then, as follows:

1. A weight of not more than 250 lb.
2. A total space requirement of approximately 150 cu. ft.
3. An electrical power requirement of not more than 500 watts and less, if possible.

4. An ability to detect a discrete target of 600 yds. dia. (30,000 sq. yds. area) from the altitude of 500 miles (2,640,000 ft.).
5. A possible method of «preferential» scanning — i. e., the selection of a smaller area within the area under surveillance — arbitrarily set at 500 miles dia., or approximately 200,000 square miles.

   A smaller scan area would seriously reduce the probability of target detection in a very large land area. Of course, a smaller scan area could be readily established and would in effect permit an increase in the net resolving power of the intelligence system. However, the reduced scan would necessitate extensive path programming of the vehicle, with all the attendant difficulties due to propellant consumption and orbit corrections. On the other hand, the coriolis forces acting on the vehicle would gradually cause orbital perturbation and consequently new sections of the terrain would be scanned. However, this method is too haphazard and slow to be of practical importance.
6. The intelligence data should be transmitted directly to a friendly home base at a maximum distance of 2,200 miles, on a wide band video carrier. Or, if this is impractical, an information storage-transmit system should be incorporated.

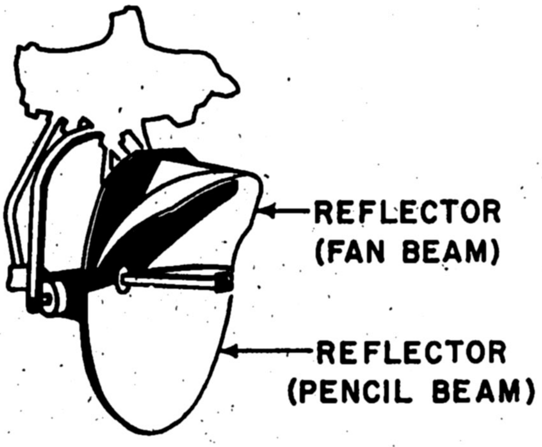
Two types of scanning systems at once suggest themselves as capable of functioning within these specifications. First, a ground illuminating system, such as obtained with radar; secondly, an optical system, utilizing the reflected earth light to form an image of the target area.

Of the analysis of these two systems, that of the radar is very much more complex and can only be treated semi-empirically with many assumptions and speculations. The characteristics of a possible radar system will be outlined first.

Radar scanning

While there are various types of radar systems, a most common type — the «pulse» radar will be treated exclusively here. This system emits intense discrete electromagnetic pulses spaced rather far apart in terms of each pulse duration. These pulses are reflected from the target area and the echoes are sensed by a receiver which is only active during the transmitter's waiting time between emitted pulses.

Since an image of the ground is desired, a particular application of radar is required — the «plan-position indicator». This system depends on the principle of «ground painting» from an airborne scanning unit. The «painting» or illumination is accomplished by sweeping the earth with a fan beam of radar pulses in a 360^0 (or less) sector. This fan beam is formed by a specially shaped so-called cosecant-squared antenna which both transmits and receives, in turn. (Fig. 1) The radar beam is distorted in order to reduce the energy level of the pulses emitted normal or nearly normal to the earth's surface, and to increase the pulse energy of the beam segment obliquely incident on the surface. This assures a more uniform echo energy level at the receiver. The beam must be narrow in azimuth in order to permit discrimination between targets, in this case, the 600 yds. dia. object within the total scanned field. As this quasi-paraboloidal antenna sweeps through its assigned area, the instantaneous information of its position is relayed to a synchronized electron sweep trace, on the video cathode ray image display tube. The radial sweep represents an instantaneous projection of the fan beam echo on the tube face. An object on the ground of sufficient reflecting power will show as a bright dot on the sweep trace. As the antenna rotates, the sweep follows, and in 360^0 displays the reflected echo from the ground, as a nonperspective picture or map. However, it must be emphasized that even the modern best-definition radar yields a ground target picture which is incomparably poorer in detail than a vertical photograph under good conditions.



1. Cosecant^2 Paraboloidal Antenna, with Mounting

The resolving power of the radar improves as the beamwidth is decreased and therefore a sharp beam is required. This indicates the use of microwave radar since the sharpness of the beam depends on the ratio of the antenna diameter to the radio wavelength. Therefore, if a microwave (in this case 3 cm) beam were used, a relatively large antenna, approximately 2 feet dia. would suffice. The 3 cm wavelength (10,000 megacycles frequency) is the lower wavelength limit which can be practically used. Shorter wavelengths, especially below 2 cm, suffer from atmospheric absorption of the microwave energy.

The atmosphere is no longer transparent in these regions and either its constituent gases or water vapor can cause serious attenuation. (2).

Enough has been said, then, to permit a very brief analysis of a possible applicable radar unit, based on existing airborne microwave systems. It must be emphasized that many assumptions are made, since each problem of radar scanning is unique and can often be approached only from an experimental standpoint. For instance, the statistical problem of the earth terrain reflections with the many and varied reflecting elements of all sizes, configurations and reflection coefficients, can be itself the basis of a very large analytical study. The weights and power outputs are also somewhat idealized but not unrealizable. Furthermore, the considerable problem of mounting a sweeping or rotating antenna whose terminals must be electrically insulated against the power leakage in the near vacuum at the altitude, is not discussed here. If the antenna is in an enclosed pressurized housing or «radome» the problems of the characteristic microwave absorption by the radome housing arises, as does that of possible gas leakage.

Analysis

The predictable radar performance can be summed up by a simple radar equation as follows: (3) (4)

$$S = \frac{P\lambda^2 \; G^2 \; (R\alpha) \cdot (1/2C.\tau. \; \sec \Theta) \; K \sin \Theta}{(4\,\pi)^3 \; R^4}$$

where:

S = Reflection signal energy in watts, available at the radar antenna.

α = Azimuthal width of radar beam in radians, here $\pi/90$ radians (or 2^0).

Θ = Declination angle of beam, or angle between line of sight (fig. 3) and edge of fan beam.

P = Peak pulse power, = 4×10^5 watts.

R = Range of target = $\frac{h}{\sin \Theta}$, where h = altitude, 2, 640,000 ft.

C = Velocity of light, 980,000,000 ft./sec.

G = Antenna gain = $G_0 \operatorname{cosec}^2 \Theta \sqrt{\cos \Theta}$. A value of approximately 1000 was chosen due to uncertainties of best value for Θ or

$$G_0 = \left[\frac{(4\,A_f)}{\lambda 2}\right] = \left[\frac{4\,Af}{\lambda^2}\right]$$

where

A = Area of antenna aperture.

f = dimensionless factor, approx. 0.6 (not related to reflection coeff.).

τ = Pulse duration, 1 microsec. A longer pulse duration increases range but decreases resolution.

K = A reflection coefficient for a flat land surface covered with normal vegetation. A common value of 0.6 has been chosen.

The solving of this radar equation yields a value of 4×10^{-11} watts for S, the reveived echo power at the radar antenna. Since an average threshold sensitivity of a good radar receiver may be 3×10^{-12} watts, the ground echo should be readily detectable and displayed on the p.p.i. video screen. In fact, the power level of the echo pulse would even be increased if a higher antenna gain were chosen. No attempt has been made to compute maximum range since the criterion of signal strength to sensitivity ratio is a sufficient one.

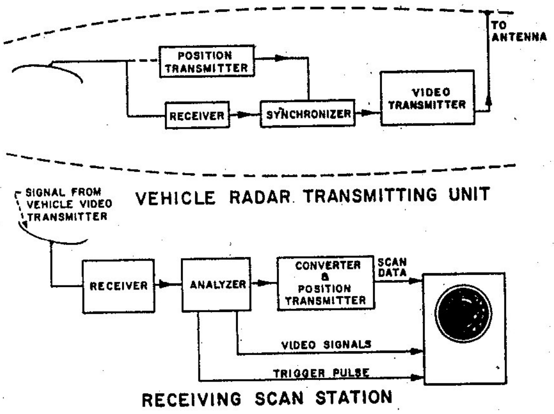
Thus while a display of the scanned area could possibly be obtained, several very disturbing factors immediately arise which overshadow the signal strength criterion.

1. The delay (T) between the transmission of a pulse and the echo from the earth, at a distance of 2,640,000 feet is, $T = \frac{2 \times \text{average Range}}{c}$, where c is the velocity of light, 980,000,000 ft./sec. This delay (T) is 0.0053 seconds. But the vehicle travels at 21,600 ft./sec. — so when the pulse returns in 0 0053 seconds, the vehicle has moved through 115 feet, well out of the way of the radar pulse.
2. As the radar antenna rotates and sweeps its fan beam through 360^0 or some fractional arc, it must not move more than approx. 1% of the beam width (2^0) for the duration of at least one illuminating pulse. That is, the returning pulse must find that the antenna is still pointing in its direction, on arrival. Furthermore, since the reflected intensity is low, it would be desirable to have multipulse illumination of the target — say 5 pulses per scan.
   If one pulse is assumed, the fastest possible scanning rate through 360^0 would be $\frac{360}{w} \times T$, where $T = 0.0053$ sec., as in (1) and w is the effective beam width, 2^0. This yields an antenna rotation of 1.05 rev. per sec., and a pulse repetition rate of $\frac{1}{0.0053}$ or 190 pulses per second.

   As stated, under (1), the vehicle moves 115 feet during the pulse travel. Therefore, the above requirement that the antenna be within the locus of the target echo path is not met. Of course, since the reflection from the earth is assumed scattered or «diffuse» rather than specular, some of the return echo will be intercepted. But the probability of receiving the actual symmetrical 600 yd. dia. target echo is vanishingly small.

Even if some way, such as twin antennas separated by 150' could be found to circumvent the signal reception lag, another phenomenon, the «Doppler Effect» might prove disturbing. This effect arises because of the high velocity of the vehicle and is manifested by a change in frequency of the received echo signal. This factor is too lengthy and complex to be discussed here, as is an associated phenomenon, that of aberration.

3. Still more serious is the question of angular resolving power. The target is 600 yds. dia.; yet, even a 2^0 beam will have an azimuth width of 13 miles at the center of the fan beam, spreading to 17.5 miles at the tip. Radar can discern two targets as separate only if the targets have a greater angular separation than the beamwidth. Therefore, details or shape of the considered target would not be defined. At best, the entire target would contribute only an insignificant portion of the instantaneous total reflected radar echo. The reflected «clutter» from the surrounding area (4250 sq. miles) covered in one 2^0 fan beam scan would completely override the small signal contributed by the target area (roughly $^1/_{10}$ square mile or $^1/_{40\,000}$ of the total area), If the reflection coefficient of the target were 0.9, 50% above that of the environment, it might be represented as a minute dot, $^1/_{150}$" dia. on the face of a 10" display oscilloscope. However, the smallest spot which can be resolved with the best modern oscilloscopes is approximately $^1/_{250}$ of the radius, or $^1/_{50}$" for the 10" tube. Therefore, unless improvements are made in cathode ray spot resolution, the difficulty of display of the described target with existing equipement remains as another limiting factor. It is possible to expand or magnify the image display with various techniques, such as «delayed P.P.I.» or «off-center P.P.I.», but these introduce new problems such as image distortion and rapidity of movement. (5) Lack of space precludes further discussion of these techniques, as it does a discussion of the complex transmitting system which must simultaneously relay the scan information, the instantaneous angular antenna position and range or position information to the home base. (Fig. 2)



2. Digram of Possible Radar Relay Unit

The tentative specifications for the described radar unit and transmitting relay system are summed up:

Radar Transmitter frequency	— 10 000 mc./sec., or 3 cm wavelength
Peak pulse power . . .	— 4×10^5 watts
Receiver sensitivity . .	— 3×10^{-12} watts
Video bandwidth . . .	— 4 mc./sec.
Pulse length	— 1 microsec.
Pulse repetition frequency	— 190 per sec.
Antenna scan rate . . .	— 63 r.p.m.
Antenna dia.	— 2 feet, cosecant-squared pattern
Antenna gain	— 1000 (arbitrarily chosen — probably higher)
Azimuth beam width . .	— 2^0
Radar a.c. and d.c. power requirement	— 350 watts (conservative)
Radar relay a.c. and d.c. power requirement . .	— 200 watts (conservative)
Relay transmitter weight	— 200 lbs. (conservative)
Radar unit weight . . .	— 100 lbs. (conservative)

Optical Scanning

On first consideration a method of optical earth scanning appears more promising than that of radar. «Optical scanning» here implies the utilization of reflected earth light for the formation of an image of the target area, with a lens unit, upon a photo receptive system which can store the information and can convert it into analogous electric signals.

Again, as in the case of radar, several assumptions must be made in the absence of confirmative data:

1. The «albedo» or reflecting power of the scanned earth surface is high enough to permit the forming of an image of sufficient intensity to stimulate the receptor — here an «image orthicon». This will be discussed further.
2. The image produced is free of the various errors associated with low focal ratio or fast lens systems.
3. Sufficient contrast exists between the actual target and the environment to permit distinction by the orthicon.

The system specifications, as for the radar, can be laid down within the framework of existing unclassified information:

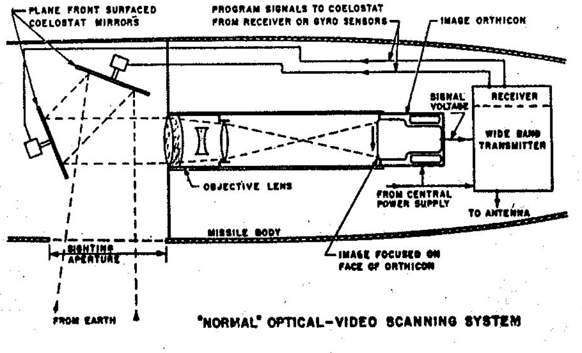
Specifications

The resolving power of the objective must be great enough to distinguish the target within the area of 500 miles diameter; some secondary stabilization must be provided to permit off-flight path scan and to direct the light rays from the object area directly into the lens system at all times; the lens system should be capable of variable focus or magnifying power to allow location of the target within the total field of view; the video sensor and relay must faithfully transmit this information to home base; some method of counteracting image movement must be included.

A basic system which would encompass these specifications is outlined and its applicability is discussed, as is that of variations of the system.

1. **Stabilizing Unit** (Fig. 4)

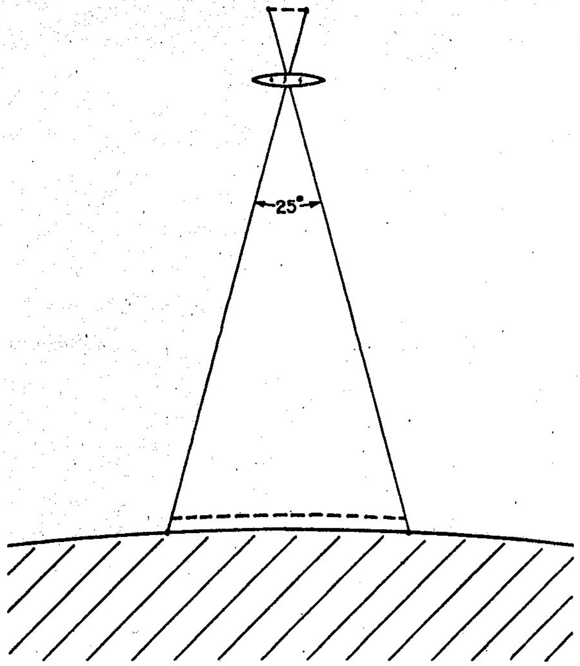
This could be a «coelostat», a device consisting of two gimbalmounted plane mirrors whose movements relative to each other and the objective lens assure a constant angle of entry from the scanned area. A more complex servo controlled gyro stabilization would be required than that for the radar antenna since the mirrors have more degrees of freedom of movement. Of course, the system must also respond to home-base corrective signals.



4. Normal Objective Lens System

2. **An objective lens** which forms an image of the terrain and focuses it on the face of the image orthicon or other detector screen.

Since a large area subtended by 25° is scanned and since a high light intensity is desirable for the sensor unit, a fast (or low «f» stop) lens is required. Also, a lens of rather large diameter is necessary in order to permit detailed resolution of the large field of view. (Fig. 3) The target of 600 yds. dia. subtends an angle of approximately 2 minutes of arc from 500 miles. The lens chosen here, 7" dia., would yield a minimum angle of resolution (r) given by the relation $r = \frac{14.1}{d}$, where d = diam. of lens in cm (200) yielding a value of 0.7 sec. of arc, well below the required limit of target resolution. A focal length of 14" would be required to give a full image on a 6" dia. orthicon face. Therefore, this lens has a focal number or stop of f/2 whereas for most low altitude air photography an f/8 ratio is used.



3. Simple Optical Ray Path from Scanned Aera to Image

3. **An image tube** (Fig. 4) which converts the image focused on its face into an analogous video signal transmitted via a wide band microwave beam to home base. The image falls on a photosensitive face which emits electrons in proportion to the intensity distribution. These photoelectrons are electrostatically focused on a target, within the tube, with subsequent conversion into an e.m.f.

The sensitivity of an orthicon is equal to or greater than that of motion picture film. The image illumination (I) obtainable with an idealized optical system is given by $I = \frac{B}{4 \times f/No^2}$, where B = ground brightness and the f/No = 2, in this case. (6)

Thus a typical ground brightness, on a sunny day, of 600 foot-lamberts, would yield an image brightness of approximately 35 foot-candles. The orthicon 2 P_{23} yields a maximum output of 5 microamperes with an illumination of 0.1 foot-candles. Therefore, more than sufficient image intensity is available. (7)

However, as in radar, the sensing screen remains a limiting factor. The target (600 yds. dia.) can be represented as an unmagnified spot of $^1/_{250}$" dia. on a 6" tube face. In order to resolve this spot horizontally and vertically, at least 1200 scanned lines per frame would be required. Assuming a square image, the number of picture elements to be then transmitted would be $(1200)^2$ or 1,440,000 equivalent to a good quality photograph. The video bandwidth required, assuming a low picture repetition rate of 20 per second would be $20 \times 1{,}440{,}000$ or 28,800,000; corresponding to an approximate practical bandwidth of 12 mc/sec., 8 mc more than the required 4 mc/sec. stated in the original specifications. Further details of this problem cannot be discussed here, neither can that of signal storage on magnetic tape or bandwidth compression. (8)

If a smaller field of view, with higher magnification is required, some modification in the optical train must be made.

The first consequence of magnification is the increased rate of image movement across the orthicon tube face. The rate of unmagnified image movement can be derived from the expression $v = \frac{V \times f}{h}$,

where

v = rate of image movement.

V = rate of orbital vehicle = 4.3 miles/sec = 272,000 in. per sec.

f = focal length of image forming lens = 14".

h = altitude in inches = 31,780,000.

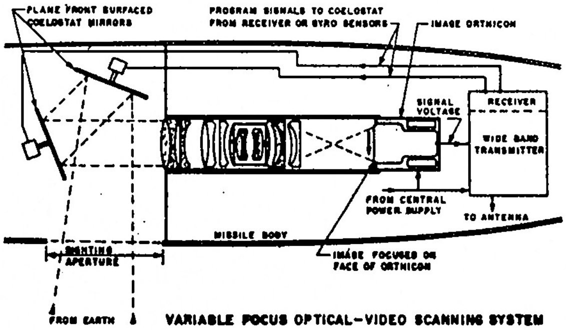
Here $v = 0.12$ inches per sec.

With a nonintegrating device (as compared to a photographic film) this movement is not serious and would show as a continuously shifting panoramic scene on the home-base video screen. But as soon as the magnification is increased, the field of view is decreased and the rate of image movement is increased, since h has really been decreased. In conventional aerial photography, a high rate of image movement is usually nullified with moving slits or rotating prisms which expose only a narrow strip of film at a time in synchronism with the image movement. The rotating prism is more suitable for stopping high speed motion, but a similar device, in conjunction with a high speed film must be used at the receiver. An associated problem here is the synchronization of the image repetition frequency with the prism rotation. Electrical «stroboscopic» freezing of the orthicon image could possibly be obtained but is too complicated to be discussed here.

The second consequence of image magnification is the change in the «f» number which results. That is, the effective «f» stop or number is increased with an increase in the magnifying power. Since the image illumination is inversely proportional to the «f» stop, a decrease in light intensity would occur. However, the image illumination is well above the threshold orthicon sensitivity so that this problem is not serious except during periods low field intensity.

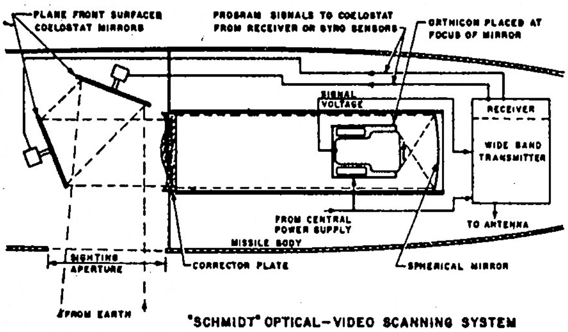
The problem of actually obtaining the increased magnification is more complicated.

In (Fig. 4, simple lens system) a second magnifying lens would have to be placed near the focal plane of the objective lens. Different magnifiers would have to be mechanically inserted at the telemetered command of home-base. This would result in a complex electromechanical system, besides the drawback of varying f-stop.



5. Variable Focus or «Zoomar» System

A system (Fig. 5 variable focus lens) could be employed utilizing a constant f-stop variable focus objective based on the «Zoomar» principle.* The objective elements can be readily moved longitudinally with respect to each other, producing close-up views of the earth at will. This system is mechanically simple and could be easily controlled with a single servo unit.



6. Schmidt Optical System

Another system (Fig. 6, Schmidt system) uses a spherical reflecting mirror with a correction plate to produce an undistorted flat wide

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* Manufactured by Taylor, Taylor & Hobson.

angle image of the ground. The aberrations associated with the high speed lens units are absent, although the Schmidt unit may have the phenomenal f-stop value of 0.8. The associated shallow depth of view is not serious due to the nature of the flat object field. However, magnification of the image would be very difficult, involving complex movements of orthicon or mirror, or both.

In general, reflecting optics instead of lenses could be used, especially for earth scanning in the near ultra-violet or infra-red regions.

The optical scanning techniques are, of course, much more susceptible than the radar technique to atmospheric errors. Since the vehicle is well above the atmosphere, air unsteadiness and turbulence could impose severe limitations on image magnification especially at oblique angles of vision. The turbulence of the atmosphere has proven very detrimental for accurate astronomical research, as it might for the optical scanning; this is especially true since the sun's rays have had to traverse the atmosphere twice in order to reach the scanner. Further high altitude research may provide some answers to this problem.

Further factors are those of absorption and scattering of light by the atmosphere and the substances it contains. The latter may be seasalt nuclii, fog, clouds and dust, with particle sizes from 10^{-2} to 0.5 microns. These factors cannot be ignored and could easily prove to be the severest limitation of the optical technique. The effects of this scattering by haze and dust and clouds have been noted for conventional aerial photography but would require further high altitude tests.

Scanning in the near infra-red region (up to 2 microns) is possible with specially sensitized orthicons. In fact, an orthicon of this type has a greater infra-red sensitivity than the best photographic film.

A simple relationship, derived from the work of Lord Rayleigh, relates the scatter coefficient A with the wavelenghth and a median particle size, by $A = M/\lambda^{-4}$, where M is a constant factor at various altitude and λ the wavelength. This shows that a longer wavelength results in a lower scatter coefficient — although when the wavelength is above 3 microns the thermal emission oft the earth terrain itself would prove disturbing. (10)

The application of infra-red scanning is complex and a spectacular increase in performance cannot be easily predicted, except in the case of light surface fog and inorganic dust haze. The possibility of penetration of heavy smog or clouds is remote, as is the detection of a well camouflaged target. It has been suggested that color photography or scanning might be useful for camouflage detection; it is not apparent why this should be so, since the color response of film or color video is not superior to that of the eye. However, small errors in color matching of the target with the surrounding terrain might be detectable with specially sensitized orthicon sensors. The color video transmission is, of course, another field in itself and it can only be suggested that a mechanical color disc (Columbia Broadcasting System) or the more complicated electronic three-image-tube system be employed. (11) Color transmission will result in a wide transmission bandwidth unless the number of lines per frame is reduced. The greater apparent definition of the color scan might permit this technique.

Conclusions

It has only been possible to point out in the barest outline the many problems inherent in the design and application of an earth-scanning unit for an orbital vehicle. If the limitations of a small, unmanned satellite are assumed, the following conclusions may be summed up:

(a) **Radar**

The described radar system is incapable of resolving the 600 yd. dia. target. A larger vehicle is indicated with larger antennas and sharper beam width. Alternately, some method of folding or expanding an antenna could be devised, since air drag is absent. Furthermore, while a trailing receiving antenna might be necessary for reception of the echo, it is possible that the small angle subtended by the transmitted and received radar pulse could permit employment of a single antenna.

The Kennelly-Heaviside and other ionized atmospheric layers could introduce serious attenuation and phase shift problems, and possibly refraction of the obliquely incident radar pulses. It is felt that not enough is known at present of the effects of these layers (on microwave radiation) to permit an adequate discussion here.

(b) **Optical Scanning**

The optical system has an enormous resolving power advantage but suffers from atmospheric image distortion, absorption by clouds and haze and lack of night perception. The wide transmission bandwidth could be circumvented by sequential signal storage on magnetic tapes for later retransmission. Changes in the terrain might be detectable by repeated scanning and comparison of received images. Color scanning would prove advantageous if a practical system could be devised. The magnification of the image is possible but introduces not insurmountable problems of stopping the image movement due to the high velocity — either mechanically with the coelostat or rotating prism or electrically by orthicon blanking.

Infra-red scanning might prove helpful for a hazy atmosphere although this cannot be rigorously demonstrated in this case. A deviation from this technique would be the detection of the target by its own thermal emission, in which case night detection would be possible.

However, the vehicle orbit period of less than two hours would yield several useful scans during daylight hours, which mitigates the «blind» night period loss.

The transmission to home-base of the video signals should prove possible due to the altitude of the vehicle; similarly, a geographical reference should be obtainable at all times. A lower altitude orbit would not be beneficial due to the greater vehicle speed and greater possibility of interception.

When the foregoing is reviewed, it must be generally concluded that the inclusion of a human observer would yield a great advantage over the described techniques. No applicable optical or electro-optical device has the contrast adaptability and resolving power of the human eye. The observer, of course, would also require a system for slowing down the image movement, but his perceptive powers could quickly translate the information and relay it immediately or later to home-base. With a larger vehicle, regular high altitude photography could be arranged with high speed film development and conveyance of the information by the observer. Instead of film, a xerographic image storing device could be substituted if the required resolving power were attainable.

Naturally, an analytical study would be necessary to determine whether the increased vehicle weight requirements due to the need for food and air for the observer would prove more costly than the remote control scanning in terms of energy required to place the vehicle in an orbit.

References

1. «Physics of Rockets», by H. S. Seifert, M. W. Mills, M. Summerfield, American Journal of Physics, Vol. 15, N. 3, p. 260, May—June 1947.
2. «Further Theoretical Investigations of the Atmospheric Absorption of Microwaves», M.I.T., Radiation Laboratory Report No. 664, March 1, 1945.
3. «Theoretical and Experimental Study of Radar Ground Return», by R. E. Clapp, M.I.T., Radiation Laboratory Report No. 1024, 1946.
4. «Mechanical Resonant Scanner», by D. B. Nickinson, M.I.T., Radiation Laboratory Report No. 782, March 1946.
5. «Weight Analysis of Airborne Radar Sets», by W. L. Meyers, M.I.T., Radiation Laboratory Report No. 340, January 1, 1945.
6. «An Electronic Frequency Stabilization System for CW Microwave Oscillators», by R. V. Pound, Rev. Sci. Inst. 17, 490 (1946).
7. RCA Tube Handbook and «Miniature Airborne Television Equipment», by R. D. Kell and G. C. Sziklai, RCA Rev., Vol. 7, pp. 338—357, 1946.
8. «Narrow Band Radar Relay», by J. L. McLucas, «Electronics», Sept. 1952, p. 142.
9. «The Development of Infra-red Technique in Germany», by V. Krezek and V. Vand, Electronic Eng., Vol. 18, pp. 316—322, 1946.
10. «An Experimental Simultaneous Color Television System», by K. R. Wend et al., Proc. Inst. Engineers, Vol. 35, pp. 861—875, 1947.