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Survey Effectiveness of Spacecraft Remote Sensors

A systems analysis study of altitude, inclination, sun angle, etc., is applied for maximizing the returns from Earth Resources survey satellites.

INTRODUCTION

NOW THAT THE feasibility of using Earth-orbiting spacecraft for the acquisition of Earth Resources data has been demonstrated,[1] there arises the need to determine efficient data acquisition profiles and attendent mission requirements for the remote sensing instrumentation being developed under the sponsorship of NASA.[2] Heretofore this has been done in a gross fashion, paying little attention to efficiency, assuming ideally non-redundant coverage, and neglecting the timing and/or sequencing of data acquisition.

This paper looks ahead to the time when vehicles and instruments will be available, and examines the problems related to the operational acquisition of resources data. Hopefully, such projections into the future will reveal design and planning contingencies which can be taken into consideration now, in the development phases, to insure efficient and accurate attainment of the operational objectives of Earth Resources survey satellites.

The purpose of this paper is to present the techniques and results of a continuing study to determine the survey effectiveness of selected instruments proposed for Earth Resources surveys from space. It must be emphasized that, due to the still somewhat undefined nature of the program, the instrument and mission specifications used in the study were *not* intended to be *definitive*, but rather *illustrative* of the types and characteristics of the requirements of the program. Thus no definitive significance should be attached to the choice of instruments, their specifications, or interactions. Their applications should be regarded as hypothetical; their specifications, nominal.

As mission objectives, instrument specifications, and orbital requirements become defined, the technique presently used in a hypothetical manner may be similarly applied to yield definitive specifications. In the meantime, as in this study, during the intermediate phases of the program, the technique

ABSTRACT: *A systems analysis technique has been developed to integrate remote sensor specifications, mapping requirements, and orbital characteristics. Using both empirical and computer methods, optimum survey profiles have been calculated. Three examples are described: a multi-band camera survey of Brazil in 1969; a photographic/infrared/radar survey of Brazil in 1970; and a multi-band camera survey from sun-synchronous orbit in 1969. Results are presented as geographic overlays and as graphs of numbers of frames acquired versus orbital stay-time. Conclusions are drawn regarding the utility of the technique and several heretofore unexplored areas of mission integration.*

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[1] "Earth-Resources Satellite System," Report for the Subcommittee on NASA Oversight of the Committee on Science and Astronautics, House of Representatives, 90th Congress, Second Session, 12/31/68, Government Printing Office.

[2] Badgley, P. C., and Vest, W. L., "Orbital Remote Sensing and Natural Resources," PHOTOGRAMMETRIC ENGINEERING, Vol. XXXII, No. 5, Sept. 1966, p. 780.

Table 1. The Utility of the Earth-Orbital Profile Analysis

Specifies sub-orbital positions and times for sensor activation; Provides a basis for estimating:
  Sensor Durations
  Flight Durations to Complete Experiments
  Data Quantity
  Equipment Duty Cycles and Sequences
  Sensor Time-Sharing Arrangements
  Launch-Window Requirements
  Comparative Advantages of Survey Alternatives

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can be usefully applied to help in the process of mission and instrument definition.

THE EARTH-ORBITAL PROFILES ANALYSIS PROCEDURE

In an effort to integrate sensor specifications, mapping requirements, and orbital characteristics, an Earth-orbital Profiles Analysis (EPA) technique was developed. This technique is capable of providing data regarding actual flight durations, sensing durations, astronaut time requirements, equipment duty cycles, alternate flight profiles for various survey plans, time-sharing requirements for multi-instrument missions, and launch windows commensurate with the complex multi-instrument capabilities. The utility of the technique is summarized in Table 1.

The basic technique for the Earth-orbital Profile Analysis is outlined in Figure 1. Starting with the orbital constraints for the vehicle and the experiment and the instrument characteristics, an empirical review is made to examine the initial compatibility. After a reasonable combination has been synthesized, the characteristics are inserted into a specially designed, high-speed digital computer program, ERSOS (Earth Resources Survey Orbital Simulator). The computer outputs are analyzed manually and two basic types of results are prepared: a pictorial profile (map with orbital tracks) and a graphical profile.

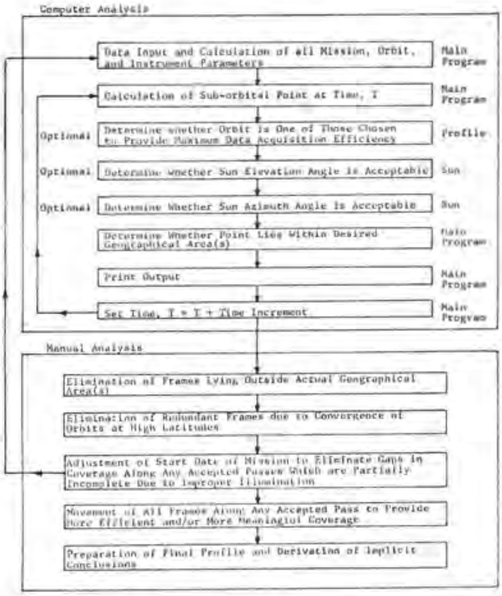


Fig. 2. Flow chart for ERSOS analysis.

A flow chart for the ERSOS procedure is shown in Figure 2. ERSOS is an adaption of TRACE, another IIT Research Institute program which provides incremental points along the ground track of any spacecraft in Earth orbit. In TRACE the time increment which determined the frequency of calculation of successive suborbital points was supplied to the program as input data. In ERSOS the time increment is adjusted constantly to be the same as the time required by the orbiter to traverse the field of view of the particular remote sensor for which the time pro-

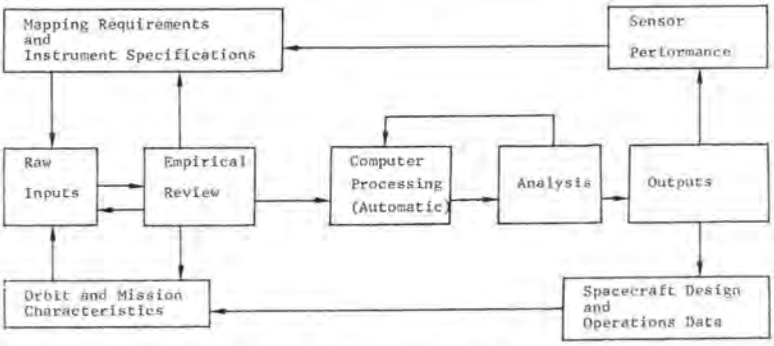


Fig. 1. Earth orbital profile analysis.

file is to be designed. Thus, each ground point calculated by ERSOS represents one sensor record (frame).

In the following sections of the paper, the results of the application of this technique are given for three cases. It must be reemphasized that the sensors and missions described are, for the most part, hypothetical, although in all cases it is expected that the as-yet-undefined systems will not differ greatly from the educated estimates presented here. The first case involves a multi-band camera survey of Brazil in July, 1969. In the second case the analysis is extended to include not only a metric camera but also a radar and infrared sensor. Finally, a multiband camera system in a sun-synchronous orbit is considered for mapping the Western hemisphere.

RESULTS

CASE 1—MULTI-BAND CAMERA SURVEY OF BRAZIL IN 1969

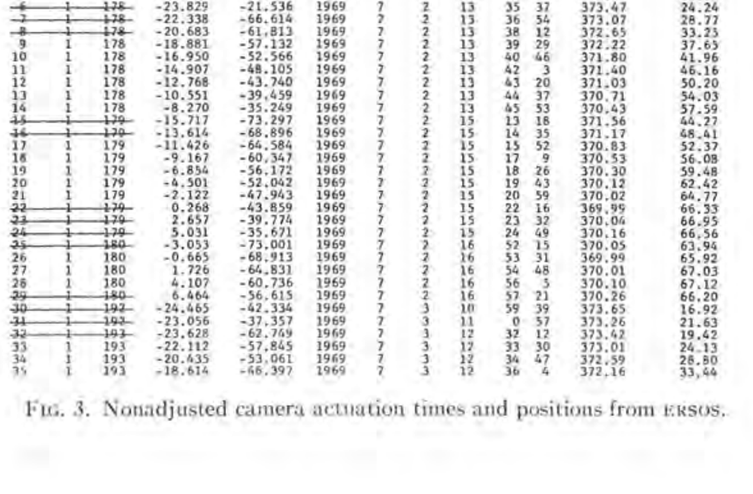
In order to illustrate the method, a 1969 survey of Brazil was hypothesized using a six-lens multiband camera. The input parameters assumed were as shown in Table 2.

The multiband camera was selected as being typical of the type of sensor which might be flown in a 1969 manned mission. It would provide film data of good spectral and spatial quality of use to scientists engaged in studies of mineral and petroleum resources, water resources and land use, and agriculture and forestry resources. In early manned missions, the propulsion limitations may restrict the orbital inclination to 28.5° so that only the extreme South of the USA could be covered. Hence, if a substantial survey is to be conducted, a country near the equator would have to be chosen. Brazil is a good candidate because it is actively participating with the USA in Earth Resources Satellite studies.

TABLE 2. INPUT PARAMETERS FOR A HYPOTHETICAL SURVEY OF BRAZIL

Instrument Parameters	
Name	Multiband camera
Field of view	74°×74°
Latitudinal overlap	0 percent
Longitudinal overlap	0 percent
Sun elevation angle limits	15–75°
Orbital Elements	
Radius	6748.38 kilometers (200 N.M.)
Eccentricity	0. (circular)
Inclination	28.5° (due east launch from Cape Kennedy; initial ascending node is 164.7° W longitude)
Mission Specifications	
Start date	June 21, 1969 6:00 (GMT)
End date	July 5, 1969 6:00 (GMT)
Launch coordinates	Cape Kennedy 28.5°N latitutde 80.6° W longitude
Geographical areas	Brazil
Boundaries	7.0°N latitude to 34.0°S latitude 37.7°W longitude to 74.0°W longitude

Figure 3 illustrates some of the tabular out-



CASE NO	AREA NO	ORBIT NO	LATITUDE (DEGREES)	LONGITUDE (DEGREES)	TIME (GMT) YEAR	MONTH	DAY	HOUR	MIN	SEC	ALTITUDE (KM)	SUN ELEVATION (DEGREES)
~~1~~	~~1~~	~~177~~	-25.843	-56.242	1969	7	2	12	1	47	374.05	17.24
~~2~~	~~1~~	~~177~~	-24.651	-51.133	1969	7	2	12	3	4	373.70	21.82
~~3~~	~~1~~	~~177~~	-23.268	-46.139	1969	7	2	12	4	22	373.32	26.36
~~4~~	~~1~~	~~177~~	-21.710	-41.265	1969	7	2	12	5	39	372.91	30.86
~~5~~	~~1~~	~~177~~	-19.996	-36.511	1969	7	2	12	6	56	372.48	35.29
~~6~~	~~1~~	~~178~~	-23.829	-21.536	1969	7	2	13	35	37	373.47	24.24
~~7~~	~~1~~	~~178~~	-22.338	-66.614	1969	7	2	13	36	54	373.07	28.77
~~8~~	~~1~~	~~178~~	-20.683	-61.813	1969	7	2	13	38	12	372.65	33.23
9	1	178	-18.881	-57.132	1969	7	2	13	39	29	372.22	37.65
10	1	178	-16.950	-52.566	1969	7	2	13	40	46	371.80	41.96
11	1	178	-14.907	-48.105	1969	7	2	13	42	3	371.40	46.16
12	1	178	-12.768	-43.740	1969	7	2	13	43	20	371.03	50.20
13	1	178	-10.551	-39.459	1969	7	2	13	44	37	370.71	54.03
14	1	178	-8.270	-35.249	1969	7	2	13	45	53	370.43	57.59
~~15~~	~~1~~	~~179~~	-15.717	-73.297	1969	7	2	15	13	18	371.56	44.27
~~16~~	~~1~~	~~179~~	-13.614	-68.896	1969	7	2	15	14	35	371.17	48.41
17	1	179	-11.426	-64.584	1969	7	2	15	15	52	370.83	52.37
18	1	179	-9.167	-60.347	1969	7	2	15	17	9	370.53	56.08
19	1	179	-6.854	-56.172	1969	7	2	15	18	26	370.30	59.48
20	1	179	-4.501	-52.042	1969	7	2	15	19	43	370.12	62.42
21	1	179	-2.122	-47.943	1969	7	2	15	20	59	370.02	64.77
~~22~~	~~1~~	~~179~~	0.268	-43.859	1969	7	2	15	22	16	369.99	66.33
~~23~~	~~1~~	~~179~~	2.657	-39.774	1969	7	2	15	23	32	370.04	66.95
~~24~~	~~1~~	~~179~~	5.031	-35.671	1969	7	2	15	24	49	370.16	66.56
~~25~~	~~1~~	~~180~~	-3.053	-73.001	1969	7	2	16	52	15	370.05	63.94
26	1	180	-0.665	-68.913	1969	7	2	16	53	31	369.99	65.92
27	1	180	1.726	-64.831	1969	7	2	16	54	48	370.01	67.03
28	1	180	4.107	-60.736	1969	7	2	16	56	5	370.10	67.12
~~29~~	~~1~~	~~180~~	6.464	-56.615	1969	7	2	16	57	21	370.26	66.20
~~30~~	~~1~~	~~192~~	-24.465	-42.334	1969	7	3	10	59	39	373.65	16.92
~~31~~	~~1~~	~~192~~	-23.056	-37.357	1969	7	3	11	0	57	373.26	21.63
~~32~~	~~1~~	~~193~~	-23.628	-62.769	1969	7	3	12	32	12	373.42	19.42
33	1	193	-22.112	-57.845	1969	7	3	12	33	30	373.01	24.13
34	1	193	-20.635	-53.061	1969	7	3	12	34	47	372.59	28.80
35	1	193	-18.614	-46.397	1969	7	3	12	36	4	372.16	33.44

FIG. 3. Nonadjusted camera actuation times and positions from ERSOS.

put from ERSOS for the given inputs. A total of 80 frames of photography were postulated. However, post-computer analysis reduced the list to 50 frames in a two-day period. A geographical presentation of the results is given in Figure 4. The location of the observations which meet the lighting and coverage specifications in a minimum time are shown. As the return film weight is light, the astronaut time requirement is modest, and the duration is short,[3] a complete survey such as this might be feasible.

FIG. 4. High temporal and spatial efficiency imaging profile derived by computer analysis (Case 1).

CASE 2—CAMERA, INFRARED, RADAR SURVEY OF BRAZIL IN JULY 1970

In the second case, the analysis is extended to include not only a metric camera, but also a radar and infrared sensor. Although not critical to the present study, the camera might have a 6-inch focal length, the radar might be a side-looking coherent, synthetic-aperture type, and the wide-range scanning imager might have a spectral range from 0.4 μ to 14 μ. The characteristics chosen for mapping are listed in Table 3. In particular, the swath widths were made to overlap.

Also listed in Table 3 are a series of solar illumination conditions reflecting the fact that, taken individually, the instruments have differing sun-angle requirements, depending on both intrinsic sensor sensitivities and user requirements. Calculations were made from the extremes of continuous operation (no solar constraints), to limited operation in the early and late morning as well as early and late afternoon. Only the radar can fully capitalize on the former condition, i.e., it need not be constrained to the limitations of the visible and infrared sensors. However, it is desirable to obtain similar imagery from all three sensors, as regards solar angle, so that cross-interpretation of data from the three images is meaningful. For instance, some question arises as to whether a photograph of a forest region taken at 1500 local

TABLE 3. INSTRUMENTS AND ILLUMINATION CONSTRAINTS (CASE 2)

Instrument Specifications

Instrument	*Swath Width (n.m.)*	*Swath Length (n.m.)*	*Ground Area (Sq.n.m.)*	*Frame Time (seconds)*	*Film Speed (in./sec)*
Metric Camera	240	150	36,000	36	N/A
Radar Imager	22	Continuous	90/second	N/A	0.47
Wide Range Scanning Imager	240	Continuous	1,000/second	N/A	0.041

Solar Illumination Conditions

Instrument	*None (Day & night)*	*−30 to +30°; −75 to −90°; +60 to +90° (Sunrise, sunset, midnight, noon)*	*15 to 75° (Morning, afternoon)*	*15 to 30°; 60 to 75° (Early & late morning, early & late afternoon)*
Metric Camera			X	X
Radar Imager	X		X	X
Wide Range Scanning Imager		X	X	X

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[3] Statistical studies of the impact of cloud interference on duration are planned.

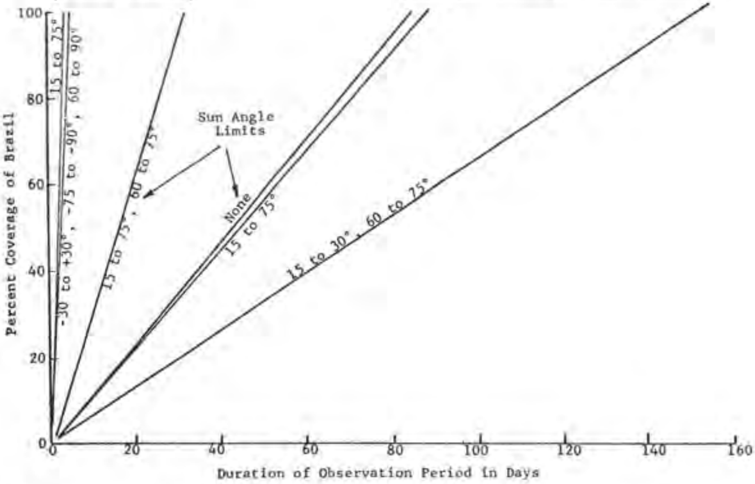

FIG. 5. Rates of data acquisition for three sensors (Case 2) under appropriate illumination constraints over Brazil. (Launch 7/1/70, 200 n. m. altitude, 50° inclination.)

sun time can be legitimately compared to a radar image of the same area nine hours later. A heavy rain during the early evening might easily render cross-analysis meaningless. Thus the purpose of applying solar constraints to the radar imager.

Because Case 2 involves a more complex and heavier sensor package, the manned flight was assumed to be a year later than Case 1, i.e., 1970. For purposes of comparison with Case 1, Brazil is selected as the country to be surveyed. The orbital altitude of 200 nautical miles is retained but the inclination is increased to 50°. If these specifications are considered to be nominal and slight deviations in either or both are permitted, much more efficient coverage in terms of areal redundancy and mission duration is possible,

TABLE 4. SUMMARY OF RESULTS FOR THE MISSION OVER BRAZIL (CASE 2)

	Dur. Obs. (Days)[1]	*Elapsed Time (Days)*[2]	*Number of Passes*	*Coverage (%)*	*Sidelap*[3] *(%)*	*Length of Film (Feet)*	*Weight of Film (Pounds)*
Metric Camera (No Overlap)							
15 to 75°	4	4	11	100	16	112[4]	3.7
15 to 30°; 60 to 75°	31	22	17	96	16	105[4]	3.5
Radar Imager							
No Sun Angle Limits	31	26	55	36	36	830	6.1
15 to 75°	31	29	54	35	36	610	4.5
15 to 30°; 60 to 75°	31	27	38	20	36	250	1.8
Wide Range Scanning Imager							
−30 to +30°; −75 to −90°; +60 to +90°	5	5	11	100	16	13	0.1
15 to 75°	4	4	11	100	16	11	0.1
15 to 30°; 60 to 75°	31	22	17	96	16	12	0.1

[1] Duration of Observation (Period of days from first to last observation).

[2] Actual Elapsed Time for Observation (Number of days during which observations were made).

[3] Maximum possible at the equator for the given swath widths.

[4] Number of frames

(Launch July 1, 1970; 200 N.M. altitude; 50-degree inclination.)

TABLE 5. DATA BULK REQUIREMENTS FOR THE MULTIBAND CAMERA SUN-SYNCHRONOUS MISSION (CASE 3)

Geographical Area Mapped	*Area (Mill. Sq. N. Mi.)*	*Operational Period (Days)*	*Percent Overlap*	*Number of Records*	*Film Weight (lb)**
North, Central, South America	11.5	7	10 50	1,533 2,760	32 57
Conterminous United States	2.7	7	10 50	393 708	9 16

* 4-mil ESTAR base film.

particularly with the radar imager. This is because the cycle time[4] is very sensitive to altitude and inclination. A ten-nautical-mile decrease in altitude would create a 30 percent saving in mission duration and data bulk for radar coverage. Commensurate savings for the other two instruments could be realized. However, the interplay between the orbital elements and instrument specifications is very complex and it is not possible to estimate the necessary adjustments and associated savings intuitively.[5]

A summary of the results for all combinations considered for this case is given in Figure 5 and Table 4. It can be seen from Figure 5 that cloud-free surveys with sensors having wide swath widths can be accomplished in a few weeks, even with restricted solar illumination conditions. A survey with the side-looking radar would take three months even when operated without sun-angle limits.[6] Using the radar during the morning and afternoon (sun angle 15°–75°) simultaneously with the other two sensors, would greatly enhance the data interpretation, and would not have a noticeably adverse effect on the length of time required to obtain the images.

In Table 4, numerical results are shown for this mission during the first month. Assuming no clouds, the camera and the scanning imager could cover almost 100 percent of Brazil even under restricted lighting conditions. The narrow swath width of the radar

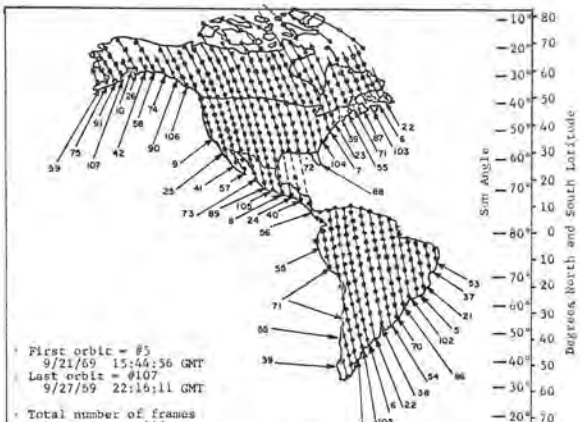

FIG. 6. Pictorial experiment profile for the multiband camera in a sun-synchronous orbit (Case 3).

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[4] By *cycle time* is meant the time required to view the entire geographical area of interest with a given sensor field of view, orbital altitude, and orbital inclination.

[5] Tables showing the cycle time as a function of swath width and inclination have been calculated by IITRI for 10-nautical-mile variations in altitude.

[6] Although the probabilities have not yet been calculated, it might take many months for the camera and infrared survey when allowance is made for cloud interference.

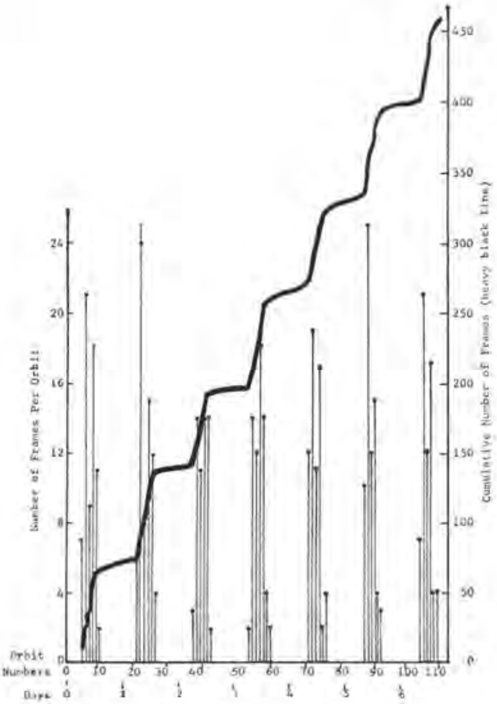

FIG. 7. Graphical profile for the multiband camera experiment in a sun-synchronous orbit. (North, South and Central America; 128 n. m. altitude; no overlap or sidelap; Case 3.)

limits the total net coverage to about a third. In all cases, the weight of the returned film is only a few pounds.

CASE 3—MULTIBAND CAMERA SURVEY FROM SUN-SYNCHRONOUS ORBIT

Experiment profiles were calculated for a multiband camera system in a sun-synchronous orbit[7] of 128 nautical miles altitude launched on September 21, 1969. The low altitude was chosen to provide good ground resolution. It was assumed that the three 6-inch focal length cameras employed 9-inch film. Each camera had a 74-degree field of view giving a 192-nautical-mile swath width. For this short flight-time mission, the number of observations at two levels of overlap were calculated as shown in Table 5. The 50-percent overlap case would be useful for stereo mapping but would require considerable film: 57 pounds for a survey of the Western Hemisphere land mass.

A pictorial profile for a 7-day Hemisphere survey with no overlap is shown in Figure 6. The number of records would be reduced from 2,760 for 50 percent overlap to 1,380 for 0 overcent overlap. At the selected altitude of 128 nautical miles and the swath width of 192 nautical miles, the cycle time for repetitive coverage is seven days.

The timing of the observations for the no-overlap Western Hemisphere survey is shown in Figure 7. It can be seen that the acquisition has regular timing (vertical bars) which is very desirable for operational control. On the order of 11 observations are made during each of the six orbits per day.

It must be emphasized that adverse weather conditions may cause many desired sites to be cloud-covered during all or a part of the mission. Ground control of the cameras may not be possible or practical for all locations. Thus, a redundancy of several hundred percent in film capacity may be desirable so that pictures over unmonitored locations may be taken at all opportunities during the mission. This will insure the greatest probability of obtaining some useful photography of all desired sites.

CONCLUSIONS

The instrument and mission conditions given are hypothetical, serving to illustrate the use of the Earth-orbital Profile Analysis technique. However, the utility of this technique to integrate the sensor designs, user requirements, and mission parameters has been demonstrated. In fact, using the technique on a feedback basis could accelerate the complex process of determining the most efficient mission/experiment combinations.

The profile analyses can provide useful recommendations concerning swath widths and orbital conditions to produce the specified coverage. Pertinent mission planning information can be furnished, such as the number and sequence of observations, mission duration, etc. Rapid parametric analyses can be completed showing the effects of variations in illumination and overlap. The profile analysis technique will be improved when tables of cycle time *vs* altitude and inclination, and statistical cloud-cover data are incorporated.

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[7] A sun-synchronous orbit enables the satellite to pass over a given latitude at the same local sun time on every orbit, e.g., constant lighting.