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SOME CONSIDERATIONS IN THE SELECTION OF AIRCRAFT FOR EARTH RESOURCE OBSERVATIONS

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16. Abstract

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The analysis is necessarily suboptimum because it does not include comparisons with satellite coverage, either satellites by themselves or satellites in conjunction with aircraft. Neither does it include consideration of the techniques or cost of data collection, data processing, or data dissemination (an unresolved problem for both aircraft and satellites that could completely overshadow the selection between aircraft or satellites or both).The data handling problems are omitted mainly because the resolution and coverage requirements of the user and the capabilities of the supplier are very speculative at the present time. Finally, no conclusions are offered without reservation because it is recognized that the actual performance and usefulness of the observation options can be known only after thorough testing.

The results obtained in this analysis show an advantage in cost and rate of coverage for a special fleet of twin engine turbojets over all other aircraft options. Special fleets of turboprop, large turbojet, piston engine planes and commercial air carriers were found to be inferior, principally because of the greater number of aircraft required to achieve comparable coverage. To illustrate, to cover 45 to 95 percent of the resources considered about every two weeks, the special fleet of twin-engine jets requires 6 to 30 aircraft, while the commercial air carrier numbers range from 36 to 180 for coverage ranging from 40 to 80 percent. Annual program operating costs would appear to run between $2 and $10 million plus the costs associated with payload and data handling. Total costs might average between $10 and $100 million annually.

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SUMMARY

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INTRODUCTION

It is not difficult to see that the increasing demands being placed on the earth's natural and cultivated resources will require more frequent and more accurate inventory. The disciplines of principal concern include geology, agriculture, forestry, oceanology, meteorology, storm damage and earthquake assessment, hydrology and snow cover, urban and suburban planning, wild and domestic wildlife population, and a better overall understanding of environment and ecology.

Despite the uncertainty concerning the proper role of aircraft and satellite borne survey equipment in future world resource evaluations, certain suboptimum analyses can be performed to explore the tradeoff areas between various aircraft and spacecraft modes of making such surveys. It was the purpose of the analysis reported here to determine what conclusions might be drawn relative to the use of aircraft in earth resource surveys, without addressing the larger questions of aircraft appropriateness in general.

This report discusses briefly the kinds of resources that might be covered in a typical survey. It examines the possibility of coverage first by a special fleet of aircraft and second by existing commercial air carrier systems. It shows some of the effects of cloud cover and discusses the costs of the various options. Only the coterminous continental United States is included in the analysis.

ANALYSIS

The analytic elements used to estimate the number of aircraft needed for the survey and the associated program costs are described below.

Resources and Coverage Potential

Four observation features (resource categories) were selected as representative of the range of areas, geographic locations, and observation schedules that would be encountered in an earth resources program: agricultural crops, snow cover, forestry, and minerals. Table 1 lists the observation schedule and area of each resource. Figure 1 shows their locations superimposed on a map of the Unites States, and figure 2 illustrates the observation schedule graphically. In figure 3 the instantaneous total coverage rate in terms of area per week is given for the four resources.

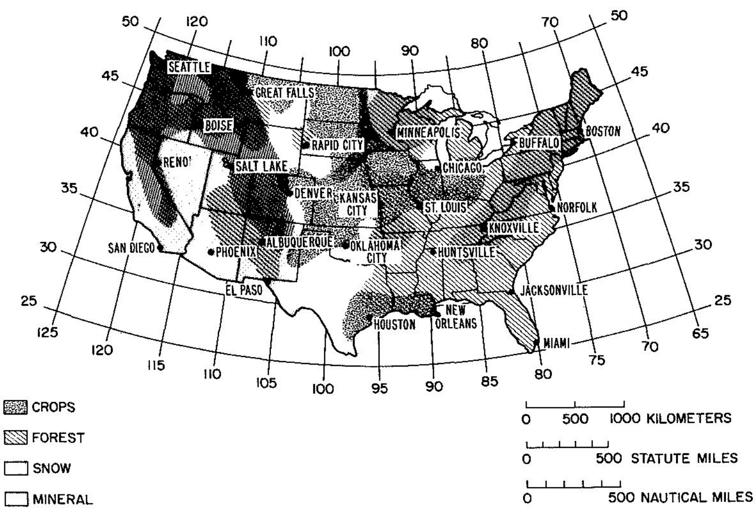

Figure 1.- Resource areas and possible base locations.

The use of aircraft to perform earth resource observations with visual imaging or other sensors permits a number of tradeoffs among altitude, swath width, resolution, and coverage rate. One tradeoff is virtually predetermined, however. If the resolution achievable from orbit with reasonable coverage rates can be considered adequate, resolution must

TABLE 1.– SELECTED EARTH RESOURCE CHARACTERISTICS

Name		Observation schedule	Area km^2 (nm^2)
Snow cover		Every two weeks Dec. 1 – June 30	1,450,000 (422,000)
Mineral Deposits	West	Twice Sept. and Oct.	2,740,000 (800,000)
	East	Twice Sept. and Oct.	1,520,000 (445,000)
Forest mapping	West	20 percent coverage once each week, March – May; Sept. – Nov.	1,600,000 (468,000)
	East	20 percent coverage once each week, March – May; Sept. – Nov.	2,840,000 (830,000)
Crop inventory	North wheat	Every two weeks	356,000 (104,000)
	South wheat	See figure 2	336,000 (98,000)
	Corn belt		878,000 (256,000)
	Texas/ Louisiana		206,000 (60,000)

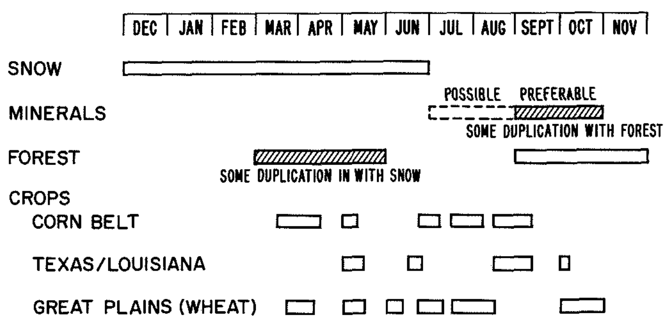

Figure 2.- Observation schedule for selected earth resources.

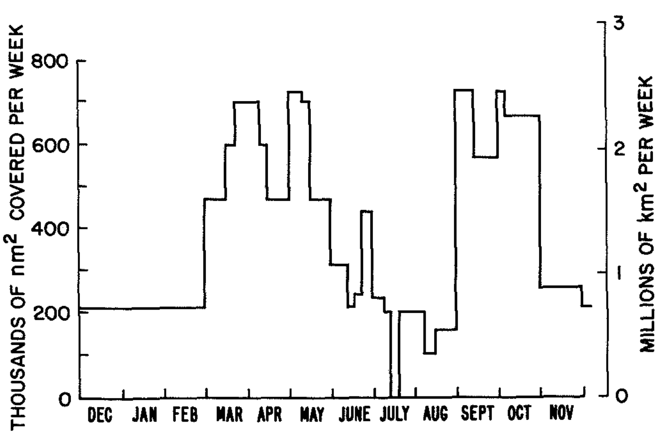

Figure 3.- Resource area coverage rate.

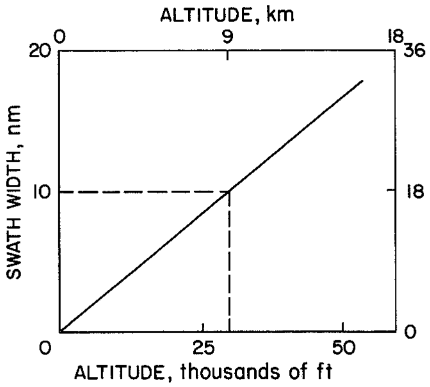

Figure 4.- Swath width vs. aircraft altitude for 90° field of view.

be adequate from aircraft altitudes. Therefore it is assumed in this analysis that aircraft will fly at maximum practical altitude to achieve maximum swath width and still retain a useful resolution.[1] Swath width is, of course, not just a function of altitude; it is dependent upon the angular field of view of the sensor or camera lens. The maximum field of view tolerable is determined by the loss of resolution and distortion at the edges of the swath. A 90° field of view approaches the limits of acceptable fidelity – producing about half the resolution at the edges as at the center of the field. The swath width from a 90° field of view is, of course, twice the aircraft altitude and is shown in figure 4 as a function of altitude.

Resource Coverage With a Special Fleet of Aircraft

The selection and deployment of aircraft depends on the characteristics of the aircraft that might be chosen and the tradeoff factors associated with logistics and base location. It seems obvious that economics should also be an important consideration in the formulation of the objectives and the methods of achieving those objectives. Intuitively it could be postulated that (1) the longer the range of the plane the better, because it allows more versatile flight patterns; (2) the more bases (and aircraft) the better because less time is spent approaching the areas to be observed; (3) bases should be located where observations are required most frequently, for the same reasons as 1 and 2; and (4) minimizing the number of bases is desirable in order to simplify logistics and data handling.

The first step in determining an aircraft's economy of usage is to measure the efficiency with which it can cover the resource areas. The efficiency is defined here as the ratio of the number of air miles that would be needed to cover an area under ideal circumstances to the number of air miles that are actually needed because of unavoidable duplication and overlap. For example, an aircraft-sensor combination with a 10 km swath width that must fly 1000 km to cover an area of 8000 km^2 has a coverage efficiency of 80 percent. By the same definition an aircraft with a 1000 km range based solely at Chicago would have zero efficiency because no matter how many hours or miles it flew, it could not cover those resource areas beyond its range capability. The fraction that it could cover could be calculated, but this case is not considered since additional bases can be located to ensure complete coverage.

The nation's resource areas (which effectively include the entire United States) can be divided into regions of almost arbitrary shape and size. Graphical exercises were performed to determine the effect of area shape and size on aircraft coverage efficiency. That is, coverage efficiencies were graphically calculated for hexagonal, square, and rectangular shaped areas of different sizes for various aircraft ranges and swath widths. It was found that as the dimensions of the area grow larger relative to the range of the aircraft, the coverage efficiency decreases gradually to about 75 percent, then drops suddenly as the range capability of the aircraft is exceeded. Many factors affect coverage

[1]Swath width is the linear dimension normal to the flight path of the ground area examined at one time. Resolution is a rough gage of the object size that can be seen by the sensor.

efficiency, but the overriding one appears to be the ratio of the distance to the farthest point within the area and the range of the aircraft, or, more precisely, the ratio of maximum excursion distance and half range since the aircraft returns to the same base. (Interbase flights were also examined and found to have no advantage.)

Figure 5 depicts the results of graphical exercises, showing coverage efficiency versus the ratio of twice the maximum excursion distance and the aircraft range. The various symbols found on the graph represent different shapes that were investigated; squares for square areas, hexagons for hexagonal, and diamonds for rectangular areas. The hexagons and squares follow a rather smooth curve because their shapes are controlled as their size changes. Rectangles with the same maximum excursion distance or diagonal, on the other hand, can vary considerably in area and coverage efficiency as illustrated on the graph. Those rectangles that offer relatively high coverage efficiency are deceiving because they are also very eccentric and consequently of low area. The investigation showed that coverage efficiency is very closely allied to the size of the region to be covered and therefore shape is not of great consequence. For this reason the curve for square areas is used as representative in the remainder of the analysis.

The size and, to some extent, the shape of an area to be covered from a base are determined by the number and location of the bases used. Figure 1 shows, in addition to the resource areas, 24 possible base locations. If only one base is to be used, it should probably be centrally located, perhaps at Kansas City. If two are to be used, some flexibility is allowed, but they too should be strategically located; in this case Salt Lake City and Knoxville are suggested. For three, the selection can be more arbitrary but is still somewhat restricted; here Salt Lake City, Kansas City, and Norfolk are suggested. When four or more bases are used, the possibilities become very large. Table 2 gives possible base combinations for various numbers of bases as labeled in figure 1. For four, five, six, and ten bases alternative groups are given. To estimate the coverage efficiencies associated with different groups of bases, estimates of the average distance between bases and the consequent maximum excursion distances were made and are plotted in figure 6. These distances then supply all

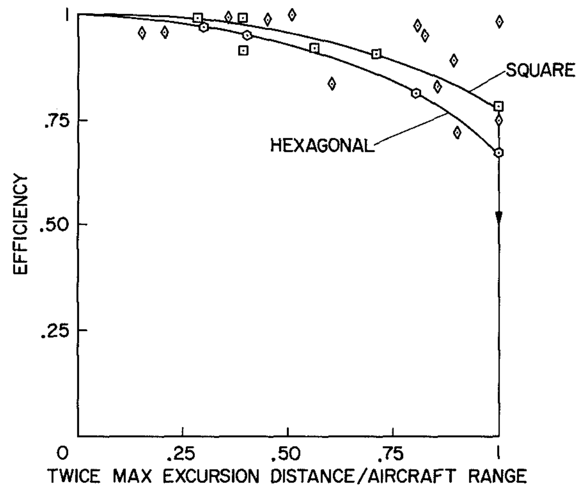

Figure 5.- Area coverage efficiency.

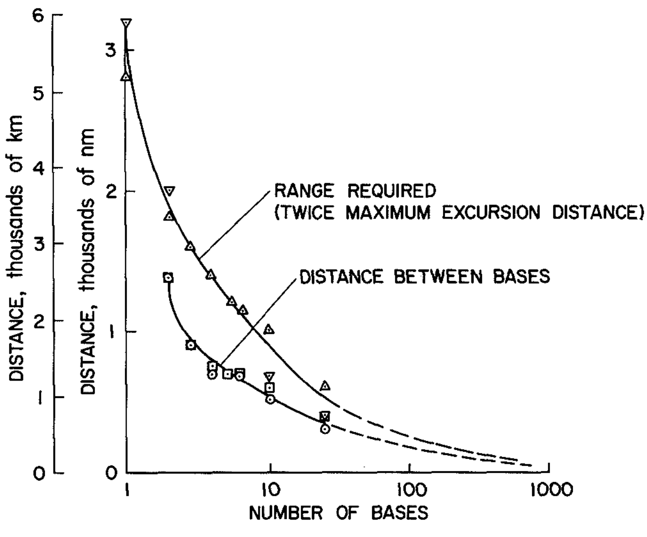

Figure 6.- Distance between bases and maximum excursion distance.

TABLE 2.– GROUPS OF BASES

Number of bases			
1	Kansas City		
2	Salt Lake City Knoxville		
3	Salt Lake City Kansas City Norfolk		
4	Reno Denver St. Louis Norfolk	Boise Albuquerque Minneapolis Knoxville	Reno Denver Huntsville Buffalo
5	Seattle Salt Lake City Oklahoma City Chicago Norfolk	Seattle Salt Lake City Kansas City Knoxville Boston	Boise Albuquerque Minneapolis New Orleans Boston
6	Seattle San Diego Denver Minneapolis New Orleans Norfolk	Reno Albuquerque Rapid City St. Louis Jacksonville Boston	Reno Albuquerque Rapid City Kansas City Knoxville Buffalo
10	Seattle San Diego Salt Lake City Albuquerque Rapid City Oklahoma City Chicago New Orleans Knoxville Boston		
24	Seattle Reno San Diego Boise Salt Lake City Great Falls Phoenix Rapid City Denver	Albuquerque El Paso Minneapolis Kansas City Oklahoma City Houston Chicago St. Louis Huntsville	New Orleans Buffalo Knoxville Jacksonville Norfolk Boston

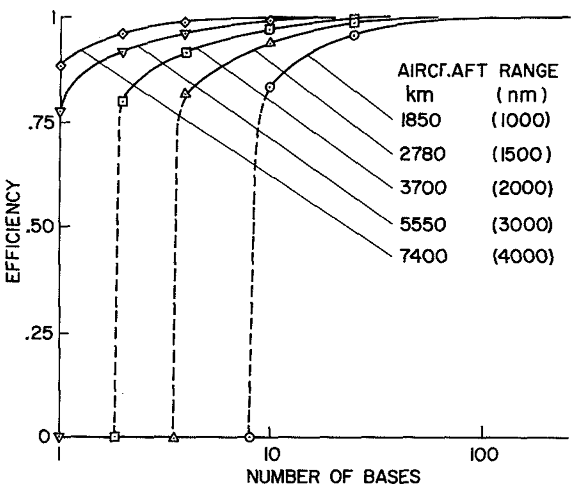

Figure 7.- Coverage efficiency vs number of bases for various aircraft ranges.

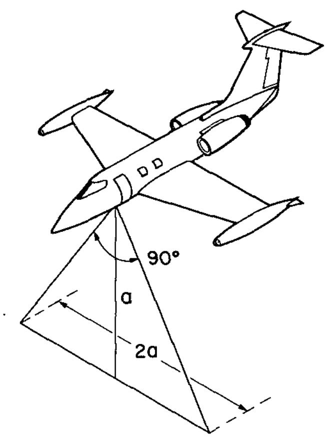

Figure 8.- Aircraft coverage parameters.

the data required to plot curves of coverage efficiency for various aircraft ranges versus the number of bases used. The efficiency curves for square areas from figure 5 were used to construct figure 7.

The number of aircraft having known range, altitude, and speed that are required to perform the earth resource survey schedule of figures 2 and 3 can now be easily calculated by dividing the required area coverage rate by the coverage rate per aircraft. Referring to figure 8, the coverage rate of an aircraft with a 90° field of view is given by the formula

$$C = 2aVhE$$

where

a altitude

V velocity

h time flown/reference time

E coverage efficiency (from fig. 7)

The peak coverage rate indicated by figure 3 is more than 2.4 million km^2 (700 thousand nm^2) per week disregarding duplication. Considering that observations of overlapping resource areas can be done simultaneously, and some minor rescheduling could reduce peak rates, the most stringent requirements should not exceed 1.7 million km^2 (500 thousand nm^2) per week, with an average coverage rate significantly less. If this required coverage rate of 1.7 million km^2 per week is assumed along with a 5-day week and an average aircraft air time of 5 hours per day the number of aircraft required is given by

$$N = \frac{(1.7 \text{ million km}^2/\text{wk})/(5 \text{ day/wk})}{2a(\text{km})V(\text{km/hr})\ 5(\text{hr/day})E} = \frac{3.4 \times 10^4}{aVE}$$

where

a altitude in km

V velocity in km/hr

E coverage efficiency

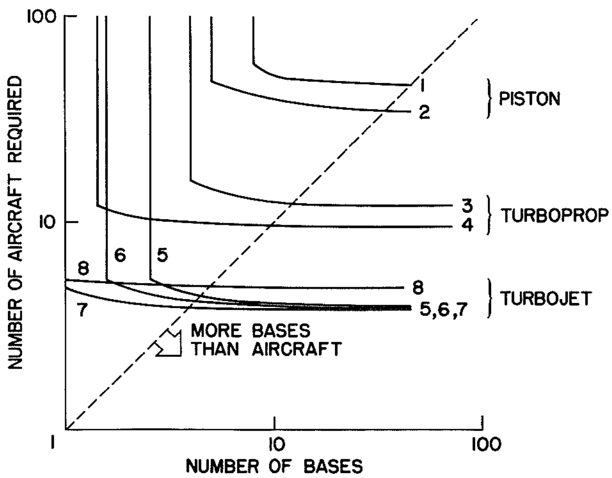

Figure 9.- Number of aircraft required vs. number of bases.

Since the coverage efficiency is a function of the number of bases and the aircraft range, it is a simple matter to plot the number of aircraft required versus the number of bases used. Figure 9 shows the aircraft required in different performance categories numbered one through eight (explained shortly). These curves emphasize again the minor effect of coverage efficiency up to the point where the aircraft range is insufficient. Because of the relative flatness of the curves it would seem advantageous to select a quantity of aircraft close to the knee of the curve in order to minimize the number of bases required. On the basis of these curves, table 3 shows the numbers of aircraft and bases that would be required for each of the eight types.

TABLE 3.– NUMBER OF AIRCRAFT REQUIRED

Aircraft type	Description	Number required	Contingency	Total	Number of bases
1	Light-piston-multiengine	54	5	59	10
2	Heavy-piston-multiengine	42	4	46	7-8
3	Small turboprop	15	2	17	5-6
4	Large turboprop	11	2	13	2-3
5	Two engine jet	5	1	6	3-4
6	Four engine jet	5	1	6	2-3
7	737	4	1	5	1-2
8	707	5	1	6	1-2

There are several types of aircraft that appear to satisfy the requirements of range, speed, altitude, and, presumably, payload for earth observation missions. Strictly speaking, the only aircraft requirements are the ability to carry adequate payload, which may be about 360 kg (800 lb) plus a crew of perhaps another 230 kg (500 lb). The categories of aircraft that could be used to satisfy these requirements range from twin piston engine to four engine jets. Table 4 (constructed from refs. 1-4) shows the salient characteristics, both performance and cost, of the eight aircraft types mentioned earlier.

It is evident from figure 9 that jet aircraft hold the advantage over other types because of their superior range, altitude, and speed. The actual selection, however, should certainly include cost considerations since the jets are more expensive than the piston and turboprop aircraft.

TABLE 4.– CANDIDATE EARTH RESOURCE AIRCRAFT CHARACTERISTICS (WITH CREW)

	Piston-multiengine		Turboprop		Jet		Commercial-type jet	
	(1) Light	(2) Heavy	(3) Small	(4) Large	(5) 2-Engine	(6) 4-Engine	(7) 2-Engine	(8) 4-Engine
Physical characteristics								
Typical example	Twin Comm. AE 500 U	BE S18	MO MU2	Gulf 1	Lear Jet	Jetstar	737	707
Purchase price – F.A.F. $	99,950	179,500	311,000	1,119,000	649,000	1,650,000	4.5 M	
Equipped $	110,000	190,000	320,000	1,300,000	650,000	1,700,000		
Passenger seats	6	9	5	24	6	10		
Utilization, hr/yr	250	300	350	400	450	500		
Block speed, km/hr - knots/hr	300 - 160	315 - 170	400 - 220	485 - 260	725 - 390	725 - 390	770 - 415	925 - 500
Distances flown								
km	74,400	93,400	141,000	193,000	325,000	362,000		
(sm)	(46,250)	(58,500)	(87,500)	(120,000)	(202,500)	(225,000)		
Range w/700 kg (1500 lb)								
km	1850	2400	2600	4100	3100	4000	6100	12,200
(nm)	(1000)	(1300)	(1400)	(2200)	(1700)	(2150)	(3300)	(6600)
Cruise altitude								
km	2.6	3	7	7.6	12	12	12	7.6
(ft)	(8500)	(10,000)	(23,000)	(25,000)	(40,000)	(40,000)	(40,000)	(25,000)
Cost								
Total variable costs	8340	19,575	37,037	85,352	97,920	217,000	$388/flight hr direct (fuel, crew, maintenance, depreciation, insurance) + 20-25 percent indirect (aircraft servicing, G&A)[a]	$628/flight hr direct 20-25 percent indirect[a]
Fuel	2425	6270	7350	28,000	40,950	91,000		
Oil	202	525	112	420	270	1000		
Inspection	1000	2700	3500	8000	6750	20,000		
Maintenance	1388	2745	8750	16,000	11,025	25,000		
Reserve for overhaul	2000	4650	9275	14,200	18,675	27,500		
Parking, fees, misc.	338	450	1400	2400	2025	2500		
Spare parts	112	135	4200	13,332	14,625	45,000		
Pilot expense	875	2100	2450	3000	3600	5000		
Total fixed costs, $/yr	26,225	46,350	55,750	143,500	91,450	195,050		
Depreciation	5500	9500	16,000	65,000	32,500	85,000		
Insurance	5225	8025	8550	34,000	14,900	37,750		
Storage	1500	2000	1800	6000	6000	25,000		
Crew salary/benefits	13,000	25,000	27,000	30,000	31,500	35,000		
Miscellaneous	1000	1800	2400	8500	6550	12,300		
Total annual costs, $/yr	34,565	65,900	92,787	228,852	189,370	412,050		

[a]These cost figures are somewhat low for this application since they are based on higher operating times than represented in this study.

Resource Coverage With Commercial Air Carriers

Commercial air carriers would seem to offer an untapped potential for observation of earth resources based on the diverse route schedule that is maintained. A quick glimpse of airway routes (ref. 5) shows that a great portion of the coterminous United States is covered by high altitude (i.e., above 5.5 km (18,000 ft)) commercial traffic.

Most crosscountry commercial jets fly at altitudes between 9 and 10 km (30,000 and 40,000 ft) that yield an 18 to 24 km (10 to 13 nm) swath width at 90° field of view. This would imply that there would be no difficulty in viewing all those resources within 9 to 12 km (5 or 6 nm) of established airways. Even this estimate is conservative because commercial aircraft frequently deviate from the established airways. In reality the effective swath width is much greater than 18 to 24 km since multiple aircraft tracing the same airway will randomly track different ground paths because radar and inertial guidance permit ease of navigation off established routes. Furthermore, flight controllers space planes to provide proper separation distances, and route flights to avoid bad weather. A random 9 km (5 mile) lateral displacement of several aircraft from the established airway will increase the side view to perhaps 18 km (10 miles) resulting in an effective swath width of 37 km (20 nm). Similarly a 28 km (15 nm) displacement will increase the effective swath width to 74 km (40 nm).

Graphical estimates of coverage were made by using the high altitude air route maps and superimposing swath widths of 18 and 37 km (20 and 40 nm) over the established air routes. In addition to resource coverage, tabulations were made for each state, the Great Lakes, and coastlines. Rhode Island, with the highest coverage, is covered completely by a 37 km (20 nm) swath from commercial airways. Coverages for other states vary from 26 percent (Montana) to 92 percent (Massachusetts); the national average is 47 percent. At an effective 74 km (40 nm) swath width, 21 states have a coverage of 90 percent or better and the national average is increased to 80 percent. Complete coverage is not so easily obtained, however, because total effective swath widths averaging 185 km (100 nm) and as much as 480 km (260 nm) would be required. Great Lakes coverage averages about 30 percent for a 37 km (20 nm) swath and 50 percent for a 74 km (40 nm) swath. Ocean shoreline coverage is 59 percent for 37 km and 82 percent for 74 km.

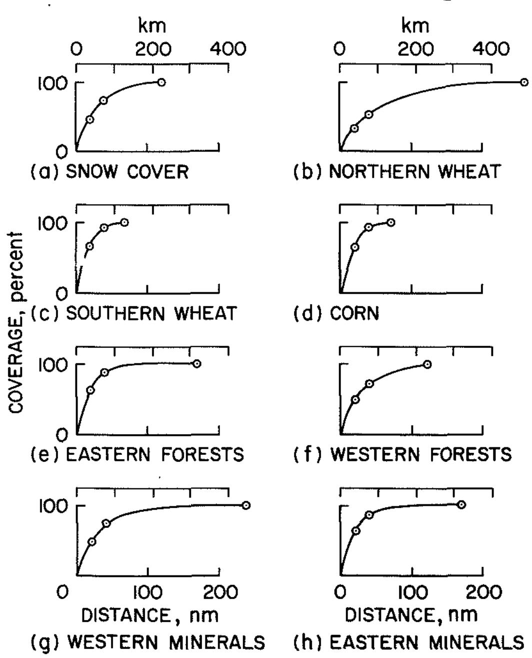

Figure 10.- Effective swath width covered from mean high altitude jet airways and corresponding resource coverage.

Resource features are, of course, the primary concern. Commercial airway coverage of these features is generally good – being 75 to 90 percent complete for all areas at 74 km swath width (with the exception of northern wheat that is about 50 percent complete). Figure 10 summarizes coverage of the resource features as a function of swath width. The results given are based only on the existence of the airways without consideration of the actual traffic. Therefore the more important question regarding the use of commercial air carriers for performing earth resource observations concerns the number of aircraft required (i.e., the number of aircraft that would have to be equipped with sensor packages to provide adequate coverage in an acceptable time). And this, in turn, requires a knowledge of the number of aircraft in service and their scheduling.

An approximation of the number of commercial aircraft available for earth resource observations can be made from the inventory of the domestic trunkline air carriers or the total inventory of the various aircraft types for all air carriers. In an earth resources observation program it would be desirable to use only a few air carriers and modify a minimum of aircraft types. Such a possibility might affect only the largest domestic air carriers and the modification of only large turbojet aircraft. Table 5 (constructed from ref. 6) lists the domestic trunk airlines and an approximation of the number of aircraft held in 1968. Reference 7 gives the composition of the U.S. airline fleet on January 1, 1968 as 706 four-engine turbojets, 410 three-engine turbojets, 196 four-engine turboprops, and 1118 smaller jet and piston-driven aircraft. As of January 1, 1970 the count was 886 four-engine turbojets, 628 three-engine turbojets, 111 four-engine turboprops, and 1065 smaller jet and piston powered aircraft.

TABLE 5.– DOMESTIC TRUNKLINE AIRCRAFT (1968)

American	235
Braniff	73
Continental	54
Delta	122
Eastern	260
National	53
Northeast	39
Northwest	100
PanAm	152
TWA	198
United	342
Western	64
Total	1692

Those air routes within the coterminous United States are regulated by the FAA through 21 air route traffic control centers. The general characteristics of these centers are summarized in table 6. Because of the complex and unpredictable patterns flown by aircraft in commercial air carrier route systems, it would be foolishly optimistic to hope that the number of aircraft required for earth surveys could be accurately specified. Some advantage, however, can be derived from the large number of flights each day and the resultant nearly random coverage. It is true that not all established airways bear the same traffic, but very few routes do not carry some traffic each day, ensuring generally consistent coverage throughout the network of airways. In addition, each air

TABLE 6.– AIR ROUTE TRAFFIC CONTROL CENTER (ARTCC) CHARACTERISTICS

Number of ARTCC in coterminous United States	21
Approximate number of air route miles per ARTCC	8350 km (4500 nm)
Approximate number of air route legs (between beacons) per ARTCC	30
Approximate average leg length	280 km (150 nm)
Total airline legs in United States	630
Total air route leg mileage	175,000 km (95,000 nm)

carrier generally schedules its aircraft somewhat randomly over its designated routes, hence any one aircraft will fly an unpredictable path within the carrier's route system. In 1970 the domestic trunk lines flew 3.26 billion aircraft revenue km (1.76 billion aircraft revenue miles) (ref. 8), which implies an average of about 1.8 million km (one million miles) per aircraft year or nearly 5600 km (3000 nm) per day. The average commercial aircraft, then, covers 20 of the 280 km (150 nm) air route legs per day, or perhaps 10 under acceptable lighting conditions. Under the most optimistic circumstances (i.e., the assumption that aircraft flights are truly random or that airlines and aircraft can be selected to achieve truly uniform coverage) the probability of coverage of a given air route leg or section of the country in n aircraft-days can be simply calculated from the formula

$$P = 1.0 - \left(\frac{629}{630}\right)^{10n}$$

Since the fractional coverage an area receives is statistically equal to the probability of coverage of any particular element, the above equation also represents fractional coverage. This fraction represents an additional restriction to the curves of figure 10 which shows fractional coverage versus swath width. For example, in 100 aircraft-days approximately 80 percent coverage could be expected of the possible 50 percent coverage of snow cover with a 56 km (30 nm) effective swath width or, in other words, only 40 percent coverage of snow cover could be expected in 100 aircraft-days with a 56 km (30 nm) swath width.

The coverage possibilities of figure 10 are, on the other hand, enhanced since commercial flights are frequently directed to fly other than the predesignated airways (entirely different routes rather than the slight deviations mentioned earlier). Since these flights are more or less random, the exact effect on coverage can only be approximated. The Department of Transportation, through the FAA, collects and compiles a great deal of statistical information concerning commercial, military, and general aviation flights (refs. 9,10). This information is primarily intended for planning aviation facilities and services, and therefore lacks the statistics that would be most useful in planning earth resource coverage. Certain general conclusions can nevertheless be drawn from such sources as the enroute IFR peak day charts (ref. 11) that show facsimiles of the actual traffic pattern for the busiest day of the year within each of the ARTCC. These charts show a significant number of high altitude flights (above 5.5 km (18,000 ft)) in other than established jet airways. In most traffic control areas there were as many directed routes carrying five or more aircraft on the busiest day as there are established airways. This would seem to imply a reasonable confidence that additional areas are and will continue to be covered as a matter of course since the average day and peak day traffic are not greatly different insofar as commercial traffic is concerned. Unfortunately, the random nature of these directed flights, the failure of most centers to distinguish between commercial, military, and general aviation flights, the omission of time of day, and manner of chart preparation precludes any definitive statement of the exact coverage that can be expected.

If it is assumed again that flights are truly random, that there are as many directed routes as established airways (for 1260 legs), that 10 of the 20 legs covered in one aircraft day have acceptable lighting conditions, and that 7 and 3 of the legs are airway and directed flights, respectively, the coverage is given by the formula below. The fractional coverage of an area is the average coverage of the airway and directed legs or half the airway fractional coverage plus half the directed fractional coverage, hence

$$F = \frac{1}{2}\left[1.0 - \left(\frac{629}{630}\right)^{7n}\right] + \frac{1}{2}\left[1.0 - \left(\frac{629}{630}\right)^{3n}\right]$$

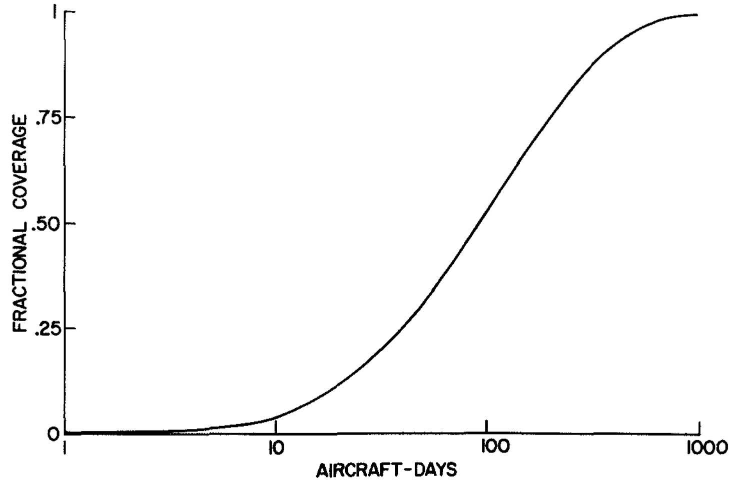

Figure 11.- Expected ground coverage from commercial aircraft.

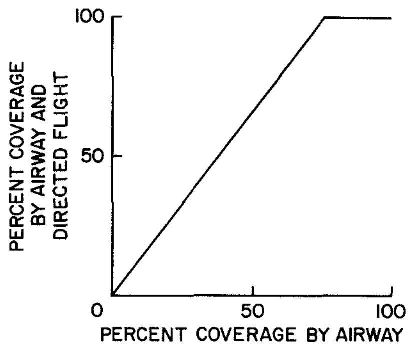

Figure 12.- Effect of directed commercial flights on expected resource coverage.

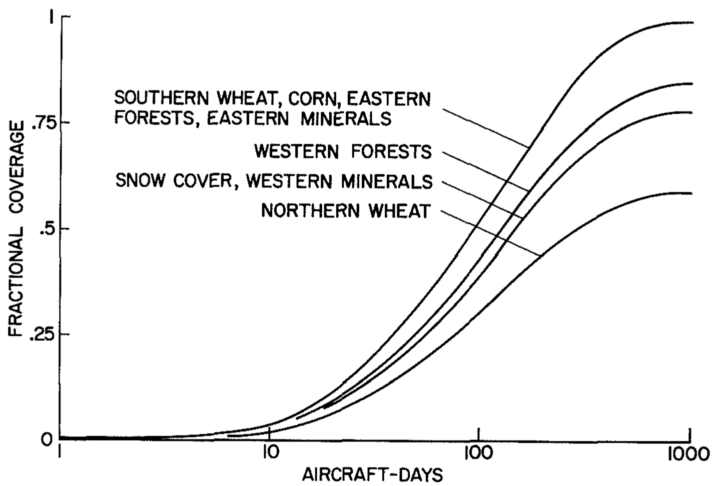

Figure 13.- Expected resource coverage from commercial airlines.

where n, again, represents the number of aircraft-days. Figure 11 shows a plot of this equation (i.e., fractional coverage against aircraft-days). This curve will show a decrease in the coverage represented by the earlier equation because the flights are spread over more routes. It represents, however, an increase in the potential coverage shown in figure 10 since more area is covered by the new routes. Actually the increased potential coverage from directed flights is not quantitatively available since the flights are, as stated earlier, random. A rough approximation can be made visually, however, and is offered in figure 12. This figure suggests that the additional random flights increase the potential coverage by an amount proportional to the original potential coverage. The resource coverage that can be expected, as a function of aircraft-days, is found by combining the data in figures 11 and 12 with that in figure 10, and is shown in figure 13 for an assumed 56 km effective swath width. The figure shows that about 95 percent of the *potential* coverage of any resource area can be achieved in 500 aircraft-days – although note, for example, that 95 percent of the potential coverage is truly only 57 percent of total coverage for northern wheat because even the addition of the new routes does not result in flights over all of that particular resource area.

If 95 percent of the potential coverage can be achieved in 500 aircraft-days, then under truly random circumstances 500 aircraft would achieve 95 percent of the potential coverage in one day, or one aircraft in 500 days, or 36 aircraft in 2 weeks.

The validity of the commercial air carrier approach may depend on the practicality of doing earth resource coverage on an incomplete or sample basis since complete coverage appears infeasible. It may also depend on the nature of the agreements that would have to be negotiated between NASA (or the sponsoring agency), the airlines, and the FAA. In addition, each piece of equipment placed on a commercial airliner must be certified by the FAA.

Cloud Cover

The completeness and quality of the data that can be collected from aircraft (and satellites) is strongly affected by cloud cover; many of the proposed observations cannot be made effectively with cloud interference. For that reason, the performances (i.e., resource coverage figures) indicated earlier are subject to degradation by clouds. Since the overall yearly average cloud cover for the United States is about 54 percent, the effect is significant. The hindrance of clouds would not be the same for a special fleet as it would for commercial flights. Commercial flights are indeed routed to avoid stormy areas, but the total effects of clouds will be nearly random. A special fleet, on the other hand, will fly under a high cloud cover rather than above it. Also, flights can easily be directed to less cloudy areas by making use of the near real time cloud pictures of meteorological satellites.

In the worst case (i.e., if aircraft were flown in a predesignated pattern without prior knowledge or consideration of the cloud cover) then 46 percent of the area would be clear in the first pass (or equivalently the area would have a 46 percent chance of being cloud free). A subsequent pass (presumably the next day) would yield 46 percent coverage of the previously uncovered area, and so on, so that the general formula for coverage, K, is

$$K = 1.0 - (0.54)^P$$

where P is the number of passes or, more realistically, the ratio of the number of planes dispersed in random fashion to the number that would be required under cloudless circumstances. From the formula it is easy to show that twice the theoretically ideal number of planes increases the expected coverage from 46 to 71 percent; $P = 3$ gives 84 percent, $P = 4$ gives 92 percent, and $P = 5$ gives 95 percent. In other words, five times the theoretical number of planes would ensure nearly complete coverage, although a factor of 3 is probably enough, considering that judgment would be used to schedule the flights in other than random fashion.

Economics

The decision between the use of commercial air carriers or a special fleet should ultimately be based on economics as well as effectiveness. Since no two resource survey system techniques or variations of those techniques provide identical coverage or have identical data handling problems, exact cost-benefit analysis cannot be performed, and precise comparisons cannot be made. It is possible, however, to approximate roughly the cost tradeoffs that do exist.

Concerning the special fleet, although fewer jet aircraft are required, it is not obvious that they are more economical than either turboprops or piston-driven aircraft. From the cost data in table 4, it is possible to calculate and plot total annual program cost parametrically against the

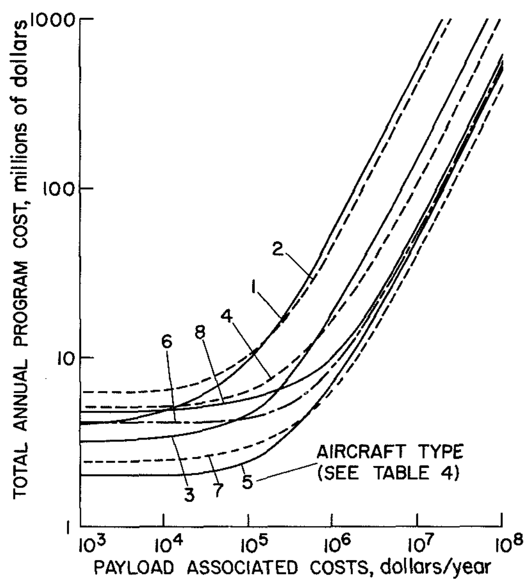

Figure 14.- Special airfleet costs.

currently unknown costs of the payload. Such a cost curve for the eight aircraft types is given in figure 14. Note that the turbojets do maintain their superiority, but at a reduced margin than indicated by the number of aircraft required. The small 2-engine turbojet is cheapest for low payload associated costs (i.e., below about $0.5 million per year) and the large 2-engine jet is best at higher payload costs, although the difference is small. There are two basic factors that determine the shape of all the curves. At low payload-associated costs the aircraft cost is dominant, making the curves basically horizontal; as payload costs increase, the slope increases until it represents virtually only the payload cost.

The payload associated cost scale in figure 14 extends over a wider range of values than of probable interest, for illustrative purposes primarily. In the simplest sense, payload associated costs represent only those costs directly connected with the aircraft operations (such as installation costs, maintenance costs, and amortized purchase cost), in which case $1 million per aircraft/year may represent an upper bound. On the other hand, it is also possible to use the upper portion of the cost curves to estimate total program costs when data handling costs are also included. If the program data handling costs are known, they can be added to the total payload-associated costs and then divided by the number of aircraft used. This figure is then used to enter the horizontal scale.

The cost model for commercial air carriers is very similar to a special fleet, except that freight cost is substituted for aircraft costs. Air carrier freight rates are not standard, being a function of commodity and transfer points. They run between $12 and $25 per 45 kg (100 lb) in the 450 kg (1000 lb) load bracket for a typical 2000 to 5000 km (1000 to 3000 mile) journey. At $20 per 45 kg (100 lb) this would amount to about $200 per aircraft day or $73,000 per aircraft year for a 450 kg (1000 lb) load. Under this assumption curves can be generated showing total annual program costs versus payload associated costs just as with the special fleet. The result has the same general shape as the special fleet curves, with cost figures lower than the piston-driven special fleet but not as low as the turbojets.

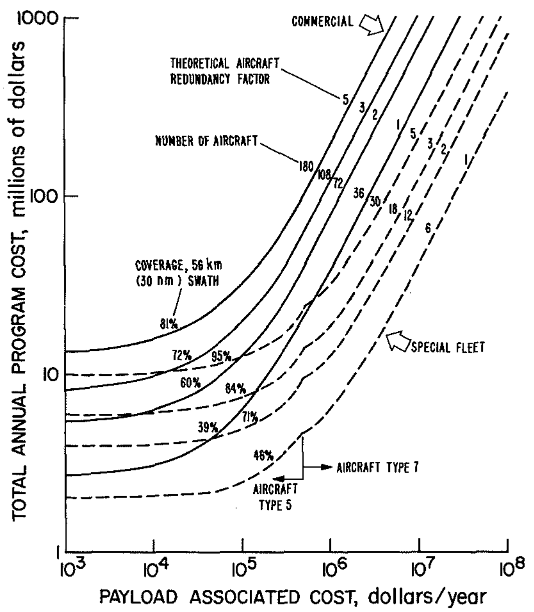

Figure 15.- Cost comparisons for commercial aircraft and a special fleet of aircraft.

Under cloudless conditions it was shown that reasonable earth resource coverage could be implemented with a special fleet of 6 2-engine turbojets or 36 properly equipped commercial air carriers. The coverage would be theoretically complete in the first instance and 85 percent complete in the second. Clouds cause a deterioration in these numbers to 46 and 39 percent, respectively. Consequently, redundancy in fleet size is an obvious consideration. In accordance with the formula given in the discussion of cloud cover, a factor of 2 in the number of aircraft used increases the expected coverage from 46 to 71 percent for the special fleet and from 39 to 60 percent for the commercial air carrier. Under the simplified assumptions made here, a factor of 2 would also be reflected in the operating costs. Figure 15 extends these data, showing the annual program cost and expected coverage for both the special fleet and commercial air carrier for various degrees of aircraft redundancy. The special fleet is seen to be more cost effective regardless of redundancy required or the payload associated costs, and furthermore, enjoys an additional advantage in potential scheduling flexibility that would improve its coverage capability.

CONCLUDING REMARKS

The use of aircraft does indeed seem to be a practical method of conducting surveys of earth resource areas, at least for the continental United States. There is little doubt that aircraft will play a role in future earth resource programs, whether it be alone or in conjunction with satellites. In addition to offering what appears to be very reasonable costs, the use of aircraft presents several attractive features: (1) low altitudes and hence good resolution; (2) ease in recovering data, especially in the form of photographic film or plates; (3) flight planning flexibility to cover areas of special interest or to avoid cloudy areas; and (4) the opportunity to do easy maintenance on systems that do not have to be rated for long life in space.

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Moffett Field, Calif., 94035, July 22, 1971

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