POINTS-TO-POINT COMMUNICATION

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Useful Applications of Earth-Oriented Satellites

POINTS-TO-POINT COMMUNICATION

Prepared by Panel 7 of the
SUMMER STUDY ON SPACE APPLICATIONS
Division of Engineering
National Research Council
for the
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PREFACE

In the fall of 1966, the National Aeronautics and Space Administration (NASA) asked the National Academy of Sciences to conduct a study on "the probable future usefulness of satellites in practical Earth-oriented applications." The study would obtain the recommendations of highly qualified scientists and engineers on the nature and scope of the research and development program needed to provide the technology required to exploit these applications. NASA subsequently asked that the study include a consideration of economic factors.

Designated the "Summer Study on Space Applications," work began in January 1967, guided by a Central Review Committee (CRC) appointed by the Academy. The Study's Chairman was Dr. W. Deming Lewis, President of Lehigh University.

Technical panels were convened to study practical space applications and worked intensively for periods of two to three weeks during the summers of 1967 and 1968 at Little Harbor Farm in Woods Hole, Massachusetts. The work of each panel was then reported to the Central Review Committee, which produced an overall report. Panels were convened in the following fields:

Panel 1: Forestry-Agriculture-Geography
Panel 2: Geology
Panel 3: Hydrology
Panel 4: Meteorology
Panel 5: Oceanography
Panel 6: Sensors and Data Systems
Panel 7: Points-to-Point Communications
Panel 8: Systems for Remote-Sensing Information and Distribution
Panel 9: Point-to-Point Communications
Panel 10: Broadcasting
Panel 11: Navigation and Traffic Control
Panel 12: Economic Analysis
Panel 13: Geodesy and Cartography

The Panel on Points-to-Point Communications was organized in the spring of 1968 and met for several two-day sessions before meeting for two weeks in Woods Hole during July 1968. This report was prepared at Woods Hole under the leadership of Dr. Richard B. Marsten, the Panel Chairman.

The major part of the Study was accomplished by the panels; the function of CRC was to review their work, to evaluate their findings, and, in the context of the total national picture, to derive certain conclusions and recommendations. The Committee was impressed by the quality of the panels' work and has asked that the panel reports be made available to specialized audiences. While the Committee is in general accord with the final panel reports, it does not necessarily endorse them in every detail. It chose to emphasize certain panel recommendations in its overall conclusions and recommendations, which have been presented in Useful Applications of Earth-Oriented Satellites: Report of the Central Review Committee.

In concluding this preface, it is emphasized that the conclusions and recommendations of this panel report should be considered within the context of the overall report of the Central Review Committee.

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1.0 INTRODUCTION

In the closing third of the twentieth century, man's control of the earth's environment and resources has become a sophisticated activity, heavily dependent upon timely technical data. Environmental and resource services provided by United States Departments such as Agriculture, Commerce, and Interior have long included the acquisition and use of such data. Data-collecting platforms (DCP) are widely distributed, among remote as well as accessible land and water regions, in the atmosphere, and in earth orbits; but many are hard to reach to retrieve the data they have gathered. The lack of complete, synoptic data, regularly retrieved and timely, prevents the degree of resource management which a regular, timely, synoptic view could make possible. Existing communication means have not provided, and in 1968 do not provide, a remedy for this deficiency. But it can be remedied with a particular application of earth-oriented communication satellites.

A communication satellite able to interrogate and collect data from large numbers and types of widely distributed data-collecting platforms, and subsequently to relay those data to specific centers for processing data, which we will call ground data-handling (GDH) centers, offers a very attractive solution to the problem. When coupled with data-processing centers geared to the requirements of particular services (in much the same manner as our work has been with that of the panels on earth resources and systems for remote-sensing information and distribution), such points-to-point communication satellites promise sizable benefits to the nation and ultimately to all mankind. The task undertaken by the Panel on Points-to-Point Communications in its study of this practical application of earth-oriented satellites begins with a survey of the global communications traffic presented by the complex of data-collecting platforms (using requirements generated mainly by the appropriate panels during the course of this study), and ends with findings and recommendations whose implementation could help make the dream a reality.

As the planet's human population expands and the technological processes of socioeconomic activities exploit our planetary resources, the need for timely, planned, complete, national (if not global) environmental and resource control becomes increasingly urgent. Accordingly, it has been a source of deep satisfaction to the Panel to have enjoyed the privilege of making this potential contribution, however small, to the benefit of our planet.

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2.0 SUMMARY

2.1 The Problem

Points-to-point communication by satellite begins with the interrogation, location when required, and reception of responses from widely distributed numbers and types of data-collecting platforms. The interrogation-location-response sequence must be regularly repeated, and the data collected by the satellite must be sorted and tagged for retransmission to ground data-handling (GDH)* centers appropriate to particular environmental or resource control services. Retransmission by the satellite to a particular service's GDH center (or net) is considered complete when the demodulated raw data are presented at the output section of the ground receiving station.

While it is possible to apply this process to all data, it is practicable to apply it only to data which are time-perishable. A data-collecting relay satellite (DCRS) may serve the purpose of complete, real-time, synoptic reporting of such data to a particular service by transmitting them to a single, national GDH center, by transmitting portions of regional interest directly to regional centers, or by both together. If certain data-gathering platforms (e.g., meteorological satellites) are "on" continuously, the DCRS may also have to track in order to satisfy the service's operating requirements.

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*The Panel uses the following terms in discussing its hypothecated systems:

GDH, ground data-handling center. This usually is a relatively large center, where the primary function is to receive and process data from the satellite.

CDA, command-and-data-acquisition station. This station controls the satellite and initiates the interrogation of data-collecting platforms. It may be combined with a GDH center.

RS, regional site. Regional sites are smaller stations that receive data for limited regions, from satellites.

DCP, data-collecting platform. This term is used to designate small platforms that may be fixed (such as collectors of hydrologic, seismic, or agricultural data on land) or moving (such as meteorological balloons or oceanographic buoys).

DCRS, data-collecting relay satellite. A satellite that collects data from a sensing platform and relays the data to a GDH or an RS.

WBDCRS, a wide-band DCRS having the capacity to handle a large amount of data, primarily from earth-resources satellites (ERS).

The state of the art in 1968 permit se functions to be performed; techniques are known and some hardware is established. Sheer numbers of platforms, however, pose questions c ectrum occupancy, technical effectiveness, cost effectiveness, and g R&D to improve the situation. Environmental forecasting servic ne are expected by 1975 to encompass 4100 land stations, 8 . and weather ships, 500 buoys, and one or more satellites obal Atmospheric Research Program (GARP) envisioning 450 rried forward, the total number of platforms to be covered nvironmental forecasting in 1975 will be nearly 10,000. Econ cale could be expected if, in addition, one 1975-vintage DCRS is e ed to cover the 6300-odd platforms providing forestry, agricultural, d seismic data and the more-than-9700 platforms envisioned for marine, oceanographic, and hydrologic data. This "vacuum-cleaner" DCRS is very different from another type required to handle ESSA's meteorological satellites, low-orbit phases of manned missions, and earth-resources satellites (ERS). We will distinguish the second type by labeling it a wide-band DCRS.

2.2 Objectives

The scale of the points-to-point problem reveals the limitations of 1968 technology in attempting to cope with it effectively. It is necessary, if findings and recommendations are to be made, to size the traffic by service, type of platform, distribution, and data rate; to construct timing, multiplexing, and system-link models; to configure a plausible DCRS model based on advancing technology; and to attempt to assess cost-effectiveness or cost-benefits. In the process, international and policy implications of points-to-point systems must be considered, especially where the services involved acquire a global interest, as in agriculture and meteorology. As these things have been pursued, the Panel on Points-to-Point Communications has actively sought contact with the panels on earth resources and on systems for remote-sensing information and distribution, so that our work will stand together and provide a systematically consistent picture. In this framework, and with support from the consultants on cost-benefits, our objectives are:

1. To hypothesize practical systems that demonstrate technical feasibility of points-to-point satellite communications systems in the postulated environment

2. To examine available tradeoffs so as to discern economically preferable technical approaches

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*Throughout this report and the report of the Panel on Meteorology, these superpressure balloons are referred to by various terms. A superpressure balloon actually floats on a constant-density surface, at the altitude where the weight of the displaced air is equal to the gross load. The constant-density surface is almost horizontal; therefore, constant-density balloons are sometimes called constant-level balloons. In this report they are frequently referred to as horizontal-sounding balloons (HSB).

3. To discover what technical areas require support if system objectives are to be realized

4. To discover technical areas that should not be supported because of irrelevance, dilution of productive R&D, or doubtful promise

5. To find areas of policy impact that could affect the way system goals are prosecuted

6. To assess effectiveness and benefits of the system models and technology developments proposed, in comparison with existing practices

2.3 Results

Different types of data of interest to different services may be collected by the same data platforms. The data collection and processing are common, but the services are distributed among various governmental Departments. A central data-management authority is needed to be sure all interests are served fairly, but if the actions of different services resulting from the distribution of data are in conflict, there is no ready arbitrator, even at Cabinet level. Examination of our resource-management structure seems called for to determine a policy with respect to overall resource-management authority.

2.3.1 Traffic

Traffic requirements for points-to-points communication divide quite clearly into two classes: the small, essentially earthbound data platforms, including balloons; and earth-orbiting satellites. Of the 26,000 separate, small, data platforms estimated to be operational in 1975, 14,300 exist in place today. Most of these remote platforms contain few data: 1500 bits is a typical message size, but the total data of 10^7 bits must be collected approximately every 6 hours. Collection of different types of data may be synoptic and regular, i.e., within about one hour of GMT 0000, 0600, 1200, and 1800; synoptic and moving, i.e., within about one hour of local sunrise, noon, and sunset; alarm or "hot-line" for warning of impending disaster; or on demand.

The dominant traffic requirement is that of position location of horizontal-sounding balloons (HSB). The Panel has assumed that the Global Atmospheric Research Program (GARP), which envisions 4500 balloons globally distributed in 1975, must be accommodated. It is feasible to locate and collect data from 4500 balloons within 1/2 hour to 1 hour, using the Omega position-location (OPL) system with bandwidth-compressing signal processing in a data-collecting relay-satellite system. Based on this requirement, the total traffic could be handled by a single transponder having an rf bandwidth of under 50 kHz. The 50-kHz band contains sufficient reserve to accommodate the number of data platforms anticipated for 1980, when the total will be approximately double, with only the number of balloons remaining constant.

Data collection and relay from earth-orbiting satellites have been confined to environmental sciences, earth resources, and low-orbiting manned missions. Military, foreign, and experimental satellites were not considered by the Panel in sizing the traffic. Continuous tracking of, and communication with, six satellites is required for 1975, with orbits of perhaps 300 to 800 miles altitude and inclinations from 28° to 101°. The total rf bandwidth for this traffic is about 90 MHz. Increases by 1980 are projected as high as 1 GHz, if the requirements for 7-channel radiometric data of 30-ft resolution advanced by the Panel on Sensors and Data Systems are to be accommodated.

2.3.2 Orbits

For the low-orbiting-satellite traffic, continuous tracking is mandatory in accomplishing the points-to-point mission. For the small, globally distributed data platforms it need not be. In both cases the choice of geostationary orbit for DCRS leads to system configurations of greatest simplicity: fewer satellites are needed, the handover function is minimal, and the small data platforms are relieved entirely of the necessity to track. Detailed attention has accordingly been given by the Panel only to systems involving geostationary DCRS's.

2.3.3 Feasible Systems and Cost-Effectiveness

The points-to-point mission for small data-collecting platforms (DCP's) can be accomplished with today's technology. A system of four simple satellites, having earth-coverage antenna patterns and programmed transmissions that are both time- and frequency-division multiplexed (TDM and FDM), satisfies the synoptic-data-collection-and-relay requirement. The system can be integrated either by two pairs of command-and-data-acquisition stations or by two ground-relay stations for multiple-hopping of data from pairs of satellites that cannot see the GDH center. The link with DCP's operates with less than 5 W transmitter power and 3-dB maximum antenna gain on each platform. The maximum ERP of 10 dBW at each platform is well below the allowable level of 55 dBW specified by the CCIR for minimizing shared-band interference with other services. Transmission programming is cooperative with the GDH center, and the relay down-link (from DCRS to GDH) antenna also provides earth coverage to allow regional stations to get data of immediate interest direct. Using a simple, narrow-band FM scheme, the data-relay link requires about 50 kHz of rf bandwidth and can be located in the standard VHF band between 136 and 138 MHz assigned to space. The interrogation-or-programming down link from DCRS to data platforms can also be located there; the command-and-programming link from GDH center to DCRS and the data-collection link from data platforms to DCRS can be located in the standard space telecommand band from 148.25 to 149.52 MHz. The satellite weight will be under 350 lb, permitting injection into geostationary orbit with a Thor-Delta booster and SVM-2 kick stage. Satellite life expectancy of 5 years leads to a total system cost, ground stations and operation and maintenance (O&M) included, of about $79 million over the entire lifetime. Comparative costs for accomplishing the same mission by conventional means—a combination of phone lines, teletype, HF radio, etc.—have been estimated at more than $1 billion. The satellite system is relatively cost-effective.

It remains to be established that the larger system of which it is a part--data-collecting platforms, vacuum cleaners, and GDH centers or regional stations—forms a cost-effective whole.

For low-orbiting satellites, a system of two geostationary DCRS's will satisfy the mission requirements. These may use either multiple-beam, multidish antenna arrays or self-focusing phased arrays. In the former type, the difficult technical problems are in structural design and in the satellite dynamics subsystem for stabilization and station-keeping. In the latter, they are in the development of the self-focusing phased array and its associated electronics. Either type of satellite will weigh less than 2000 lb, permitting injection into orbit with a Titan III-C. Frequency allocation for the links between the DCRS and the target satellite is suggested at 10.7 to 11.7 GHz; that for the links between the DCRS and the ground is suggested at 8.4 to 8.5 GHz. Both bands are allocated to space, but the lower is fully occupied by this points-to-point service at 90 MHz bandwidth. To accommodate the bandwidth of over 1 GHz projected for 1980 earth-resources growth requirements, new allocations will be needed.

Even if an allocation can be found, the feasibility of providing a practical DCRS service for the 1980 system is questionable. The ERP-aperture product of 105 dB above 1 watt-ft^2 for each ERS in the system may well mean a dedicated DCRS for each ERS. This is economically unsound and technically unattractive. (It should be noted that the feasibility of other approaches to data collection for the 1980's is also in question.)

The initial system will cost $310 million for a 4-year period. Compared with other means for acquiring global target-satellite data, its differential cost is about $117 million spread over 4 years. While the using agencies (Agriculture, Commerce, Interior) do not all express a need for real-time acquisition of the data, they do desire the data on a global basis. Supporting development of this system depends upon justifying the differential cost. The Panel is skeptical that justification can be established. Moreover, the initial ERS segment can be in orbit and operating by 1971, while the earliest time for the initial wideband DCRS to be in orbit is in 1973. The selection of DCRS over the simpler, direct-readout system thus carries with it a 2- or perhaps 3-year penalty for obtaining global earth-resources data.

This does not imply that no mission exists for geostationary DCRS's. A type not considered by the Panel in any detail is that required to cooperate solely with low-orbiting manned missions. This problem has been, and continues to be, addressed by the NASA programs on orbiting data-relay networks and data-relay-satellite systems (DRN/DRSS); these are studies directed toward wide-band data-relay capability. Here the Panel can only observe that there is a need to maintain full-time contact with men in orbit. This contact can be made via voice and narrow-band telemetry links, since there appears to be no necessity for video contact. The costs for such a system, with a satellite life of 5 years, are likely to be less than those for the wide-band DCRS system configured in detail by the Panel. Operating costs for such a narrow-band system are roughly comparable to those for the vacuum-cleaner* system. Compared

* See Sections 3.1.4 and 3.3.1.

with tracking-net operating costs of $40 to $60 million per year, the 4-year operating cost of about $32 million for this narrow-band system would make it cost-effective as well as operationally desirable for the added security of manned orbital missions.

In the event the narrow-band system could be broadened in function to supplant the current satellite-tracking and data-acquisition network (STADAN) with full-time tracking and data collection from NASA low-orbiting experimental satellites, its cost-effectiveness might be even greater. This would suggest that the DRSS program might be reoriented along these lines.

One alternative system to the wide-band DCRS places a self-focusing antenna on the earth-resources satellite for direct communication into regional ground stations concerned with the satellite data of the moment. The option of distributing copies of regional data could rest with the individual ground station. In the absence of data storage on the satellite, this option might provide a technical solution to a political problem, but it would do so at the expense of data recovery; global landmass data would be available only at the options of other nations. The minimum 4-year cost for such a system, with coverage restricted to the earth's landmass excepting the U. S. S. R. and China, would be about $237 million. This includes the ERS segment of $152 million for the satellites in orbit. The configuration is based on four land stations covering the United States and 32 covering the rest of the world. The initial investment for each land station is about $800, 000, and the 4-year operational cost about $800, 000 additional. This would be the normal buy-in cost for other countries, totalling $51 million for the 32 additional stations.

Because the availability of global data would rest with independent local options, the Panel believes this is not the most attractive alternative economically. ESSA satellite data are collected now at Fairbanks, Alaska, and at Wallops Island, Va. ; conversion to DCRS for ESSA is unnecessary. Plans for earth-resources satellites could include complete global landmass data collection via tape-recorder storage and delayed readout, and this is still a practical alternative. Rather than spend at least $70 million on a regional-ground-station system (see Configuration III in Section 8. 0) with doubtful data return, and which will require extended technological development, the major data-gathering objectives could be realized for 4-year incremental costs of $12 million (see Section 3. 1. 4) plus the earth-resources satellite costs which appear in every system, recognizing there is no need for real-time reporting of earth-resources imagery. In this system the originally proposed passive, broad-beam, S-band antenna is retained on the spacecraft; a wide-band receiver with an 85-ft, S-band dish is added to the Mojave, Calif. , ATS station, and a serious product-development-and-reliability program is undertaken with the proposed spacecraft-video-tape recorder. The limitation of this approach as described is its lack of capacity to accommodate growth. If earth-resources data requirements are expected to grow from the present three bands at 100-ft ground resolution to seven bands at 60-ft or 30-ft ground resolution, the data-bandwidth growth will demand further development--not only in data-storage technology, but in highly linear, wide-band signal-processing and communication techniques. The Panel considers that this additional cost will approximate $20 million. To accommodate a 1980 system, the improved technology must be in hand by 1977.

2.4 Conclusions

1. Today's technology permits development and acquisition of a cost-effective, integrated system (vacuum-cleaner) for real-time data collection and relay by geostationary satellite from the globally distributed complex of environmental and earth-resources data platforms.

2. The vacuum-cleaner DCRS system will impose an additional strain on the limited resource of geostationary-orbital space.

3. Common use of collected data by different services distributed among many Departments and Agencies, coupled with centralization of real-time processing in the GDH net, indicates the need for a centralized data-management authority. This would facilitate hardware and format commonality.

4. The distribution of different services for segments of environmental and resource management among many Departments indicates a need for examination of environmental- and earth-resources-management policy.

5. Existing frequency allocations in the VHF band for space telemetry and command can easily accommodate the vacuum-cleaner system, including capacity for growth—and will do so without forcing violation of the CCIR restrictions on allowable radiation for controlling interference in shared bands.

6. While data collection and relay by satellite from low-orbit, data-gathering target satellites is technically feasible, it is not a cost-effective way to obtain landmass data.

7. Because there is no stated user need for real-time earth-resources data, a wide-band DCRS system to acquire the data in real time cannot be justified. The only advantage of this type of data-collecting system over a cost-effective, non-real-time system is its ability to acquire complete, global data rather than complete global landmass and partial global-water data.

8. The earliest acquisition of a wide-band DCRS system is 2 years behind acquisition of the initial ERS system, and the technical feasibility of extending it to accommodate earth-resources data growth in 1980 is doubtful.

9. The potential loss of much global earth-resources data to the exercise of local options by other nations makes questionable the implementation of a complicated earth-resources-satellite antenna with a series of independent, nationally controlled regional sites, each collecting data of local interest only.

10. A cost-effective means of acquiring complete North American continent and global landmass earth-resources data involves augmenting the receiving capability of the Mojave ATS station for inclusion in the earth-resources-system ground net and investing adequately in: video-tape-recorder product development and reliability; highly linear, wide-band,

signal-processing techniques; and wide-band transmission and reception techniques. This system will also acquire partial global-water data.

11. Proposed growth of earth-resources-data requirements from three spectral bands at 100-ft ground resolution to seven bands at 30-ft ground resolution presents serious technical problems in frequency selection, wide-band signal storage and processing, and wide-band communication techniques. Available frequency-allocation bandwidths will be completely occupied by the initial requirement at 100 ft.

12. Proposed growth of earth-resources-data requirements will necessitate examination of policy positions for ground resolution finer than 60 ft.

2.5 Findings and Recommendations

1. The end-to-end system, from data platforms to GDH centers or regional data-handling centers, contains the vacuum-cleaner system as one of its components. While the vacuum-cleaner system by itself is cost-effective, the effectiveness of the end-to-end system remains to be established. This recommendation is qualified accordingly.

2. Because 60 percent or more of the globally distributed, small data platforms expected for 1975 are currently in place and operating; because only restricted synoptic, real-time, data-collection service now exists; and because the vacuum-cleaner system for providing this needed service is cost-effective, the Panel recommends that development, acquisition, and operational deployment of this type of system be planned and supported. As first steps, detailed studies should be conducted to define the traffic in more detail and to develop standard specifications for the data-platform electronics.

3. An early decision is required concerning the level of support of the GARP balloon program. If the support is substantial and a vacuum-cleaner system is approved, development of low-cost, compact, frangible electronics for balloons, including OPL-type receivers and signal processing, must be accelerated.

4. As more and more operational, geostationary satellite applications are shown to be cost-beneficial, the potential strain on the limits of orbital parking space becomes increasingly important. The Panel finds a need now for resource planning to include allocation of orbital stations for space applications in priority order.

5. The Panel finds a need for a centralized data-management authority, responsible for the integrated data collection, relay, processing, and distribution of all environmental and earth-resources data to the various resource services in government Departments.

6. The Panel finds a need for examination of our environmental- and earth-resources-management policy, having the objective of developing an

overall responsible agency for resource management with an integrated program.

7. A determination should be made of the differential cost-benefit obtainable from the global-water coverage provided by a wide-band DCRS system over that available from the direct-delayed readout system.

8. The planning, development, and acquisition of a wide-band DCRS system should be supported only if the cost-benefit determination of recommendation 7 justifiably exceeds the 4-year cost.

9. In the event the wide-band DCRS for ERS and meteorological satellites is, indeed, not justified, development of technology and systems for a narrow-band DRSS to cooperate with orbiting manned missions should continue. Implementation of such a DRSS appears justified, with heavier funding support, once it has been shown to be practical to use it as a replacement for the STADAN tracking net.

10. Support is not recommended for the system of real-time readout of earth-resources-satellite data directly into regional ground stations having local-option control over redistribution of their processed data.

11. If increased earth-resources data requirements are to be supported, a grave need exists for developing frequency allocations and assignments broad enough to sustain rf bandwidths up to 1 GHz. We recommend commencement of effort to develop such allocations and assignments, preferably in the microwave region at 10.7 to 11.7 GHz.

12. Support is recommended for acquiring global earth-resources data directly from the earth-resources satellites. This recommendation supports a $28 million investment in: data-storage technology, both magnetic-tape and electro-optical; highly linear, wide-band, signal-processing techniques; wide-band transmission and reception techniques, possibly in S-band; and the addition of a wide-band, S-band receiver and an 85-ft S-band dish to the Mojave ATS station.

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3.0 SERVICES AND TRAFFIC REQUIREMENTS

Points-to-point communication by satellite can provide operating advantages to several kinds of natural-resource services. Data-gathering platforms may be of interest to several services even though they are counted only once in the sequence of interrogation, data collection, and relay to a ground data-handling center. Large moored buoys, instrumented drifting buoys, ocean-station vessels, and government research ships, for example, may all collect atmospheric data, surface data, and subsurface data. This complex of platforms gathers data ensembles of interest to meteorological, oceanographic, and marine-data services. Similar overlap respecting meteorological and hydrologic services may be found in the complex of offshore platforms, land (weather) stations, and hydrologic stations. In attempting to size traffic requirements, therefore, care must be taken to count relevant platforms once only while matching the platform count with the services' requirements. A clear understanding is required of the assumptions on which this traffic sizing is based.

3.1 Assumptions

Because of the overlap of functional data coverage, the platforms from which data are to be collected have been divided into three main groups: those collecting data primarily of interest in meteorology, oceanography, marine data, and hydrology; those collecting data primarily of interest in agriculture, forestry, and geology; and unmanned, experimental spacecraft in earth orbits under about 1000 miles altitude. In this somewhat arbitrary but convenient division, it is recognized that the DCRS function, while directed primarily to operational systems, could probably accommodate the total NASA data-relay requirement on such satellites without greatly extending the DCRS itself. Since one objective assumed for the DCRS is that it should obviate the need for onboard tape recorders in data-collecting satellites, this provision of an operational, real-time, data-relay capability for spacecraft in low earth orbits is not unreasonable.

Our attention has been confined to time-perishable data. Some of these data have been available locally via telephone lines, but in a sporadic and somewhat desultory way, with only restricted synoptic data available to any service. The need for a synoptic view of all such time-perishable data has been assumed. Platforms having recorders for data of long-term value, platforms whose use routinely involves periodic repositioning, such as sensors used in agriculture whose data record may be read and which may be manually repositioned every 4 hours or so, and platforms of local interest only have been excluded.

Air-pollution monitoring is an important activity having primarily local interest. It has been assumed that air-pollution data are required primarily in the vicinity of major metropolitan areas: the Pacific coast region from Seattle to San Diego, the Great Lakes area from west of Chicago to Erie, the East coast area from north of Boston to perhaps north of Richmond, the greater St. Louis area, and the greater Cincinnati area are examples. In each area the data are of greatest use to the local air-pollution-control systems, so synoptic data can be effectively and economically collected by using the existing terrestrial communications means. No practical justification for DCRS capability can yet be seen here. Although distribution of regional high-resolution imagery could be of help in providing synoptic pictorial data against which to correlate locally gathered air-pollution data, this could be done by retransmission of processed imagery from a central data-processing station.

High-resolution imagery can be gathered for local regions by aircraft or by satellite. The aircraft case is not of interest here; its application for air-pollution monitoring is viewed in the light of other locally gathered data. Satellite data will be a by-product of earth-resources imagery: multispectral, high-resolution, wide-band video whose display may show the geographical extent of air pollution. This video is assumed to run through a data-collection system consisting of either DCRS's and a GDH center for all data or a network of real-time regional collection centers with retransmission option through a DCRS to the GDH center. In either case, display copies of regional video can be retransmitted from the GDH center to appropriate regional control points for use with their own air-pollution data.

Because the data from low-orbit phases of manned missions may be comparable in bandwidth to earth-resources-satellite video, it is assumed that the type of DCRS which handles the former will handle the latter also. This leads to the general supposition that there will be two types of DCRS's: one for the proliferation of small sensors, and one for data from both low-orbit earth-resources and ESSA satellites and low-orbit phases of manned missions.

Using sources of information presently available, the Panel has identified, or has been given suggestions for, many different sensor platforms and networks that may best be served by the DCRS. The Panel does not suggest that a highly accurate assessment of this subject has been made; indeed, it recognizes that a government-wide synthesis of requirements for environmental-data collection should be made as a step toward establishing the characteristics of an evolutionary global data-collection system, including satellites and other modes of communications, and serving all the various needs discussed below, as well as others that the Panel has not been able to identify clearly in the short period of time available.

The categories of sensor platforms and networks the Panel has identified include those serving meteorology, hydrology, oceanography, geology, agriculture, and forestry. Without question, there is considerable overlap among the data needs of these disciplines, and in many instances relatively crude approximations have been used to arrive at a potential number of platforms that might best be served by the DCRS in the 1975 era.

3.1.1 Meteorologic and Aquatic Data Platforms

In this group of platforms, real-time, synoptic measurements are assumed at 6-hour intervals, always about standard recording times (SRT) of 0000, 0600, 1200, and 1800 GMT. Marine and oceanographic data are reported to collection centers within ± 15 minutes of SRT; while meteorological data, except from balloons, are allowed -30 minutes to +60 minutes of SRT. Hydrologic data may be reported either in the meteorological window or on a moving base referred to sunrise, as are agricultural data. Balloon data are allowed -1 hour to +2 hours of SRT, but in this window each balloon must provide two data inputs spaced 2 hours apart. Meteorological satellites, operating continuously, must be tracked continuously for the DCRS function, and thus represent a different communication problem.

This data-gathering group will consist of land weather stations; ships of opportunity and ocean-station vessels; moored, drifting, and manned buoys; aircraft of opportunity; hydrologic stations; offshore platforms; low-altitude, polar-orbiting satellites; and, possibly, superpressure balloons. Position fixes are necessary on the balloons and drifting buoys. Ships and aircraft are presumed to have navigation equipment, as determined to be necessary by the Panel on Navigation and Traffic Control, which supplies their position fixes independently from the DCRS system. The data-gathering group population is estimated for 1975, on the assumption that the global atmospheric research program will proceed. Of the 26,000 platforms projected for 1975, 14,300 exist today and need only to be instrumented for cooperation with DCRS (see Tables 7.3.1 and 7.3.2). The severe problem is that of position fixing and subsequent multiplexing within the prescribed reporting windows.

While it is recognized that ESSA has plans for a synchronous environmental-sciences satellite in the 1970's as part of the global meteorological system, no provision is made in DCRS to relay its data. Since this satellite will be synchronous, it can transmit its own data directly to the appropriate GDH centers.

Woodrick et al. (see Appendix B) have identified an advanced World Weather Watch requirement for collection of upper-air data using 1560 superpressure balloons (three levels above 500 millibars). The Panel on Meteorology has stated that an effective numerical weather-prediction system would require balloons at four or five levels, spaced 500 miles apart, resulting in a need for approximately 4500 balloons. This number has been used to size the DCRS.

The World Meteorological Organization (WMO) has identified a global need for approximately 500 upper-air-observing stations and 3600 surface-observing stations. The great majority of these stations are presently in operation, although not all are reporting within WMO standards. The Panel recognizes that at present these weather-observing stations communicate data by conventional means, but the Panel also recognizes the possible efficiencies in time and in central data collection that may ultimately be realized by use of the DCRS to collect data from these globally distributed sites. Efficiencies would occur because satellite-collected data for other meteorological, hydrologic, and oceanographic prediction systems will also, probably, be processed in the same facility or facilities served by the ground receiving terminals for the DCRS. Although these weather-observation stations have been included for the purpose of sizing the DCRS, the Panel does not suggest that the DCRS would alleviate the local and regional communication needs that are, and may continue to be, satisfied by other communication means.

The U.S. Weather Bureau (ESSA) receives daily more than 1400 surface observations from ships. The World Weather Watch (WWW) hopes, by the mid-70's, to have 200 or more ships of opportunity equipped with upper-air-measuring capability. The United States in 1968 manned a total of 80 ships with ESSA and DOD meteorological personnel for making surface marine observations. (Not all these ships were at sea at all times.) The Panel has chosen to assume that 60 ships with upper-air-observation capability and 800 cooperating merchant ships might be reporting up to four times per day via the DCRS during any 24-hour period.

The 1967 feasibility study of national data buoy systems indicated that buoys were a cost-effective means for satisfying many surface marine-meteorological and subsurface oceanographic-data requirements (see also Appendix B). The buoy-system feasibility study indicates that 500 moored buoys would meet many operational-data requirements in the northern hemisphere. The report of the Panel on Oceanography proffers a strong concern for inclusion of moored and drifting data buoys as part of a complete marine-data-acquisition system, but total numbers of required platforms are not given. With this background information, the Panel has chosen to assume that approximately 500 moored buoys, 200 drifting buoys, and five manned buoys (comparable to the FLIP manned research buoys) provide a representative number of such platforms in the 1975 era.

In 1968 the National Meteorological Center processed approximately 500 aircraft reports daily from Air Force and Navy weather reconnaissance aircraft and other aircraft of opportunity. The Panel assumes for the 1975 era that approximately 200 such aircraft might be reporting during a 6-hour reporting interval via the DCRS.

The Panel on Hydrology has outlined a hydrologic-data-collecting and processing system evolving from 10,000 sensor platforms, through 25,000 and 50,000 platforms. Most of the platforms would report at least once daily. We have chosen the 10,000-platform system for the purpose of sizing the DCRS. All of the sensors are assumed to be in the United States. Also, it is presumed that, of the 5500 precipitation reports required, approximately 1000 come from U.S. land weather stations that are a part of the WWW network of 4100 sites. Of the remaining 9000 sites, 1700 are identified by the Panel on Hydrology as reporting only once per week, or less frequently. For the purpose of sizing the DCRS, all 9000 additional hydrologic sites have been included. (It should be noted that, in the United States at present, there are 8500 recording stream gauges and approximately the same number of nonrecording stream gauges. For comparison, the postulated 10,000-platform hydrologic system includes only 3500 water-level gauges of several types. In fact, essentially all the postulated 10,000 platforms exist today, but not all are capable of providing data in an efficient and timely manner. The DCRS has been sized to alleviate that need.)

The study of the feasibility of a national data-buoy system identified needs for several hundred fixed platforms in U.S. lakes, estuaries, and near-shore ocean locations. Many of the requirements may best be satisfied by fixed platforms rather than moored buoys. The Panel has assumed that as many as 500 fixed platforms may be required for a wide variety of data needs during the 1975 era. It is recognized, however, that a relatively clear set of data requirements from this form of sensor platform is not presently as well established as for many of the other platforms considered.

TABLE 7.3.1

1975 PLATFORM POPULATION FOR METEOROLOGY, MARINE DATA, OCEANOGRAPHY, AND HYDROLOGY

Platform Type	Existing in 1968	Planned for 1975	Total
Balloons		4500	4500
(a) Weather stations, land	4100		4100
Ships of opportunity	830	30	860
Ocean-station vessels	10	75	25[(d)]
Buoys, drifting and moored		700	700
Buoys, manned	2	3	5
Aircraft of opportunity	40	160	200
(b) Hydrologic	9000		9000
Offshore platforms		500	500
Low-altitude, polar-orbiting satellites	2[(c)]	2[(c)]	2
TOTALS	13,984	5,970	19,892

(a) 500 weather stations with upper-air capability and 3600 without are anticipated as reporting for the World Weather Watch, as well as for local weather forecasting.

(b) Hydrologists will also use some of the data collected at 1000 U.S. weather stations.

(c) Existing satellites will be retired as new ones become available. Two of the current ESSA satellites are required to do the work of one TIROS-M type. The 1975 system is expected to include two TIROS-M-type satellites.

(d) On station and operating.

3.1.2 Agriculture, Forestry, and Geology Platforms

Table 7.3.2 shows the population figures for this group of data platforms based on desires and long-range plans of the using services.

TABLE 7.3.2

1975 PLATFORM POPULATION FOR AGRICULTURE, FORESTRY, AND GEOLOGY

Platform Type	Existing in 1968	Planned for 1975	Total
Agriculture	200	3800	4000
Forestry	75	1925	2000
Seismic	30	210	240
Volcanic	15	35	50
TOTALS	320	5970	6290

The use of remote-satellite sensing to further productivity and efficiency has been treated by the Panel on Forestry, Agriculture, and Geography. That Panel has established an additional need for terrestrially based sensors to obtain in situ data for establishing "ground truth" and for monitoring with finer resolution certain parameters such as soil moisture and soil temperature. For the purposes of sizing the DCRS, an initial estimate of 4000 agricultural ground-sensor sites has been given (3000 in the United States, 500 in Canada, 500 at other locations) in 1975. Their maximum distribution density is one per 300 square miles. Forestry platforms are anticipated only in the United States (1500) and Canada (500) by 1975, at an average density of one per 1000 square miles of forest. The collection of data from these platforms must occur on a moving time base three times daily: just prior to sunrise, sunrise + 6 hours, and sunrise + 12 hours. Since the longitudinal rate of sun-line motion is 15° per hour, all data from agriculture and forestry platforms within any 15° segment on the surface must be collected in less than 1 hour--a distinct practical possibility if the data rates are high enough or the message content is low enough. This will be examined when traffic is sized.

There are 1200 seismographic stations around the world that detect a half million tremblors a year. About 1000 of these tremblors cause damage, and 50 are of great magnitude. Because considerable life and property are at stake in some regions of high seismic activity, a need exists for a worldwide seismic detection system for warning and appropriate coordination of emergency assistance. The Panel assumes that approximately eight major geological fault zones, distributed globally, will be instrumented with about 30 sensor clusters per zone by the 1975 era. It is further assumed that the DCRS would be used for interrogation and data collection from these remotely located sensors. One such set of sensor clusters is now in operation along the San Adreas fault zone.

The approximately 600 active and 10,000 inactive or dormant volcanoes of the world lie in three regions that closely match the major earthquake regions: the coastal rim of the Pacific Ocean, a belt extending from the Mediterranean Sea to the East Indies, and along the mid-ocean ridge extending through the major oceans of the world. Volcanoes pose direct and indirect threats to human life and activity in several of these global regions. The Panel has chosen to assume that approximately 50 clusters of volcanic sensors will be operational in the 1975 era; the DCRS is sized to include interrogation and data collection from these 50 sensor clusters.

The seismic and volcanic sensors in Table 7. 3. 2 are likely to be distributed in the Pacific and Mediterranean basins. Seismic-sensor platforms would be distributed in fault areas encompassing less than 100, 000 square miles, such as that of the San Andreas fault, at a maximum density of one per 10 linear nautical miles. Volcanic-sensor platforms would be placed in clusters around the 50 volcanic areas most likely to threaten human resources or of greatest interest to geologists. Both ensembles of platforms would have their data collected every 6 hours. The data-collection reference times could be established in any manner suitable to the using services.

Seismic and volcanic platforms located in the most critical areas should be equipped with threshold detection logic to sense potentially dangerous levels of activity. "Hot-line" capacity would be provided in the DCRS, independently from the normal, scheduled data-collection functions, to permit on-demand or more frequent data collection for a predetermined period following the detection of abnormal activity.

No provision appears here for tsunami detection. The tsunami is characterized by long, high-velocity waves on the ocean surface; typical values for crest separation and velocity are about 60 miles and 600 mph, respectively. Detection of this sort of oceanic change depends upon measurements of sea-level changes and local-pressure changes taking place over time intervals of, say, 5 to 20 minutes. This could best be done from a buoy network; these measurements are not seismic, but are made subsequent to the seismic action causing the tsunami. Capacity to respond to tsunami detection would require special instrumentation in the buoy system and possibly a "hot-line" provision in the DCRS.

Finally, no earth-resources-imaging satellite appears in Table 7. 3. 2. This particular platform, which appeared in Section 3. 1 of the FAG report as part of the global land-use (GLU) system and which received much detailed technical attention during 1967-68 as the earth-resources-technology satellite (ERTS), is of prime importance in resource management. Its bandwidth requirements, however, are enormous when compared with those for the proliferation of small data-gathering platforms. As indicated in Section 3. 1, this implies that the earth-resources satellite will work into a DCRS different from the type which handles the small sensors. Accordingly, it will be treated separately under the discussion of traffic.

3. 1. 3 Low-Altitude, Unmanned Satellites

The availability of a DCRS link to cooperate with earth-orbiting, unmanned satellites could obviate the need for satellite-borne tape recorders and provide continuous data-gathering contact with the satellites. If such a link required a separate DCRS entirely for itself, the application benefits would be questionable. Since this study concerns itself with applications of earth-oriented spacecraft, primary consideration is given to spacecraft occupying low-altitude earth orbits. For highly eccentric orbits, such as that of OGO-III with a 170-mile perigee and a 75,769-mile apogee, demands of tracking and handover complicate the DCRS instrumentation unduly. Based on the conclusions of the ODRN studies in 1967, the DCRS power, size, and weight required to handle spacecraft orbital altitudes greater than about 1000 miles become impractical; they imply boosters of capacity greater than Titan III-C with transstage. For interplanetary spacecraft, even at low data rates, the advantage of essentially duplicating deep-space-information facility (DSIF) installations on a DCRS is questionable.

Since the applications envisioned are civil, military spacecraft are excluded. And, unless specifically requested by foreign nations, capacity would not be planned for data collection from foreign spacecraft.

The operational requirement then is to collect and relay data from two ESSA satellites in about 775 nautical-mile, near-polar orbits, three earth-resources satellites in 500 nautical-mile, near-polar orbits, and the low-orbit phases of manned missions.

3.1.4 Satellite Services and Orbits

The need for synoptic, real-time data collection and relay from great numbers of data platforms distributed over large areas makes the geostationary orbit the inevitable choice for "vacuum-cleaner" DCRS's. Satellites in any other orbit would have time-varying coverage of portions of the earth, implying incompatibility with simultaneous requirements for synoptic and moving-reference data collection. Further, they would place constraints of tracking on both DCRS and data-platform antennas, complicating both unnecessarily. Similar considerations apply to the wide-band DCRS, which must track satellites in 98° orbits, 101° orbits, and 28° orbits simultaneously and continuously. Here, while the tracking requirement evidently applies to both low-orbit satellite and DCRS, the requirement for continuous communication leads to many more DCRS's in a nongeostationary system than would be needed in a geostationary one. In both vacuum-cleaner and wide-band DCRS services then, the choice is for geostationary orbits.

Each service is expected to operate with a main GDH center, regional ground stations being served either by data distribution from the GDH or by concurrent reception of data of local interest by receiving DCRS down-link-data transmission. Since the Panel on Remote-Sensing Information and Distribution has expressed a desire for vacuum-cleaner data to be available to regional centers of various environmental and resource services without their waiting for the data to be processed by the GDH center, the vacuum-cleaner down-link should cover the earth disk in a single beam, much as it will for platform-data collection. Programming of regional-station "on" times for data reception from the vacuum-cleaner transmitting beam will then provide each regional station the real-time local data it wants, while concurrently the GDH center can collect the entire transmission.

Four geostationary vacuum cleaners are sufficient to provide earth coverage up to about 70° N latitude; if worked with ground relays to provide two-hop paths for those satellites unable to see the GDH center directly, a single GDH center could handle the whole system. For vacuum cleaners at 50° and 140° W longitude, a ground relay station in the western United States is appropriate for a GDH center in the East. For the same GDH center, vacuum cleaners at 40° and 130° E longitude might require a ground relay in a foreign nation—possibly in Africa.

For the wide-band DCRS service, two geostationary satellites at 10° W and 170° E longitude could provide complete, continuous coverage. A third is suggested as a supplement, so that, in the event one fails, coverage is not lost. For a GDH center in the eastern United States, wide-band DCRS readout at NASA's Rosman, N. C., station is practical. No satellite-to-satellite hopping is needed if both Rosman and Mojave can be equipped with ground receivers, both of which get their data to the GDH center by phone lines or microwave link. With this system the receiving-station antenna elevation angles are never less than 5°, and immunity to multiple interference is good.

Two very important, nontechnical considerations arise from these DCRS services: (1) all the data for various environmental and resource services having different interests must be collected at a common center; (2) the processing and distribution must be managed to the satisfaction of all. There is substantial commonality in data needed by the various services and in the data collection; for example, large buoys serve common data-collection objectives for meteorology, marine data, and oceanography, and some agricultural and hydrologic data come from common data platforms. There is a need to reexamine the organization and assignment of responsibility for these resource services, and almost certainly a need for a centralized resource-data-management authority responsible for integrated DCRS and GDH systems and services.

The second problem is that of international participation. Not only is cooperation by other nations important if a ground-hopping station is to be provided for the vacuum cleaner; there is also the consideration of relaying worldwide high-resolution ground data to a U. S. GDH center. One alternative is to allow each interested nation to get data transmission directly from the ERS, with its own option for passing it on to the GDH center. In this case, our interest in earth-resources data in the continental United States could be satisfied by a ground-station network at the expense of global, wide-band DCRS coverage altogether. This technical solution to a political problem envisions the ERS reporting directly to regional receiving stations in the area of local surveillance, with each station having local control. Global data would be available only at the options of other nations: options to acquire ground stations at about $800,000 each, to train and support O&M crews, and to provide the GDH center with copies of the regional data they may have.

This may not be acceptable to U. S. resource agencies, who desire global data but not necessarily in real time. The choices may well be dictated by costs. While it is not within the scope of this panel's assignment to assess the relative cost-benefits of real-time relay by wide-band DCRS compared with direct but limited earth-resources coverage into regional stations, comparative costs can be stated. Total cost for real-time relay in a 4-year, operational-system mode is about $310 million, including $149 million for the ERS component in orbit (Configuration I in Section 8. 0).

For the global-coverage alternative with local option (Configuration II in Section 8. 0), the total 4-year cost for worldwide coverage, less the China and U. S. S. R. landmasses, would be about $1132 million. For the limited-landmass-coverage alternative with local option (Configuration III in Section 8. 0), the total 4-year cost would be $237 million. In both configurations, the ERS-segment cost remains the same, at $152 million. Both configurations are based on about 36 land stations (four covering the United States; the remaining 32 covering the rest of the world, less the U. S. S. R. and China), but Configuration II requires an additional component of 84 ship stations to provide complete global coverage. If only the U. S. land and near-land areas were covered, costs would be reduced by $25. 6 million for ground stations and another $25. 6 million for their 4 years of operation and maintenance. This $51 million, required to cover land areas outside the United States, would normally be a prorated charge to each participating country at $800, 000 to acquire a station and $800, 000 to operate it for 4 years. If the United States underwrote the entire cost of this system, it would still be subject to loss of global data at the local option of other nations.

Perhaps more economically attractive alternatives can be found without a global, real-time, data-collection constituent. Complete coverage of North America can be obtained directly from the ERS in real time, using the Satellite Tracking and Data Acquisition Network (STADAN) stations at Fairbanks, Alaska, and Rosman, N. C., and adding a wide-band, 85-foot S-band capability at the Mojave, Calif., ATS station comparable to those at the STADAN stations. This would give ERS data for the United States in real time. But, since the users do not require ERS data in real time and the Panel on Systems for Remote-Sensing Information and Distribution (SRSID) has not, therefore, included processing provisions for ERS data, some thought must be given to the cost of getting reliable earth-resources data in delayed time. Although one objective of DCRS has been stated as "obviating the need for tape recorders," a cost comparison of what is involved is in order. Of the $310-million, 4-year cost for the wide-band DCRS, the ERS segment was $149 million. A reliable, product-improved tape recorder could be developed and a prototype qualified for the ERS for less than $5 million, including the special attention necessary to settle tape-head wear problems, bearing materials and lubrication problems, drive problems, positioning problems, and questions of long life in space, and enough flight articles to satisfy a 4-year operational requirement. The station at Mojave could be modified for $2. 3 million, and the other two for $0. 4 million each. Four-year operational costs would be increased by about $4. 0 million which, with the R&D, would total $12. 0 million. This would permit delayed, global, earth-resources data to be acquired by the three ground stations, in addition to the real-time data for North America, and would be considerably more attractive in cost than any of the other alternatives. While the Panel recognizes the problems NASA has had with tape recorders, we cannot conscientiously recommend either that data be sacrificed or that a real-time relay system which the users do not appear to need be developed when a calculated, relatively small investment in device technology would appear capable of overcoming the device problem.

This approach, if limited as described above, lacks growth capacity. If earth-resources-data requirements are expected to grow from the present three bands at 100-ft ground resolution to seven bands at 60-ft or 30-ft resolution, the data bandwidth growth accompanying this improvement will demand further development, not only in wider-band video data storage but in highly linear, wide-band techniques for signal processing, transmission, and reception. The Panel believes that the additional cost to develop the appropriate technology will be about $20 million, and the technology should be in hand by 1977 to accommodate the improved system of 1980.

This does not imply that no mission exists for geostationary, wide-band DCRS's. A type not considered by the Panel in any detail is that required to cooperate solely with low-orbiting manned missions. This problem continues to be addressed by the NASA programs on ODRN/DRSS; these are studies directed toward wide-band data-relay capability. Here the Panel can only observe that there is need to maintain full-time contact with men in orbit. This contact can be via voice and narrow-band telemetry links, since there appears to be no necessity for video contact. The costs for such a system, with a 5-year life, would certainly be less than those for the wide-band DCRS system configured in detail by the Panel. Operating costs for such a narrow-band system are roughly comparable to those for the vacuum-cleaner system. Compared with tracking-net operating costs of $40 to $60 million per year, the 4-year operating cost of about $32 million for this narrow-band system would make it cost-effective as well as operationally desirable for the added security of manned orbital missions.

A further service which such a system could provide is that of real-time telemetry, tracking, and command (TTC) for experimental satellites. The low-altitude, orbiting geophysical observatory (OGO), solar observatory (OSO), astronomical observatory (OAO), and Nimbus satellites represent an important part of the space effort. Even though those particular missions may be past, experience would indicate that the experimental-satellite traffic of the future might be comparable. Nimbus, with new experiments digitized as current planning directs, would require a data bandwidth of under 1 MHz; three OGO, 2 kHz each; one OAO, 2 kHz; and three OSO, 0.4 kHz each. Except for the Nimbus requirement, the narrow-band DRSS could probably accommodate the remaining traffic. Extension to wide-band capability remains a question for the post-1975 period.

3.2 Traffic

The total DCP population with which the DCRS must work, excluding satellites, is about 26,000. Some 14,300 of these DCP's exist today. In order to hypothesize practical DCRS systems for this platform population, a determination must be made of the communication traffic it generates.

This traffic "sizing" is based on the expectation that the DCRS will not be involved in range/range-rate transponding or relaying. Those functions remain with the space-ground-link system (SGLS) and the existing range-tracking facilities.

Total message size has been determined for each type of data platform; then multiplying each message size by the number of platforms gives the quantity of information expected from that type of platform within the specified reporting interval. Dividing this number by the allowable reporting time within the reporting interval could provide a minimum allowable data rate for each platform type. As an example, balloons in the global-atmospheric-research program (GARP) must provide data on pressure, temperature, and humidity; must be individually identified; and must give position location data. Ten bits are allocated for each of the weather parameters. To identify 4500 balloons unambiguously, a 13-bit address code will suffice; but to provide address verification or expansion capacity for the future, one or two more bits are needed. An additional three to five bits may be allotted for synchronization of the bit timing, and 50 for position-location data. This all adds to 100 bits per balloon. For 4500 balloons, the total information content is then 450 kbits per report. But balloons must report twice in a 3-hour interval every 6 hours, with two reports spaced 2 hours apart. Thus 1 hour is allowed for each batch of 450 kbits. Ignoring global distribution, a single DCRS would have to collect data from all 4500 balloons within the available hour's time (clearly a pessimistic "worst case"). Neglecting the time required to address each balloon, lock on it, and locate its position, the assumption of serial addressing leads to a minimum allowable data rate of 125 bits per second. Table 7. 3. 3 shows the results of this process applied to all platform types.

In Table 7. 3. 3, the highest of the possible minimum allowable data rates is stated wherever a range appears for the total quantity of information expected from a particular type of platform. The highest minimum allowable data rate expected is 278 bps so that standardization on a data-channel-transmission bandwidth of 250 Hz would easily allow all data to be collected serially within the allotted time, except for the data from moored buoys and from hydrologic-(A) stations*. Because some of the data rates are low compared with 250 bps, the possibility of frequency-multiplexing some data-platform types suggests itself to achieve economy of spectrum utilization. If this were not done, and two channels each were allocated to the fixed-buoy and hydrologic-(A) data to obtain all the data within the allotted time at 250 Hz per channel, the 18 platform types would require at least 20 times 250 Hz, or 5000 Hz total rf bandwidth. But this must be augmented by about 20 percent for guard bands to avoid adjacent-channel crosstalk in the multiplexing process; thus, if the full reporting time were taken for each platform type, a minimum rf bandwidth of 6000 Hz is required. Increasing the bit rate to 800 bps, or the number of 250-Hz channels by a factor of 3, reduces the collection time to half an hour maximum and increases the required rf bandwidth to 18, 250 Hz. Since the band-

*Tables 3. 3. 1 and 3. 3. 2 in the report of the Panel on Hydrology place ground hydrologic stations in three classes of networks: A (10, 000 stations), B (25, 000 stations), and C (50, 000 stations).

TABLE 7. 3. 3

INITIAL TRAFFIC ESTIMATES, NEGLECTING POSITION-LOCATION REQUIREMENTS

Platform Type	Distribution	Position Fix Required	Number Plat-forms	Message Size (bits)	Reporting Interval (hours)	Total Quantity of Infor-mation (kilobits) per Reporting Interval	Allowable Reporting Time (hours) per Reporting Interval	Minimum Allowable Data Rate (bps)	COMMENTS		
									Future System	% of System Existing	Existing Platforms
1. Balloons	Global	Yes	4500	100	6	450	1(twice in 3 hrs)	125	Yes		
2. Land weather stations with U/A*	Global	No	500	1400	6	700	1.5	130		100	500
3. Land weather stations without U/A*	Global	No	3600	225	6	810	1.5	152		100	3600
4. Ships-of-opportunity with U/A*	Global	No	60	1400	6	84	1.5	15.6		50	30
5. Ships-of-opportunity without U/A*	Global	No	800	275	6	220	1.5	40.8		100	800
6. Ocean-station vessels	Global	No	25	1400	6	35	1.5	6.5		40	10
7. Buoys (moored)	Global	No	500	2000-3000	6	1000-1500	1.5	278	Yes		
8. Buoys (drifting)	Global	Yes	200	500	6	100	1.5	18.5	Yes		
9. Buoys (manned)	Global	No	5	3000-10,000	6	15-500	1.5	93.0		40	2
10. Aircraft-of-opportunity	Global	No	200	500	6	100	1.5	18.5		20	40
11. Hydrologic (A)	U.S.	No	7300	200	24	1460	1.5	270		100	7300
12. Hydrologic (B)	U.S.	No	1100	1000	7 days	1100	1.5	204		100	1100
13. Hydrologic (C)	U.S.	No	600	2000	30 days	1200	1.5	222		100	600
14. Offshore platforms (ocean, estuaries, & lakes)	U.S.	No	500	500	6	250	1.5	46.3	Yes		
15. Seismic	Global	No	240	350	6	84	1	23.4		12	30
16. Volcanic	Global	No	50	1800	6	90	1	25.0		30	15
17. Agriculture	U.S., Canada	No	4000	100	6	400	1	114		5	200
18. Forestry	U.S., Canada	No	2000	100	6	200	1	55.5		4	75

*U/A=upper-atmosphere capability.

width requirements for this application appear compatible with propagation in the VHF space-telemetry bands, it can be seen at once that the required oscillator stability to maintain integrity of each 250-Hz channel over a lifetime of one year must be at least one part in 10^7 during that length of time. This identifies an important technological requirement, and one which would have many other uses.

It is evident from this process that if identification and location are neglected, bandwidth is not a restriction on working a DCRS with the projected 1975 global population of data platforms. Even assuming these to double or triple by 1980, bandwidth is not a restriction. But it may become one if the identification and location of balloons and floating buoys require too much time.

3.2.1 The Location Problem

Even though, in 1968, it is not clear that the GARP costs will be underwritten to the extent of 4500 balloons aloft in 1975 and 10,000 in 1980, planning of DCRS systems for the 1970's cannot ignore the potential demand made by balloon-data traffic on the satellite. The identification and position-location problem for 4500 balloons appears to be constraining, since all balloons must be covered within one hour.

Three approaches to this problem are currently being pursued: one based on the U.S. Navy's Omega position-location (OPL) system; one based on interrogation, response, and time counting for range determinations (IRLS); and one based on simultaneous ranging and doppler-shift measurement for location (EOLE—a French system). Identification-and-location times for each balloon in these systems are: OPL, less than 3 minutes; IRLS, at least 50 milliseconds; EOLE, 16 seconds.

The OPL and IRLS systems require two ranging fixes between a balloon and known references. In OPL, simultaneous relative fixes are obtained between the balloon and any two sets of two out of a total of eight VLF ground stations whose radiation covers the globe. In IRLS, two fixes on the balloon are obtained at different times from a satellite in a known orbit. The two range fixes are used to determine balloon location: in OPL, in the Omega coordinate system of families of intersecting hyperbolae; in IRLS, in triangulation from the known satellite ephemerides to the balloon. In IRLS, the optimum time between fixes for minimum range error has been determined as 150 seconds for satellite altitudes between 600 and 1800 miles; for a geostationary satellite, the system could not work with balloons within the time constraints, because the time between fixes would increase intolerably. In OPL, the 3-minute maximum time required for identification and location arises from having to integrate location-data signals with a signal-to-noise ratio between -9dB and zero dB. This condition is expected by the NASA technical management of the OPL experiment; not all of the four existing OPL ground stations are operating at the rated transmitter power of 10 kW; one is currently operating at only 300 watts. Increasing the ground-station-transmitter power to rated output could increase the location-data signal-to-noise ratio to as much as 3 dB, so that the total integration time would be reduced to about 1 1/3 minutes.

In the OPL system, each ground station can transmit a group of three ranging tones, and phase differences between tones at the same frequency are developed in a balloon to determine possible intersections of the hyperbolae defined by two ground stations. The tones, which occupy a band 3.4 kHz wide, are compressed in width and relayed through a satellite to a central station (possibly the GDH center in our case). At the central station, half-wavelength distances, corresponding to a series of difference frequencies developed from the ranging tones, are used to resolve position and range ambiguities and to complete the position location. By a continued mixing process, the tones and their difference frequencies can be used to generate a compressed band about 226 Hz wide, in which all the information is contained. The inverse process must be applied to all the tones in this band at the ground station, but it is then possible to transmit all the position-location data, using one tone in the band as a reference, within a band 250 Hz wide. Then, with a total integration time of about 1 1/3 minutes per balloon, each data channel in DCRS can handle at least 45 balloons in an hour. Allocating 100 channels to the balloon complex takes care of the 4500 balloons in the allocated hour's time. The bandwidth for DCRS then is augmented by 99 more 250-Hz channels plus 20 percent for guard bands, or 29,700 Hz, and the total bandwidth now is 29,700 plus the 18,250 previously identified, or 48 kHz.

There remains only consideration of the EOLE approach to identification and location. The very short process time required with EOLE results in part from having a beacon signal on all the time, so that balloons are always locked on the signal and ready to transmit. But the doppler shift in frequency derived from a balloon depends upon the relative velocity between it and the cooperating satellite, if the velocity is low, the integration time is high. The 16-second time specified for EOLE arises from the low orbit altitude of 700 miles for the cooperating satellite. A geostationary DCRS would see very low doppler shift, if any, and the time to fix location would be intolerably long if the system worked at all. The attractive feature of having a beacon on all the time can be borrowed, however; the DCRS can have a channel available for transmission of beacon interrogation to all balloons. If the beacon is derived from an ultrastable oscillator transmitted up to DCRS from the GDH center, it can serve the whole system as a reference tone for OPL location-data bandwidth compression and for retransmission (if necessary) for use in the GDH frequency-synthesis process to resolve ambiguities in fixing location.

3.2.2 Multiplexing

Another look at Table 7.3.3 shows that the 200 floating buoys which require position fixing cannot be handled serially in the 90 minutes allotted with an integration time of about 1 minute per buoy. But with three 250-Hz channels allotted, they can be handled three at a time in 67 minutes. This implies a multiplexing requirement for all the data channels in Table 7.3.3. Any multiplexing scheme developed must consider both time and frequency wherever the minimum data rates can be combined in 800-Hz data channels to minimize the total data bandwidth required.

Based upon the parameters developed above, it is possible to propose a time/frequency multiplexing scheme that will enable a single DCRS to handle all the platforms of Table 7. 3. 3 within the required times. One simple scheme is to allocate 250-Hz channels as required to cover all sensors: if this is done in the context of the foregoing discussion, a bandwidth of 48 kHz is all that is needed. Excess capacity to anticipate doubling of all the small sensors, except balloons, by 1980 exists within this band. (See Table 7. 3. 4.)

This could be very wasteful of spectrum, since it ignores actual reporting times for groups of platforms in different locations. Taking account of the moving time base, sunrise, and the actual time a channel is needed to collect data from a group of platforms having the distribution described in Sections 3. 1. 1 and 3. 1. 2, it is possible to devise a time-assignment scheme that requires only three 250-Hz channels, exclusive of balloons and floating buoys, and is economical of spectrum. In this case the system is dominated by the 100 250-Hz channels needed for position location, but now the total data bandwidth is under 30 kHz, and capacity can be doubled, balloons excepted, by adding one or two kHz in additional channels.

The scheme, shown in Figure 7. 3. 1, is explained in detail in Appendix A. Using either multiplexing scheme—that of Figure 7. 3. 1, or that of service-dedicated channels with total bandwidth of 50 kHz—there is a major programming and distribution problem for the GDH center.

3. 3 DCRS Services

3. 3. 1 Vacuum Cleaner

Since it is clearly possible to collect data on schedule from all 26, 000 small platforms utilizing a single, relatively narrow band, it is appealing to think of a vacuum-cleaner satellite in which the whole job is done with one transponder. Because the balloons are used for upper-air data, coverage will be needed at fairly northerly latitudes, suggesting that more than three satellites may be needed. Four geostationary satellites, stationed at 40° and 130° E and 50° and 140° W longitude, could provide balloon coverage to 60° N latitude and coverage of other platforms to 70°. The satellite must be stabilized; it could use either a quad-helix antenna or a deployable umbrella type, such as the lunar-excursion module (LEM) S-band antenna. A simple beam to cover the earth disk, interrogate according to program, and receive sensor responses is adequate for the requirement. Because the bandwidth required is low, and because space-communication technology is well developed there, the VHF region is attractive for a frequency allocation. From 136 to 138 MHz and from 148. 25 to 149. 52 MHz, the spectrum is already allocated to space research, telemetering, tracking, and meteorological satellites. Down-link data can be provided to the GDH center and to regional data-acquisition stations in these bands. Vacuum-cleaner satellites, having no provision for data-gathering from low-orbiting satellites, can be developed with 1968 technology and launched on Thor-Delta boosters.

TABLE 7.3.4

ALLOCATION OF TWENTY 2500-Hz CHANNELS FOR 26,000 SMALL DATA PLATFORMS

Channel	Function or Service	"On" Time
1	Interrogation	Continuous
2	Agriculture & Forestry	Programmed
3	Seismic & Volcanic	Programmed
4	Hydrology	Programmed
5	Hot line	Demand/Program
6	Hot line	Demand/Program
7	Voice; Administrative Traffic	Demand
8	Space	
9*	Meteorological #1	0530-0600 1130-1200
10*	Meteorological #2	1730-1800 2320-2400
11-20*	Balloons	0330-0400 0530-0600 0930-1000 1130-1200 etc.

*9-20	Data Dissemination Research Vessels Other	Programmed in normally "off" time from above

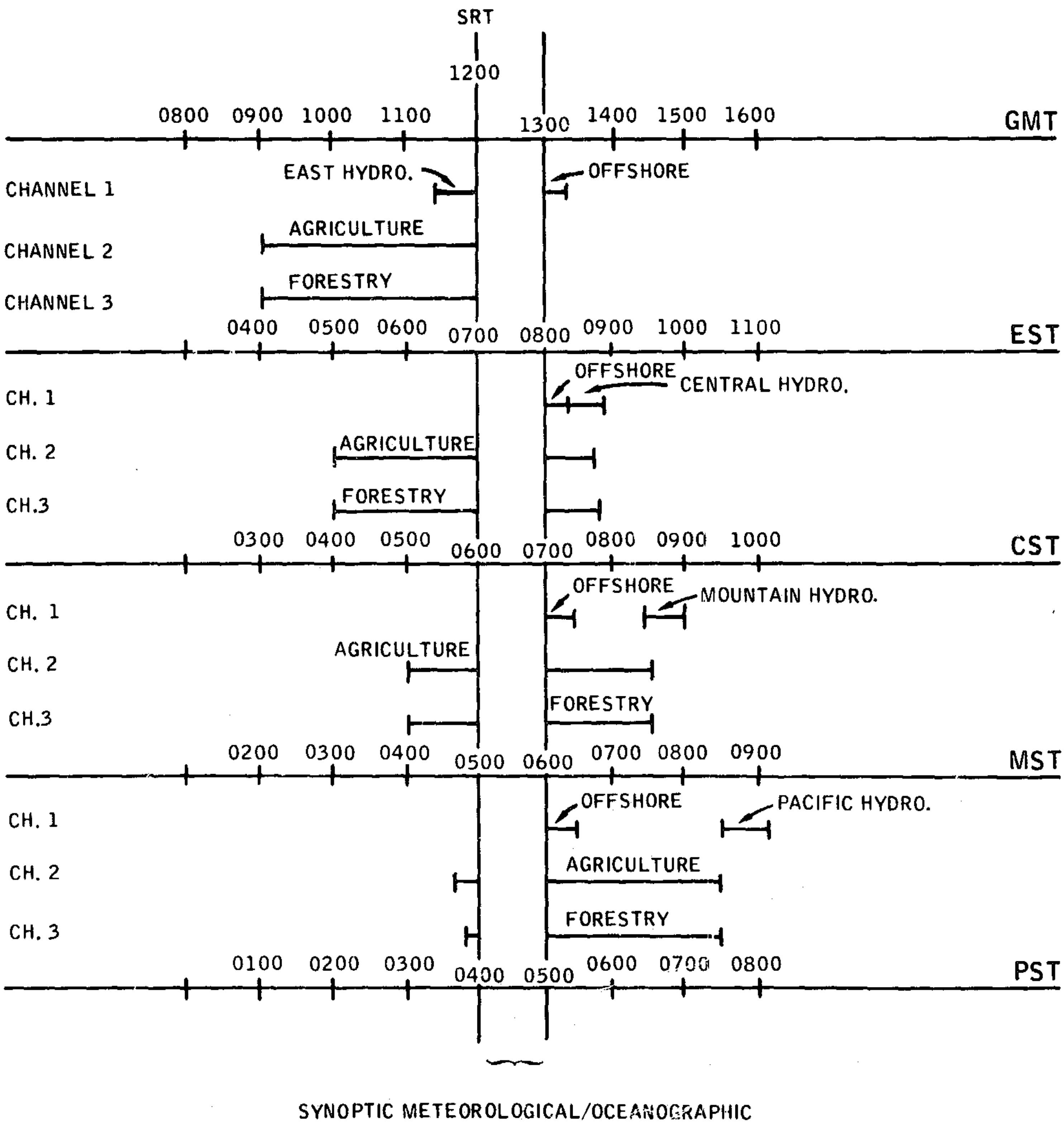

FIGURE 7.3.1 Synoptic and moving-base occupancy of three 250-Hz channels for 26,000 small data platforms.

3.3.2 Wide-Band Data-Collecting Relay Satellite (WBDCRS)

WBDCRS service would be intended to handle the traffic from three earth-resources satellites (ERS) providing high-resolution imaging of the entire earth, two polar-orbiting ESSA satellites, and the low-orbit phases of manned missions. The data bandwidth of a single ERS is 4.0 MHz; that for an ESSA satellite, giving effect to plans for digitizing the imaging-sensor data, about 840 kHz; and that for manned missions could be as high as 4 to 5 MHz in the 1975 era. WBDCRS must handle a total data bandwidth of about 20 MHz, while tracking and maintaining continuous communication with six satellites in different orbits. Two types of spacecraft antenna could handle this requirement: a straightforward, multiple-dish array with independently controlled tracking mounts for each of the six dishes; or a self-focusing phased array. The technology of the former is straightforward, but the spacecraft stabilization and station-keeping requirements are not. While the technology of the latter has been studied at S-band for a narrower-bandwidth application (Orbiting Data Relay Network, 1966-67) and some device development has been carried out, the bandwidth requirements for WBDCRS force a move to higher-frequency regions. In this case the electronics and self-focusing array present the difficult problems, while the structure and dynamics require good engineering with known technologies. Some deployment technology will have to be developed for both; it is regarded as more difficult for the self-focusing array. In either case, weight projections indicate a maximum expectation of about 2000 lb, which can be placed into orbit by a Titan III-C booster. For service including manned missions, the self-focused array approach will weigh and cost less.

To accommodate the total data bandwidth of the six satellites, the transmission links must have rf bandwidths of about 90 MHz. Frequency allocations for the WBDCRS-to-target-spacecraft links do not appear to present problems, but a 90-MHz band allocated to space for the DCRS-to-ground-station link might. The band from 8.4 to 8.5 GHz satisfies the requirement, but if assigned to WBDCRS service it will be almost completely occupied with establishment of the initial system. No growth capacity is available in this channel.

Earth-resources-data resolution requirements are projected to increase from three spectral bands at 100-ft ground resolution today to seven bands at 60-ft or 30-ft ground resolution in 1980. Apart from the need for policy statements concerning ground resulution finer than 60 ft, these growth demands are projected into bandwidth requirements of 250 to 1000 MHz by 1980. In order to accommodate these growth requirements, the spacecraft-to-spacecraft link for WBDCRS service has been considered in X-band at 10.7 to 11.7 GHz. But a 1-GHz-wide assignment for the down link would have to be sought if the growth is to be accommodated. This might be possible on a shared basis in the 10.7- to 11.7-GHz band, but for the initial system the available 8.4- to 8.5-GHz allocation will be used.

Even if an allocation can be found, the feasibility of providing a practical WBDCRS service for a 1980 ERS system is questionable. For seven bands at 30-ft resolution, the satellite-to-satellite relay has to provide an ERP-aperture product of 105 dB above 1 watt-ft^2 for each ERS in the system, which may well mean a dedicated WBDCRS for each ERS. In this case, the system's economic viability as well as its technical feasibility becomes increasingly questionable.

The system consists of three WBDCRS spacecraft and two ground receiving stations connected to the GDH center by land lines or microwave link. Two spacecraft are stationed at 10° W and 170° E longitude, and work with ground receivers at Rosman, N. C., and Mojave, Calif., respectively. The third spacecraft will be in a parking orbit, ready to position at either orbital station in case of failure. Ground-antenna elevation angles always exceed 5°, and multipath immunity is high because the minimum angle between line of sight and earth tangent is 21°. This system continuously tracks and communicates with the six target satellites: one ERS in a 98°, 9 a.m.,* 499-mile orbit; two at 180° apart, in a 98°, noon,* 499-mile orbit; two ESSA satellites in 101°, 750-mile orbits; and a manned mission in a 28° orbit at a few hundred miles.

Because of the high-resolution requirements placed on earth-resources data, the wide-band DCRS link must be ultra-linear and produce little degradation of the video signal. Comparative analyses of PCM and FM show the latter to be preferable for this; it is considerably more economical of spectrum, an overriding consideration for this particular service. The linearity needed over the wide bands can only be achieved with microwave modulators, however, so that an important aspect of this service is the development of signal-processing and communications technology at the appropriate frequencies.

A problem of timing, however, may make this system unjustifiable. The initial ERS can be in orbit by 1971, while the initial WBDCRS could not be until about mid-1973. During this time, other means would have been used to acquire data from ERS, and by the time WBDCRS could be up, the ERS technology might have advanced to the point where WBDCRS is no longer compatible with it. Long-range systems planning must provide the answer if, as indicated earlier, ERS-data growth outstrips the technical feasibility of advanced DCRS's.

3.3.3 Regional Data Collection without DCRS

The initial (1975) earth-resources-satellite data are requested in three spectral bands, with a ground resolution of 100 ft. As earth resources data acquisition technology improves, ground resolution is expected to refine to 60 ft 2 to 3 years later, and possibly to 30 ft in the 1980's. While this is far short of reconnaissance resolution, it may be considered sensitive by some potential users or beneficiaries of data acquired by ERS (in fact, a policy decision by the Government is needed before action can be taken on systems or technology providing resolution finer than 60 ft). To encourage full international participation in the global land-use system and still provide protection for sovereign rights, consideration has been given to a system which provides initial access to the satellite video only to the country being

* The times at which the satellites cross the equator from south to north.

surveyed at the moment. This system envisi. ns ERS transmitting its video in real time to a regional ground station within the country under view and tape or photographic records being made of the satellite video at the ground station. At the option of the sovereign nation or region, the received video may then be sent to the GDH center.

From the viewpoint of the using services, ERS data are not needed in real time. Thus, even within the United States, this system serves the purpose of getting earth-resources data to the GDH center. Once recorded, the data may be sent in a film or tape pack, or the data may be relayed to the GDH by some other communication means.

The system requires a tracking antenna on the ERS spacecraft and a handover programmer to cooperate with adjoining regional sites. To retain the basic structure and spacecraft dynamics, it has been convenient to assess the effects on the ERS spacecraft of a self-focusing array. This can be done at S-band with a 32.5 in. x 32.5 in. array, or at X-band with a 9.5 in. x 9.5 in. array, which appears easier to fit on the satellite.

High-quality video may be obtained from ERS whenever the spacecraft is 5° above the horizon. This permits unobstructed ground coverage of nearly 1500 miles, a span that exceeds the boundary span of many nations which might participate in the system. Considerations of regional integrity and the admission costs to small nations of $800,000 for the ground station and $800,000 for 4-year O&M might well encourage international cooperation. But the minimum cost to the United States, satellites and launches included, could be as high as $1132 million for 4 years, and the risk seems reasonably high that some global landmass data would not be available to the GDH center. Economically, this approach does not seem very promising.

3.3.4 Direct/Delayed Data-Collecting System with Three Ground Stations

Current proposals for earth-resources systems have the ERS either transmitting its data in real time or storing it in a tape recorder for delayed transmission to receiving stations at Fairbanks and Rosman. This system provides North American continental landmass coverage, and some coverage of other landmasses. If the same system were augmented by adding an 85-ft S-band receiving capability to the Mojave ATS station and including it in the ERS ground net, complete global landmass coverage could be obtained from a pair of satellites every 18 days, barring cloud cover. A three-ERS system (one in a 9:00 a.m. orbit, two in noon orbits 52 minutes apart) might reduce the survey time, while providing added data of interest to different services.

The S-band receiving station, the recording and processing equipment to make records of the transmission for distribution to GDH centers and other interested participants, and 4-year O&M costs per station would total about $7 million, as discussed in Section 3.1.4. But there has been objection to the use of video-tape-recorder storage in the spacecraft because the recorder reliability is suspect. The recorder proposed for the ERS mission has been space qualified in the Apollo program; one has been run for more than 500 hours without degrading below specification requirements. The total operating time for a 1-year ERS life is approximately 500 hours.

To double this and assure reliability, a serious program in recorder product development would investigate head materials and design, tape materials, head-tape-interface behavior in the recorder can atmosphere, bearing materials and design, lubricants, tape path, and drives. This might cost several million dollars (perhaps 5), but the result would be a reliable, life-tested design in time for the ERS spacecraft of 1970. (If greater reliability and longer life could be achieved, the ERS lifetime might be extended to 2 years, thus cutting down the ERS segment cost.)

Together with the incremental cost for the Mojave station, this seems to provide the most cost-effective means for getting global earth-resources data to the GDH and to interested users. Since this system (using three ERS) can collect data on more than 100 million of the 147 million square nautical miles on the earth's surface every 18 days, and the total land area is only 37 million, a considerable portion of the ocean surface can also be imaged for interested users. It seems that the wide-band DCRS mission cannot be economically justified. Even if it could have been for the initial mission, it could not be for growth, since dedicated WBDCRS's would be required. In the last analysis, it should be easier for the ERS to transmit directly down than to transmit 40 times further upward to a one-channel down-link repeater. Accordingly, the growth program should be accommodated by supporting new technology in data storage, both magnetic-tape and electro-optic.

4.0 VACUUM-CLEANER-SATELLITE SYSTEM (VCSS)

In order to understand our atmospheric and earth environment properly and to predict its immediate future, a large number of data points, taken at frequent intervals, is required. One technique for obtaining the data is sensing the atmosphere and the earth remotely from either aircraft or satellites. This technique is limited by the capabilities of remote sensors to infer the properties of the atmosphere and the earth from electromagnetic radiation. An alternate, and more direct, way of obtaining the data uses in situ sensors. These in situ sensors, or data-collecting platforms, (DCP's), discussed in further detail in Sections 3. 1 and 3. 2 and Appendix A, are located within the atmosphere and on the earth's surface, and sense the environment directly. At the present time, more than 14, 000 DCP's are deployed around the globe. Plans are being made which may lead to approximately 26, 000 of these DCP's being operational by 1975. In order to utilize these platforms properly, it is important that the data collection be timely. Rapid collection with radio techniques is an important characteristic of the data-collection system. In this section it will be shown how a data-collecting vacuum-cleaner-satellite system is especially appropriate for this function and, properly applied, offers a possibility of obtaining important atmospheric and earth-resources data with correspondingly high potential benefits.

4.1 System Considerations

Location of balloons represents the most challenging problem for a vacuum-cleaner-satellite system (VCSS) and also its most urgent requirement. Use of VCSS appears to be the only feasible method of collecting data from the balloons over ocean areas, where they are most needed. An important aspect of balloon-data collection is that balloon location is required within 2-hour intervals in order to get gross wind-vector information.

It is planned that the land weather stations, the merchant vessels, the buoys, and the balloons are to fit in the world weather-watch (WWW) system. This system operates on a synoptic interval, as do the current weather systems. The synoptic interval is defined by standard recording times (SRT) of 0000, 0600, 1200, and 1800 GMT. Further, it is desired to take the information from the meteorological remote platforms in a short time, so that the output information can be disseminated rapidly. At the present time, meteorological information is disseminated between 1 and 2 hours after SRT. It is intended that this information be disseminated within 1 hour after SRT. For this study, we have designed for 1/2 hour of collection time at each SRT for all meteorological platforms.

In order to evaluate the feasibility and potential benefits of a data-collection system, the Panel has postulated the in situ platforms of the 1975 era. The summary of the postulated in situ sensors is shown in Table 7.3.3. Here it should be recalled that 14,000 of the 26,000 sensors have already been deployed. Very few are equipped with telemetry, however.

In reviewing Table 7.3.3, it is apparent that the types, locations, message lengths, and reporting intervals vary widely among the platforms from which data must be collected. In addition, the users of the data and the agencies which will deploy the platforms will vary widely. A sample of expected users includes the Department of Commerce, the Department of the Interior, the Department of Transportation, and the Department of Agriculture. In addition, many of the sensors will be deployed on a global basis, some by other countries.

These remote platforms generally contain relatively small amounts of data, varying from 100 to 3000 bits. Summing data from all the sources, the amount of information to be collected in 1975 from 26,000 platforms is about 6×10^6 bits every 6 hours. This data rate is extremely low when compared to expected video rates from an earth-resources satellite, which might exceed an equivalent of 50×10^6 bits every second.

Four general types of data collection can be identified. The first is synoptic collection of data within 1/2 hour of SRT. The second type of data collection is in local time and results in a uniform global data rate. For example, it is desired to collect agricultural and forestry data just before dawn, so data collection should just precede the movement of the terminator* across the earth. A third type of data collection consists of emergency data, which would be collected on an alarm basis. For example, detection of sufficiently high-amplitude seismic waves could provide a warning or could alert other sensors to report more frequently to provide information on the impending disaster. A fourth kind of data collection is based upon demand from remote users.

For wind vectoring, position fixing of horizontal-sounding balloons (HSB) is required within a period of 2 hours. The global atmospheric-research program requires determination of wind data at least every 24 hours and possibly as frequently as every 12 hours. It will be just as easy to collect data within the regular 6-hour synoptic interval, so the model system provides two position fixes 2 hours apart, every 6 hours.

For certain types of platforms, there are several ways of collecting the data other than via a data-collecting satellite. The other alternatives include land lines, microwave link, VHF link, high-frequency (HF) communication utilizing reflections from the ionospheric layer, and meteor-burst communication utilizing reflection of HF from meteor trails.

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*The dividing line between day and night on the planetary surface as observed from orbit.

Land lines are applicable in heavily populated areas where they have already been laid. For example, the existing ESSA weather network depends upon the teletype communication net; but, in remote and inaccessible areas, the laying of new land lines to collect data from sensor platforms can cost $5 thousand to $10 thousand a mile. A recent study conducted by the Department of Interior showed that it would cost $5 million to lay the land lines necessary to collect data from hydrologic sensors in the Pilot River Basin area in California. This price is comparable to the cost of one data-collecting satellite.

The use of direct line-of-sight communication such as VHF is limited by the need to have many collection stations for remote platforms such as buoys, ocean vessels, or balloons. Even on the landmass, this sort of communication does not necessarily compete with land lines.

High-frequency (HF) communication utilizing reflection of radio waves from the ionosphere is a well-known and frequently utilized technique for communicating beyond line of sight. This system offers the possibility for collecting data from buoys, balloons, and ships. In fact, HF is now being used in this capacity on experimental systems. Data collection from a buoy has been made by HF with a utilization factor of 80 to 90 percent. The superpressure-balloon experiment being run by the National Center for Atmospheric Research (NCAR) is also transmitting data via HF. High-frequency communication, however, is limited: in order to obtain high-reliability communication, it is necessary to utilize frequency, spatial, and time diversity as well as high transmission-power levels. But available bandwidth in the HF spectrum is extremely limited. Consequently, HF communication is considered inapplicable to an operational system. However, it may continue to be useful for experimental purposes.

In order to compare conventional means of collecting data with a VCSS, a relative-cost study was performed. The object was to obtain a representative figure for the difference in cost between a conventional data-collection system for more than 26,000 platforms interrogated synoptically and a VCSS for collecting data from a large number of platforms. Conventional systems would cost more than $1 billion for a 4-year period, whereas the VCSS would cost $74 million in the same period. These estimates include the data-communication system only, not the sensor platforms.

Several techniques could be employed to provide appropriate coverage of the data-collecting platforms and to locate those that are moving (balloons and drifting buoys). The simplest technique for collecting data would employ a low-altitude satellite in an inclined orbit of approximately 60°, which would provide sufficient coverage to interrogate and collect the data from all platforms in 1 day's time. The difficulty with this scheme is that there would be no adherence to the synoptic interval; data would be collected at a fairly uniform rate. This disadvantage could be overcome by putting six satellites into polar orbits. In this manner, synoptic coverage could be obtained, since complete earth coverage would be obtained every 2 hours for each satellite. However, the objective of collecting data in a short interval every synoptic period could not be achieved, since time lags of at least 2 hours would be encountered. It would be necessary on a low-altitude polar orbiter either to store the data for delayed transmission direct to the GDH center, or, if the system had to provide continuous coverage, to relay the data through a geostationary satellite which would be required.

The location of the balloon and drifting-buoy platforms is accomplished from a low-altitude polar satellite using geometric measurements. Several techniques are feasible and are presently under development. One is a range-range scheme which will be utilized by the Interrogation Recording and Location Subsystem (IRLS). This system makes two or more measurements of range during one orbital pass. Information on the balloon altitude, satellite ephemeris, and two range measurements provides a unique position determination. A subsequent-pass position location will provide the desired wind-vector information with about 2 hours separation.

Another technique for location is being developed by the French in their EOLE experiments. This system measures both range and range-rate instantaneously. The range-rate, together with known satellite ephemeris information, determines a unique angle for the remote platform. With range information and platform altitude, a location fix is provided. Sucessive orbits will give wind-vector information.

A third technique for location would measure the variation in range-rate as measured by doppler shift as a function of time. Time of zero doppler indicates the relative latitude of the platform. The time between given levels of positive and negative doppler shift is related to the longitude of the platform relative to the satellite orbit. In order to get a sufficiently accurate measure of doppler, either extremely high stability of the local oscillator is required, or it is necessary to transmit the local oscillator reference back to the command station. For that reason it is most desirable to have this system operate in conjunction with a geostationary satellite.

The Omega system can also be utilized for platform location. This system, under development by the Navy, operates with very stable VLF (10- to 14-kHz) transmitters. A total of eight would be deployed worldwide, and any platform should be able to receive from three of them. Phase measurements between three such transmitters are utilized to obtain a position fix. Location of a DCP would be obtained by receiving the VLF signals, up-converting them to VHF frequencies, and transmitting the VHF signals through a geostationary satellite into a ground station for computation of the platform location. This technique is being developed by NASA in the Omega position-location experiment (OPLE). Experiments have been conducted with the ATS-III satellite and feasibility has been successfully demonstrated.

Use of Omega position location (OPL) for platform location in an operational system would depend upon the completion of the Omega system. At this time, only four of the required eight stations have been completed. It is estimated that the additional four stations would cost about $8 million apiece. Since the Omega system is being developed independently by the Navy for navigation, the incremental cost to the data-collection system is nil.

The requirement for synoptic global coverage, with all platforms interrogated within a relatively short interval, leads naturally to the consideration of geostationary satellites. One system would consist of four equatorial, geostationary satellites placed at 90° intervals on the equator. This system considerably simplifies the data logistics, particularly for the fixed platforms. Such platforms could utilize fixed, high-gain antennas pointed toward the geostationary satellite to cope with the greater ranges associated with geostationary altitude. Synoptic coverage is readily obtained, since all points between 70° N and 70° S latitudes are in constant sight of at least one of the four satellites.

Balloons represent a difficult problem, since there is no a priori knowledge as to the exact relationship between the balloon antenna and the satellite antennas. Hence, it is necessary to build a nearly hemispherical balloon-antenna pattern. For the coverage analysis conducted in the study, it is assumed that balloon coverage could not be obtained at elevation angles less than 15°. This constraint implies that coverage above 60° latitude for balloons is not obtainable. Figures 7. 4. 1 and 7. 4. 2 show two methods of obtaining total coverage between 60° N and 60° S latitudes with four satellites. Figure 7. 4. 1 shows the coverage for balloons (elevation angles greater than 15°), using geostationary satellites. Figure 7. 4. 2 shows the coverage for four satellites in synchronous (24-hour), inclined (32°) orbits. Ground tracks for satellites in similar orbits, but at greater inclination, are shown in Figure 7. 4. 3. The use of four satellites offers the additional advantage of graceful degradation under failure, since three satellites will still offer significant coverage.

There are two possibilities for obtaining coverage up to the poles. The first of these consists of inclining the synchronous orbit. For example, four stationary satellites inclined at 48° latitude will obtain complete global coverage every 6 hours. This system will suffer, since position fixes will not be obtained with 2 hours' duration on balloons at high latitudes. In order to obtain the polar coverage, it will also be necessary to forego some of the other advantages of geostationary satellites; that is, continuous surveillance of an area. There will be times in which areas will not be covered. An example of polar coverage with geostationary equatorial satellites is compared with that of inclined orbits in Figures 7. 4. 1 and 7. 4. 2. Inclined-orbit tracks are shown in Figure 7. 4. 3.

Another technique for obtaining complete global coverage would employ a combination of three geostationary satellites plus one or two polar orbiters. The polar orbiter would obtain position location by the use of the Omega system. The information obtained by the low-altitude satellite could then be relayed to ground stations. In this way, near-global coverage could be obtained every 2 hours, and requirements for obtaining the information within the synoptic interval and for obtaining balloon fixes 2 hours apart could be met, although the low-altitude polar orbiter would be absent from the poles a large percentage of the time, and some small gaps would remain (Figure 7. 4. 5).

Still another possibility for polar coverage uses three geostationary satellites together with one satellite in a highly elliptical, inclined orbit. Figure 7. 4. 4 shows the coverage obtained for balloon-antenna elevation angles exceeding 15°, with elliptical orbit parameters of 63. 5° inclination, 20, 000-kilometer apogee, and 480-kilometer perigee. If the satellite in inclined orbit is replaced by one in a polar orbit, the coverage changes

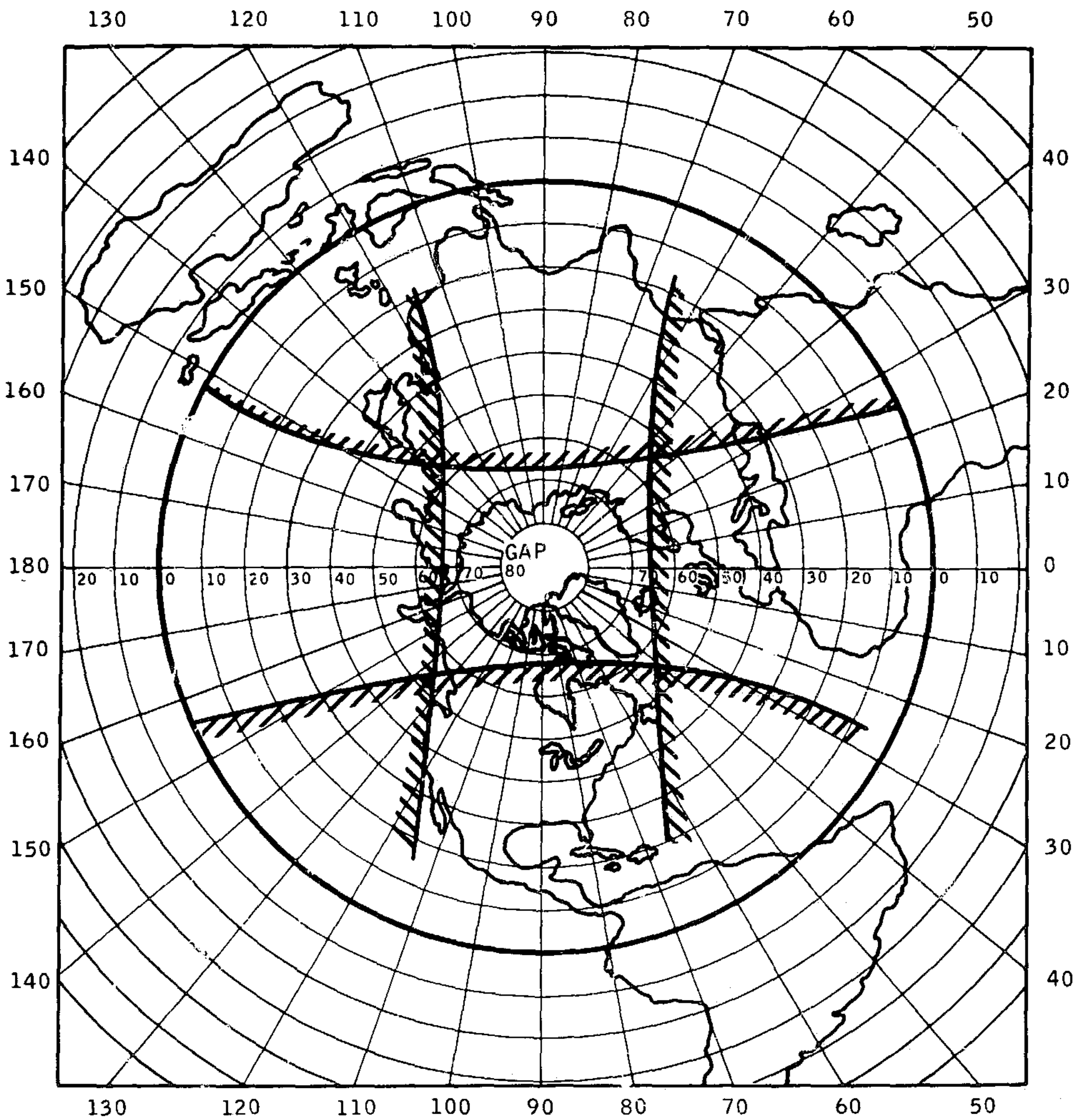


FIGURE 7. 4. 1 Example of polar coverage for four geostationary satellites, for elevation angles greater than 15°. The minimum elevation angle for balloon data-collecting platforms is 15°.

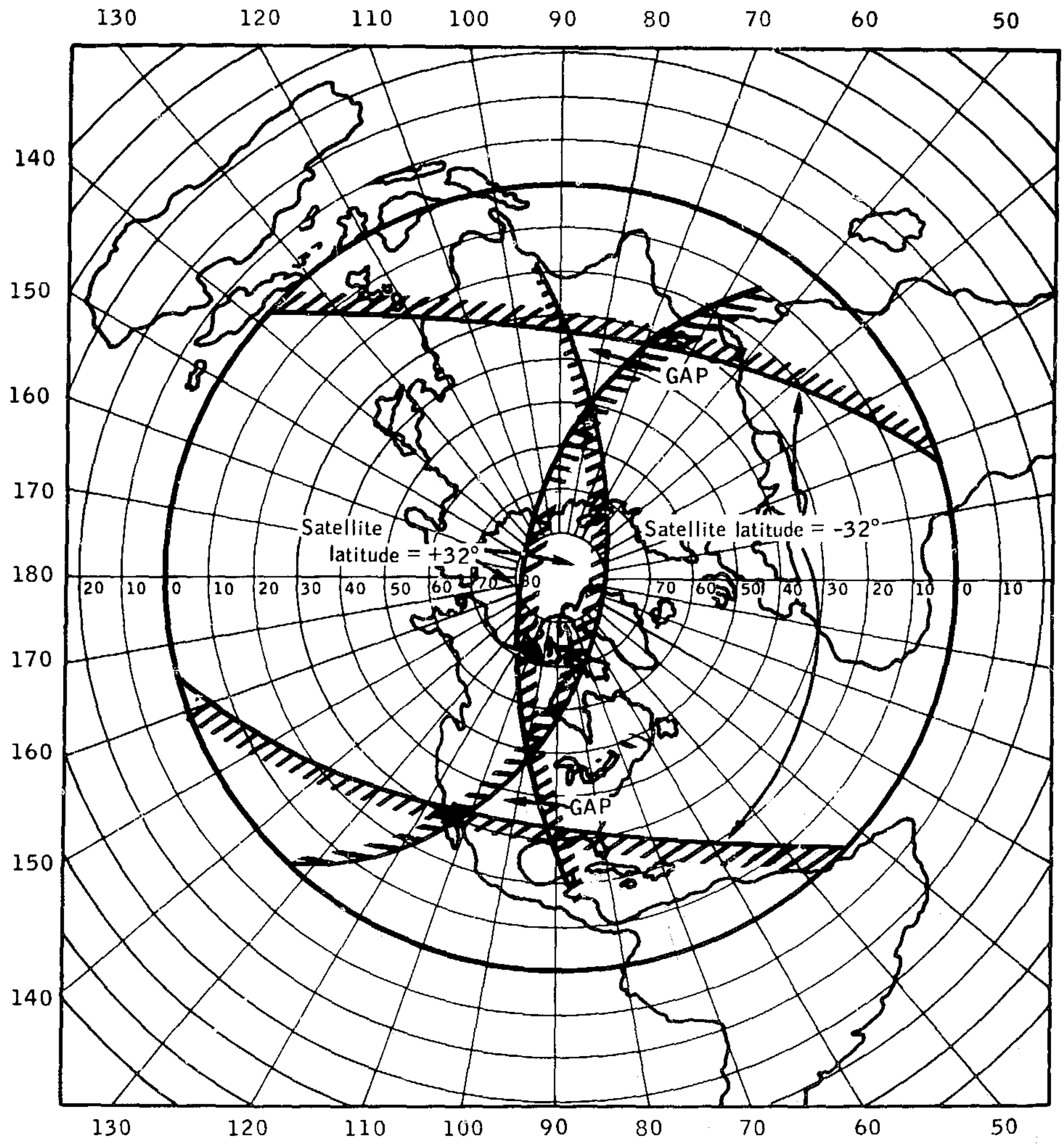


FIGURE 7. 4. 2 Example of polar coverage for four synchronous (24-hour) satellites in 32° inclined orbits.

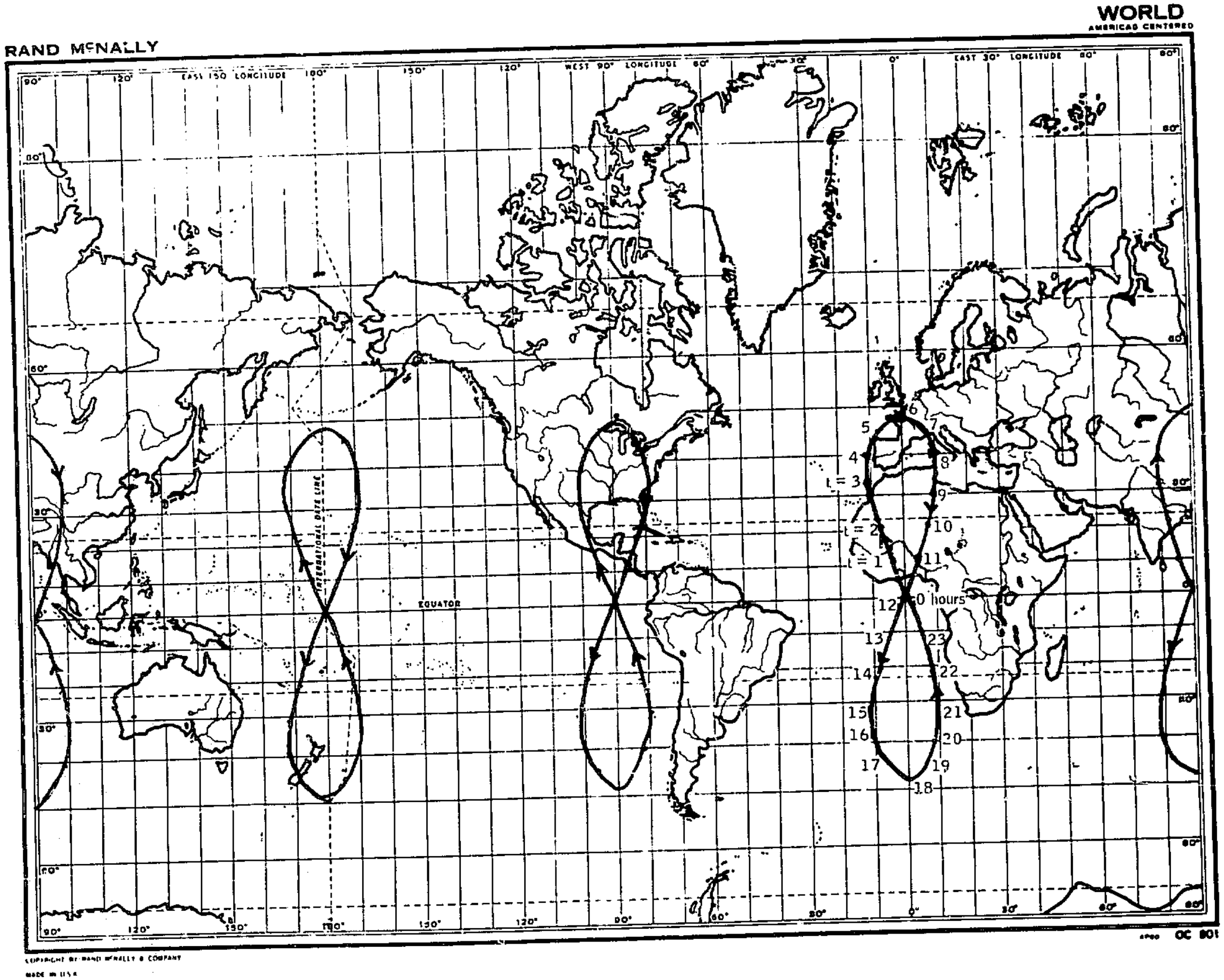


FIGURE 7.4.3 Tracks of subsatellite points of four satellites in synchronous (24-hour), inclined orbits, crossing the equator at the longitudes shown. Coverage would vary approximately 70° about the subsatellite points. See Figure 7.4.2.

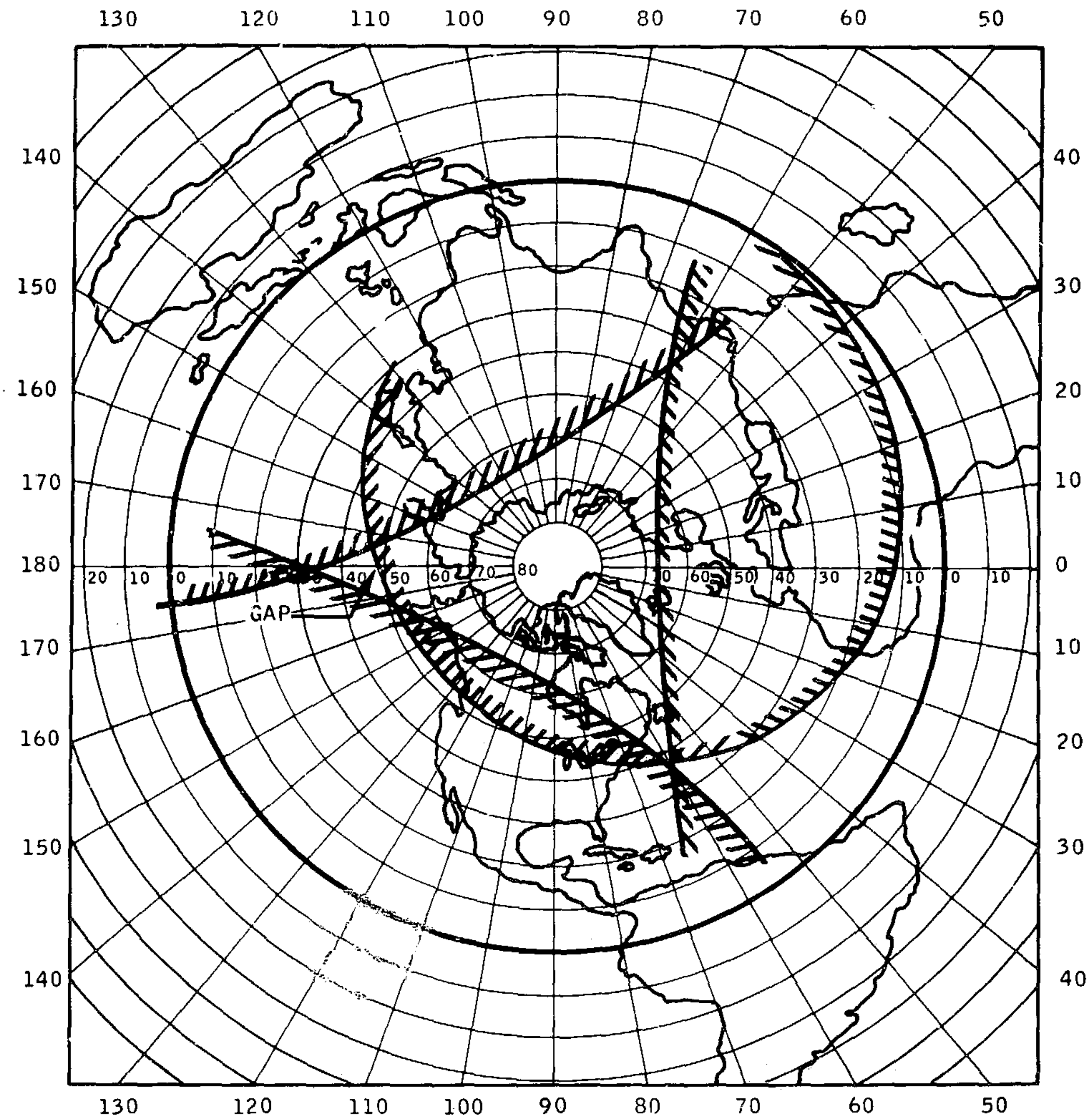


FIGURE 7.4.4 Example of polar coverage for three geostationary satellites, for elevation angles greater than 15°, plus one satellite in an elliptical, inclined orbit.

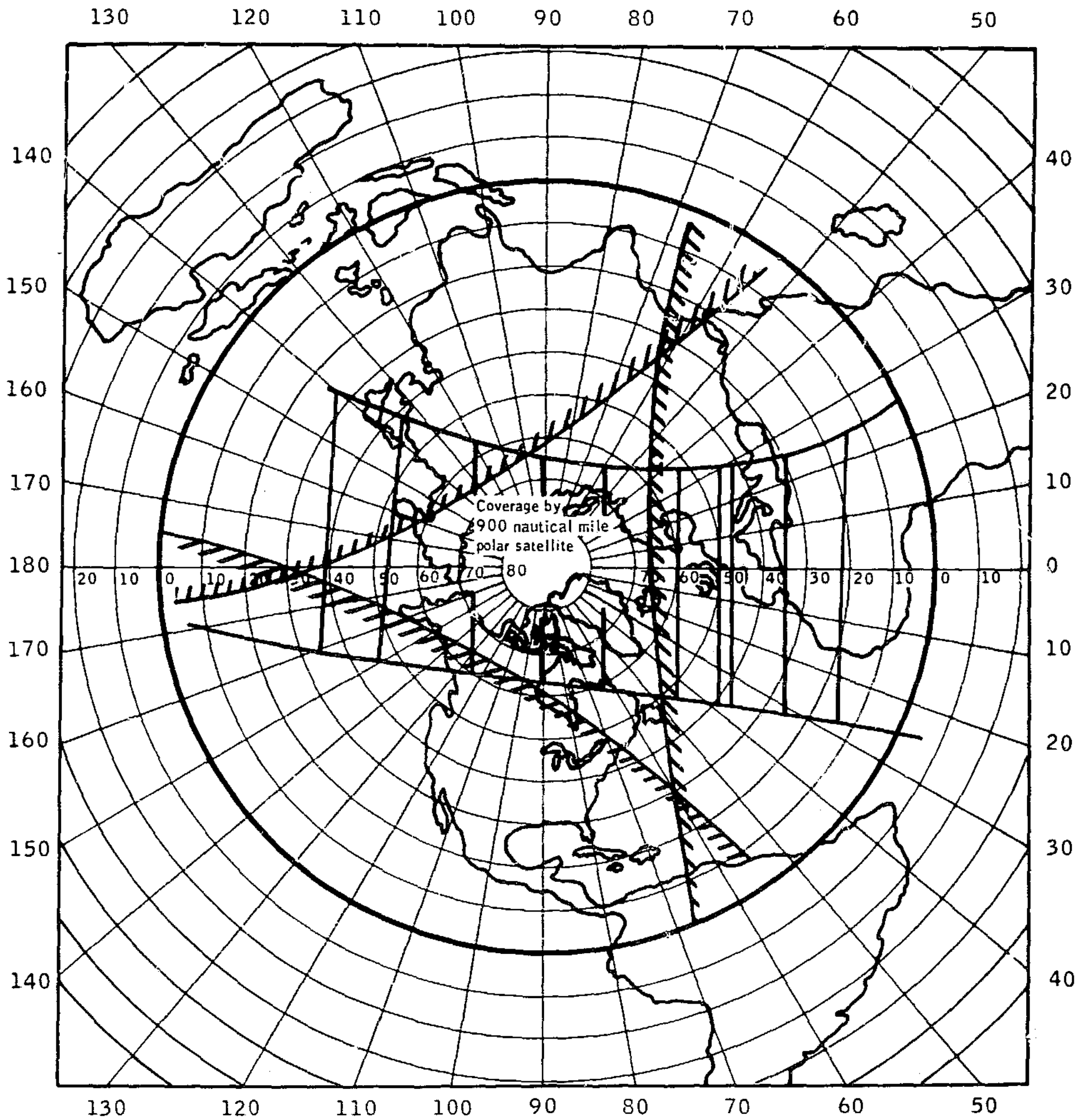


FIGURE 7.4.5 Example of polar coverage for three geostationary satellites, for elevation angles greater than 15°, plus one polar-orbiting satellite.

to that shown in Figure 7.4.5. Here the coverage gap at the poles is much larger and can be seen to change with time.

Properties of the techniques described above are compared in Table 7.4.1. Geostationary orbit using four satellites has been selected.

4.2 Current Experiments

The balloon platform is the most speculative of the platforms postulated for the 1975 era. There are still two major technical questions which must be resolved prior to the implementation of a large-scale horizontal-sounding-balloon system. The first question concerns the lifetime and cost of the balloons. If substantial departure from the expected 1-month minimum lifetime of the balloons is found, or if balloon electronics costs are much higher than anticipated, the horizontal-sounding-balloon system may become economically unattractive. A second problem with horizontal-sounding balloons (HSB) is that the deployment of a large number of HSB's in an operational system may represent a hazard to aircraft; hence, the balloons will have to be fabricated in such a manner as to make balloon-aircraft collisions nonhazardous.

Experimental programs for interrogating and locating balloons which are presently underway include the French EOLE experiment to be tested from the International Applications Satellite A (IAS-A), the NASA Interrogation Recording and Location Subsystem (IRLS), and the Omega position-location experiment (OPLE). The objectives of these experiments are all similar: to establish the feasibility of measuring meteorological parameters on a global scale, utilizing satellites to process, store, and relay the data rapidly. Block diagrams for these systems are similar, as illustrated in Figure 7.4.6. The basic elements are:

1. Data-collecting platforms (DCP's) provided with sensors to measure the environmental parameters
2. A satellite to interrogate the DCP's periodically to determine their locations and measurements
3. A control-and-data-acquisition (CDA) station to retrieve the results of the satellite interrogations and to command the satellite interrogation schedules

Hence, four communications links must be established:

1. CDA-to-satellite for command and interrogation sequence
2. Satellite-to-DCP for interrogation of the platform
3. DCP-to-satellite for the transmission of measurement data and position-location information
4. Satellite-to-CDA to transmit the DCP-measurement data and position-location information data

The experiments represent two basically different types of approaches to the interrogation and location of the DCP's. The EOLE and IRLS experiment will use medium-altitude satellites (between 800 and 1200 kilometers

TABLE 7.4.1
DATA-COLLECTING TECHNIQUES

SATELLITE	NUMBER OF SATELLITES REQUIRED AND COVERAGE	LOCATION	ADVANTAGES	DISADVANTAGES
1. Low-altitude polar orbiter	1: daily 4: 6 hours 6: synoptic (a)	Range-range (IRLS) or range-rate (EOLE) (b)	Relatively low DCP power (c) Obtains polar data Can share function, i.e., imaging Ranging geometry simpler	Difficult to obtain a synoptic coverage Storage with irregular readout or geostationary relay required Does not obtain continuous coverage Requires deployment of Omega
2. Geostationary	4, equatorial, synoptic (d)	Omega	Synoptic coverage Simpler data logistics particularly for fixed platform High-gain antenna may be used.	Requires deployment of Omega system for location Poor polar coverage Omega requires relatively wide band widths, long integration time
3. Geostationary	6 to 8 equatorial, synoptic (e)	Range-range using cooperative satellites	Same as above No need for Omega Allows shorter integration time	Poor polar coverage Requires 2 to 4 more satellites
4. Geostationary & polar orbiters	3+2 (f)	Omega Range-range	Obtains global and synoptic coverage (but not totally continuous)	Same as above for Omega Requires two extra satellites
5. Geosynchronous inclined	4 inclined at 48° (g)	Omega	Obtains global coverage	Synoptic-interval problems—only one coverage per day per satellite for poles—no wind vector Absentee problem

(a) One satellite can report an area once per day; two can report an area every 6 hours; six can provide synoptic coverage—i.e., worldwide coverage within the synoptic reporting interval.
(b) Interrogation Recording and Location Subsystem (IRLS) requires two range measurements during one orbital pass to obtain trilateration data to fix balloon positions; EOLE measures range and range-rate simultaneously.
(c) Only 1/18 of the power required for geostationary satellite communication; but fixed DCP may use high-gain antenna, reducing the importance of this advantage.
(d) Four satellites in 24-hour equatorial orbit give nearly full coverage between 60° N and 60° S latitudes for elevation angles greater than 15°.
(e) Six to eight satellites required for full location and coverage of balloons between 60° N and 60° S latitudes for elevation angles greater than 15°.
(f) Three geostationary satellites and two low-altitude satellites in highly elliptic polar orbits, with orbiting periods ranging from 6 to 24 hours.
(g) Four satellites in 24-hour orbits inclined at 48°. Each satellite sees each pole once per day.

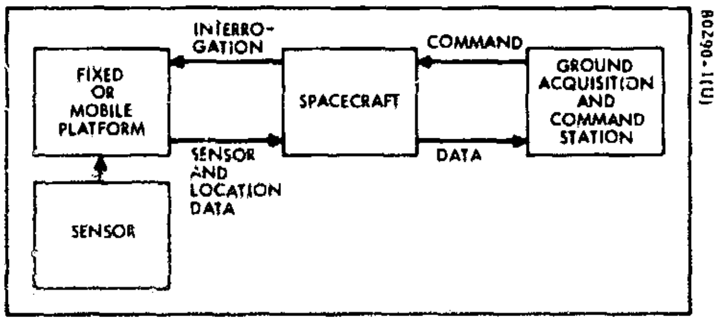


FIGURE 7. 4. 6 Data flow of experiments.

altitude). These satellites will be the IAS-A and the Nimbus, respectively. The OPL experiment uses a synchronous satellite. The ATS-I and ATS-III are equipped to perform OPL experiments. In Section 3. 0, the basis for choosing OPL as the location system to work with the vacuum cleaner was set forth.

4. 2. 1 OPL

In the operational Omega system, a total of eight VLF stations will be deployed. Signals will be received from three of these stations at any point on the earth. The VLF signals are propagated with very small phase shift over ranges of 5000 miles. Two lines of position (isophase contours) are generated by the phase differences between each of two pairs of Omega transmitters, and the DCP positions are established by the intersection of the isophase contours. Hence, the basic ranging information is obtained on the DCP's and then relayed through the satellite.

Figure 7. 4. 7 illustrates the operational sequence of OPLE. The OPLE control center (OCC), located at the Goddard Space Flight Center (GSFC), originates the DCP interrogations, which are preprogrammed at the OCC and relayed through the ATS satellite. Several DCP's may be interrogated simultaneously by frequency-division multiplexing of the ATS transponder. Platforms that identify their addresses correctly respond by transmitting tones through the ATS satellite to the OCC to allow phase-lock loops to acquire the platform signal. After acquisition, the DCP transmits its measured data. Following this, the VLF-relayed signals are frequency-translated up to VHF, compressed into a 2500-Hz bandwidth, and transmitted through the ATS satellite to the OCC. A period of 3 minutes is required to obtain a position fix, since signal-to-noise ratios of Omega signals at the platform can be below zero dB.

Testing of the OPLE system started in 1967 with the successful orbiting of the ATS-III satellite. Many successful interrogations on position locations have been performed over the last year, and the feasibility of this approach has been established.

A summary of the basic characteristics of the EOLE, IRLS, and OPLE experiments is given in Table 7. 4. 2.

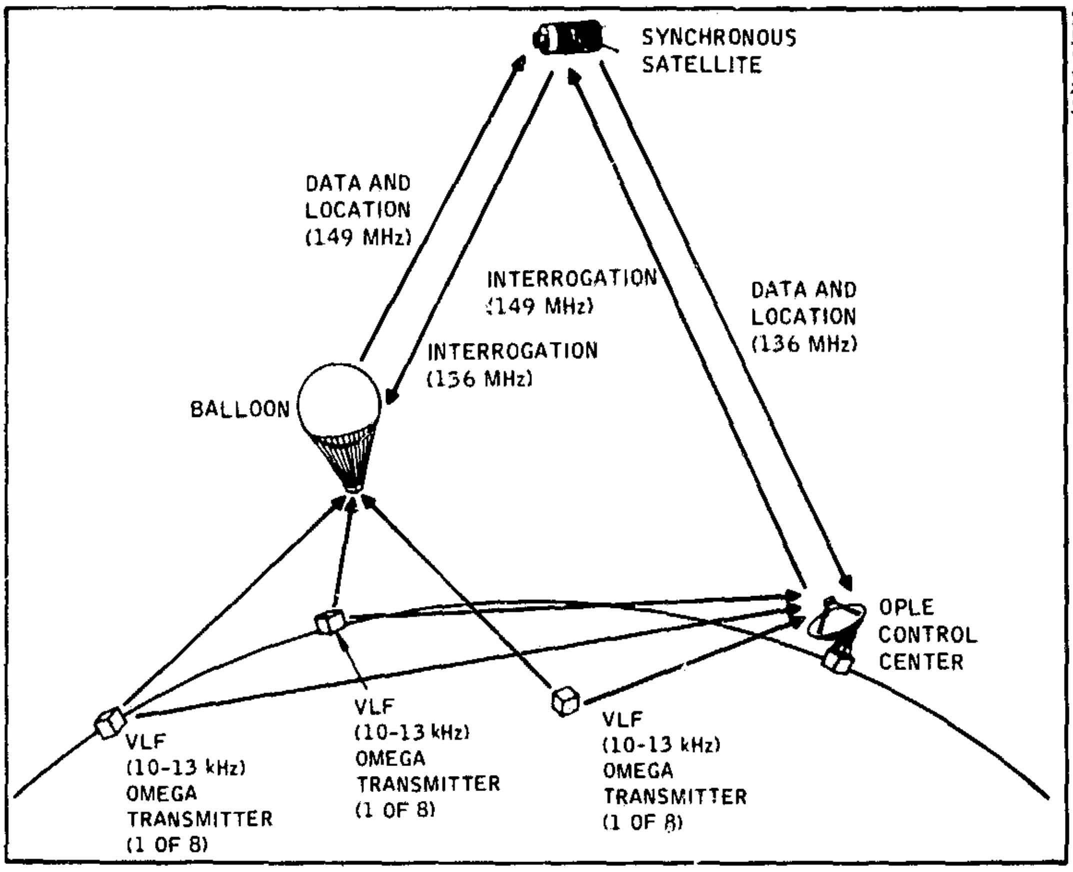


FIGURE 7.4.7 OPLE operational sequence.

4.2.2 Other Experiments

In late 1967 a hydrologic sensor was successfully interrogated and transmitted its data through the ATS satellite. No location was performed, since this was a fixed and located platform.

An experiment using the ATS-I and ATS-III satellites in conjunction is being planned by NASA. This system would use cooperative ranging. A carrier plus sidetones will be transmitted through the ATS-I satellite to a DCP. This signal will then be retransmitted by the DCP back through the ATS-I and ATS-III platforms. The phase shift on the sidetone of a transmitted signal will be utilized to determine the ranges between the ATS-I satellite and the DCP and the ATS-III satellite and the DCP. This information will then be used to obtain a location fix on the DCP.

4.2.3 System Studies

Studies of a data-collection system have been conducted by the National Environmental Satellite Center (NESC) of ESSA. This system, called the Geostationary Operational Environmental Satellite (GOES), will be in a geostationary orbit and perform two functions: data collection and mesoscale cloud picture photography. A VHF and/or a UHF transponder

TABLE 7.4.2
SUMMARY OF EOLE, IRLS, AND OPLE FEATURES

	EOLE	IRLS	OPLE
Satellite:	IAS-A	Nimbus	ATS
Altitude	800 km	800 km	19,323 nm
Inclination	50°		Equatorial
Satellite:			
Telemetering transmitter frequency	148 MHz	401.5 MHz	135.6 MHz
Command receiver frequency	136 MHz	466.0 MHz	149.2 MHz
Interrogation transmitter frequency	460 MHz	401.5 MHz	135.6 MHz
Interrogation receiver frequency	400 MHz	466.0 MHz	149.2 MHz
Transmitter power	4 W	21 W	40 W
Antenna gain	3 dB (max.)	3 dB (max.)	8.5 dB
Polarization	Circular	Circular	Linear
Receiver threshold	-128 dBm	-120 dBm	
Frequency stability	0.2 ppm/year	1 ppm	
Noise bandwidth	200 Hz	100 kHz	100 kHz
Equipment weight	54.6 lb	25.8 lb	31 lb
Total power required	23 W	128 W	96 W
Balloon:			
Altitude	30,000 (300 mb)	55,000 ft (100 mb) 80,000 ft (30 mb)	Variable
Transmitter frequency	400 MHz	466.0 MHz	149.2 MHz
Receiver frequency	460 MHz	401.5 MHz	135.6 MHz; 10-13 kHz
Transmitter power	4 W	6 W	5 W
Antenna gain	3 dB (max.)	3 dB (max.)	3 dB (max.)
Polarization	Circular	Circular	Linear
Receiver threshold	-129 dBm	-112 dBm	-126 dBm
Location time	16 seconds	150 seconds*	3 minutes
Frequency stability	3 ppm/month	10 ppm	1 ppm
Noise bandwidth	300 Hz	100 kHz	2.5 kHz
Thermal control	Yes	No	No
Power	5 mW (standby) 350 mW (detection) 18 W (transmit)	65 mW (standby) 360 mW (detection) 25 W (transmit)	1.1 W (standby) 35 W (peak)
Lifetime	6 mos.	6 mos.	1 day
Frangibility	Yes	No	No
Equipment weight	4 lb	9 lb	44 lb
Estimate cost	$3000 to $10,000	$15,000	
Interrogation Command Message Stored in Satellite Command Memory			
Number	64	370	Satellite does not have command memory. All interrogations are in real time
Length	22-bit message	32-bit message	
Composition			
Time	(9 bits)	(11 bits)	
DCP address	(9 bits)	(16 bits)	
Format		(3 bits)	
Mode	(4 bits)		
DCP type		(2 bits)	

*Separation time between two required fixes.

TABLE 7.4.2 (Continued)

	EOLE	IRLS	OPLE
Types of Interrogation Command Instructions to Data-Collecting Platforms (DCP)			
Programmed in command memory	Start sequential call End sequential call Destroy sequentially called DCP Start nonsequential call Destroy nonsequentially called DCP Turn off satellite transmitter Turn on satellite transmitter (sync signals only)	Call balloon Destroy balloon Call surface platform (up to 30 data frames)	
Nonprogrammed commands (real time)	Turn off transmitter Start sequential call		Call DCP Destroy DCP Turn off DCP electronics until next day/night transition Transmit sensor data only
Interrogation Signal from Satellite to Data-Collecting Platform			
Transmitter frequency	460 MHz	401.5 MHz	135.6 MHz
Modulation	Burst-blank PM	PCM/FM	FSK
Index	$\pi/4$ radians		
Deviation	±20 kHz	±2.4 kHz	
Transmitter power	4 W	21 W	40 W
Polarization	Circular	Circular	Linear
Bit rate	48 bits/sec RZ	12,500 bits/sec NRZ	48 bits/sec RZ
Interrogation sequence	30 bits	16 bits = 192 binits	16 bits
Sequences transmitted	One per DCP	Repeated continuously	45 (one per DCP)
Duration of interrogation	0.625 sec	3.8 sec (for balloons or if no response) 14.6 sec (max.)	15 sec
Sequence composition	18 pseudo-noise (PN) bits, 6 zeros, 6 ones 9 last bits of PN = DCP address 2304-Hz burst tone = zero 2688-Hz burst tone = one	16 bits = DCP address or DCP address complement 1 bit = M-word (8 binits) + N-word (4 binits) M-word = bit one or zero N-word = sync	16 bits = DCP address +command+parity First five 16-bit sequences for DCP synchronization Next forty 16-bit sequences to address DCPs
Same DCP interrogations per pass	Sequential	Instructed by program	One

TABLE 7. 4. 2 (Continued)

	IAS-A	IRLS	OPLE
Interrogation Signal from Satellite to Data-Collecting Platform (continued)			
Maximum DCP's interrogated per orbit			
Sequential	511	370	
Nonsequential	64		
Signal between interrogations			
Normal	Sync signal (24 zeros, 6 ones)	Satellite transmitter turned off	Satellite transmitter turned off
By command	Transmitter turned off		
Signal Transmitted from DCP			
Transmitter power	4 W	6 W	5 W
Carrier frequency	400 MHz	466 MHz	149.2 MHz
Polarization	Circular	Circular	Linear
Modulation	Burst-blank PM FSK/PM	PCM/FM	(Sensor data) PSK
Index	$\pm\pi/4$ radians		±1 radian
Deviation		±20 kHz	
Satellite received signal			
Level	-128 dBm	-133 dBm	-126 dBm
Bit rate	48 bits/sec RZ 24 bits/sec	12,500 bits/sec NRZ	56 Bits/sec Omega tones
Response sequence	Carrier only (0.1 seconds) 12 bits (at 48 bit sec) 4 tones (24/sec) (transmitted once)	192 binit lines repeated continuously until sync verified; 10,192 binit lines after sync verified	Carrier only (11 seconds) Sensor data (3.9 seconds) Omega (180 seconds)
Duration of response	0.625 sec	3.8 sec (maximum if balloon) 14.6 sec (maximum if surface platform)	194.9 sec
Sequence composition	Carrier only (0.1 sec) 6 zeros, 6 ones (distance measured) Zero = 2304 MHz, one = 2688 MHz 4 data tones	16 bit lines corresponding to DCP address or two 7-bit data words 1 bit encoded into M-word (8 binits) + N-word (4 binits) M-word = bit one or zero N-word = sync	Carrier only (11 sec) Sensor data (7-bit words) Omega tones retransmitted for 3 min
Data transmitted	4 data tones	7 data words (balloon) 21 to 126 data words (platform) 630 data words maximum (extended data platform)	8 data words Omega tones
DCP signals transmitted simultaneously	1	1	40

TABLE 7.4.2 (Continued)

	IAS-A	IRLS	OPLE
Satellite Measurements			
Measurement			
Doppler frequency shift	Phase lock carrier Count zero crossings in time T Measure T by reference with stable clock (4.6 MHz) 0.2 ppm stability		All data processing is performed at OPLE Control Center. Satellite only relays DCS signals
Accuracy*	0.2 Hz		
Distance	Phase lock carrier Determine phase of 3 tones by measuring quadrature components Compute from them distance	Synchronize digital data Measure time between receiving and transmitting same signal by reference with stable clock (1.6 MHz) 1 ppm stability	Phase lock Omega signals relayed by balloon Phase lock signals received directly from Omega station Compare
Accuracy*	0.1 radian (0.5 kilometer)	1 kilometer	1 kilometer
Data Recording			
Data memory capacity	121,072 bits	100,640 bits	No data are stored on satellite
Data memory format			
Bits/line	103	16	
Lines/frame	1	10 (balloon) 17 (balloon)	
Frames/DCP	1	1 (balloon) 1 to 6 (platform) 30 (extended data)	

*Accuracy based only on instrument performance.

will be provided for DCP interrogation and location. The OPL scheme is utilized as a basis for locating balloons. Capability for interrogating meteorological land stations, marine surface vessels, buoys, hydrologic stations, and balloons is provided. This study is continuing; it emphasizes problems of multiple access with a multitude of DCP's. No money has been allocated for the implementation of a GOES system.

4.3 System Design

As an exercise, a model vacuum-cleaner-satellite system (VCSS) design was performed by the Panel. The functions of this design exercise were:

1. To show that a VCSS to meet user requirements was technically feasible
2. To understand some of the fundamental problems that will be encountered in the implementation of a VCSS and hence to establish technology areas and tradeoffs that must be pursued in further detail
3. To determine the magnitude of cost and complexity of a VCSS in order to establish its cost-effectiveness

There are several requirements and constraints on a VCSS. The most important of these are:

1. The system design should minimize the complexity and cost of the DCP's, even at the price of increasing the complexity of the satellite, since there will be more than 26,000 platforms and only three or four satellites.
2. The system must be able to collect data every 6 hours and, in the case of meteorology, in the time period of 1/2 hour every 6 hours.
3. The 1975 system should be sized to collect data from balloons, even though the feasibility of an operational system with balloons has not yet been demonstrated.

It is desirable to maximize the flexibility of the VCSS both in its technical implementation and in its daily operation. For example, it is useful to be able to alter interrogation schedules with time and to provide alarm capability, in which some sensors automatically activate themselves and report more frequently.

4.3.1 Coverage

Geostationary orbits are not without their attendant coverage problems. Figure 7.4.8 shows the area of coverage of a geostationary equatorial satellite as a function of the elevation angle from horizontal. It is expected that it will be feasible to interrogate from DCP's with elevation angles as low as 5° (70° latitude), since they can utilize directive antennas. On the other hand, balloon antennas must be nearly omnidirectional in order to accommodate the full range of balloon-to-satellite

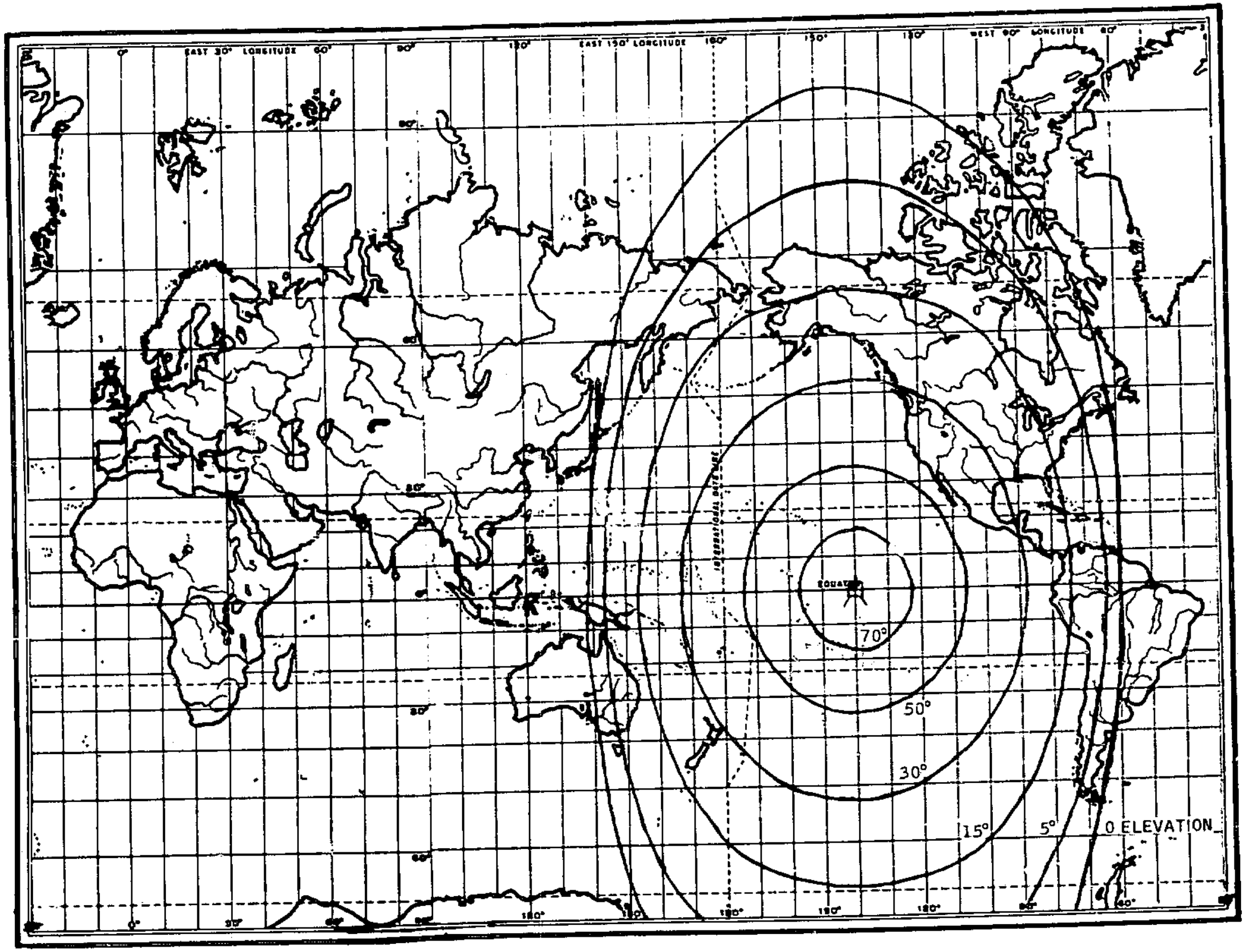


FIGURE 7.4.8 Typical coverage curves for a single geostationary satellite, for various elevation angles.

aspect angles. For this reason, it will be difficult to obtain satisfactory gain throughout the entire upper hemisphere, and also include elevation angles as low as 15°. Consequently, for four geostationary satellites, fixed-platform coverage at latitudes up to 70° should be expected. For horizontal-sounding balloons (HSB), anticipated coverage would be only up to 60° latitude with some gaps. Many balloons between 60° and 70° latitudes, i.e. 15° and 5° elevation, may be able to transmit to the VCSS, but with lower probability. Coverage of a four-satellite VCSS is shown in Figure 7.4.9, for 5° and 15° elevation angles.

Although there is a coverage problem at high latitudes, it should be pointed out that most of the landmass and population of the world are below these latitudes. The Panel on Meteorology planned deployment of HSB's primarily around the equatorial regions. Hence, VCSS coverage of the polar region is of relatively low importance.

4.3.2 Traffic Characteristics and the Location Problem

Examination of Table 7.3.3 indicates that the traffic loading on the data-collection system would average less than 6×10^6 bits per 6-hour synoptic interval. The average bit rate for all sensors, neglecting location requirements, is then less than 300 bps, which is extremely low. However, in order to ascertain the required bandwidth of a data-collecting-relay satellite system, the influence of the location problem on frequency-division and time-division multiplexing of the total traffic must be examined. Location will impose significantly higher data rates than the minimum of 300 bps.

Two DCP-location schemes were considered by the Panel: (1) utilization of the Omega system, and (2) cooperative ranging. A third approach—utilization of range plus interferometric-angle measurement—was dismissed as unnecessarily complicated.

The feasibility of utilizing the Omega system for locating data-collection platforms has been verified by NASA's OPLE experiment.

The feasibility of cooperative ranging will be tested on the ATS-I and the ATS-III. Preliminary test results indicate feasibility for this approach, and no major problems are anticipated with this scheme. But there are certain disadvantages, which are discussed below.

Cooperative ranging suffers from the disadvantage of having low accuracy in the plane containing the two cooperating satellites and the platform. This means that, for equatorial satellites, data-collection platforms near the equator would have location errors. As an approximation, the position error in latitude is inversely proportional to the sine of the latitude angle, but saturates at a large value near the equator.

The range is generally measured by transmitting a carrier and a sidetone down through the DCP and back through the satellite to the CDA. There the phase shift between the original sidetone frequency and the received sidetone frequency is measured. This phase shift is indicative of

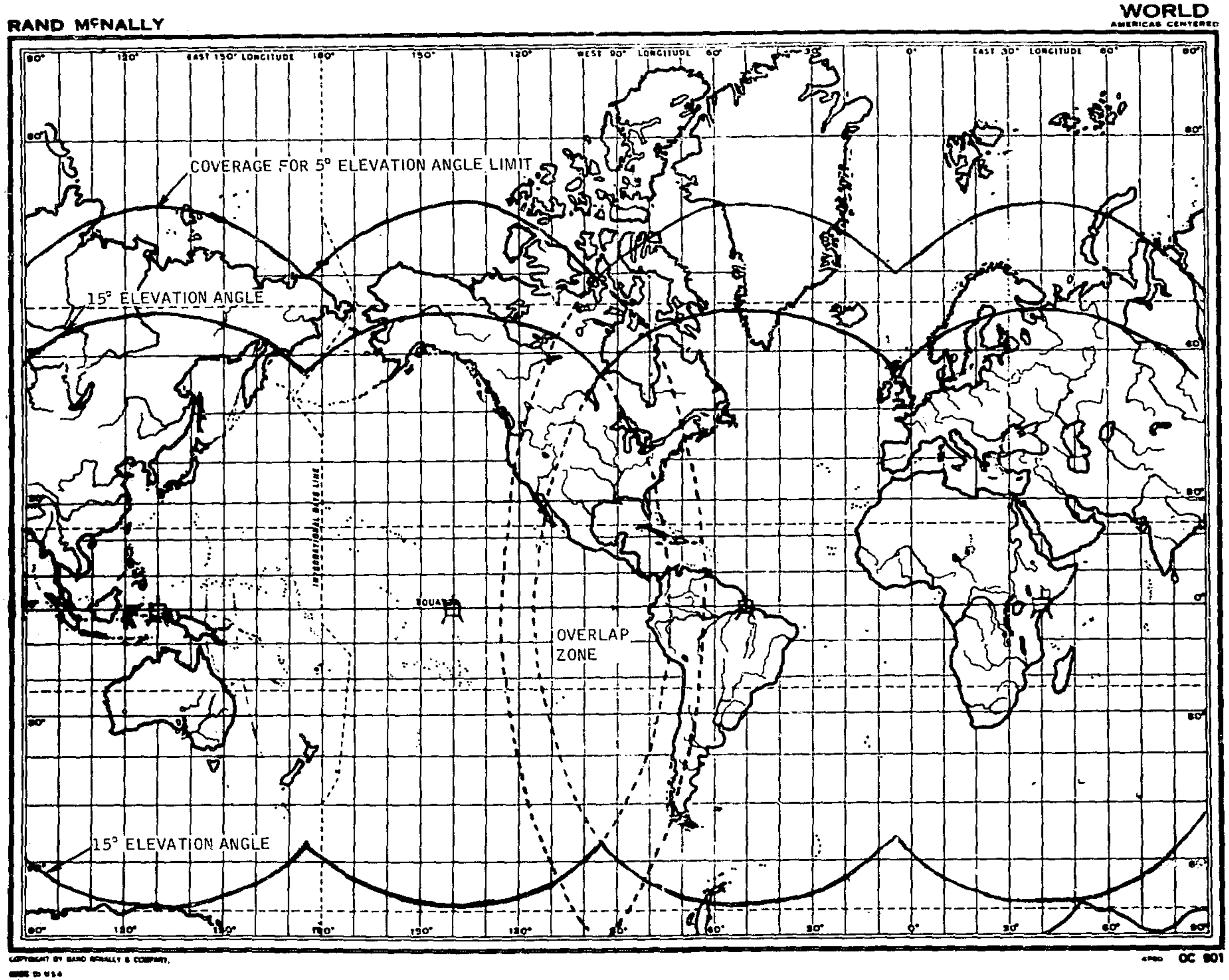


FIGURE 7.4.9 Coverage of a vacuum-cleaner-satellite system (VCSS), using four equatorial geostationary satellites. Difference in coverage for 5° and 15° elevation angles is shown.

the round-trip transit time and, hence, the satellite range. The accuracy with which this range can be measured is a function of the sidetone frequency, i. e., the equivalent spatial wavelength, and the accuracy with which phase can be measured. Range ambiguities are resolved by sending a series of lower sidetones at differing frequencies. However, the highest frequency sidetone determines the system bandwidth. It is of interest to minimize the highest sidetone frequency, while still meeting range-accuracy requirements. Figure 7. 4. 10 shows range accuracy as a function of the sidetone frequency and the phase accuracy. Phase accuracy is, in turn, a function of integration time and system phase lags. Position accuracies not coarser than 5 kilometers are required for balloon location in order to obtain desired accuracy on wind vectors.

Phase errors in the range of 1° to 10° can be expected for operational systems. Utilizing these numbers, it appears that sidetone frequencies in the range of 10^4 to 10^5 Hz will be necessary in order to get adequate range accuracy in the equatorial region. Since the VHF spectrum is already cramped for space, it was considered undesirable to recommend a cooperative ranging system.

The alternate ranging scheme, utilizing the Omega system, has been successfully tested by NASA. As indicated in Table 7. 4. 2, the existing system utilizes a 2500-Hz rf band and takes 3 min of integration time per platform. The Omega stations transmit tones of 10. 2, 11. 33, and 13. 6 kHz, as well as other identifying tones. In addition, each of the carrier tones is modulated by 11. 33-Hz, 45. 33-Hz, and 226. 66-Hz subtones, respectively. The combination of tones and subtones is utilized to resolve ambiguity. The three basic tones are compressed into a 2500-Hz channel, along with an acquisition-reference tone, and transmitted from the data-collection platform, through the satellite, into the Omega Control Center. The basic tones from the Omega stations are time multiplexed; a total of 10 sec is required to poll all the Omega stations. In the period of 3 min a total of 18 samples per station tone is received at the control center. These 18 tone samples are integrated at the control center, in order to establish a sufficiently accurate relative-phase signal. The relative phases are used to generate isophase contours, which, in turn, determine system range. The Omega system is expected to have range accuracies of better than 5 km.

A VCSS constrained to utilize the existing OPL integrating times and bandwidths would have limited performance. For example, each 2500-Hz channel of OPL information could interrogate and locate only 20 balloons per hour. As many as 2000 balloons could be expected to be within view of one satellite, so that 100 hours would be needed for one channel to locate and collect the data from all balloons.

An alternate is to provide multiple channels, frequency-multiplexing the balloon transmissions. If it were desired to obtain all the balloon data within 6 hours, 17 channels (42 kHz of rf data) would be required. Bandwidth allocation will be a constraint upon the system design, so, rather than utilize 500 kHz of rf bandwidth in order to obtain the balloon data in a timely manner, it would be desirable to reduce the OPL integration time and bandwidth.

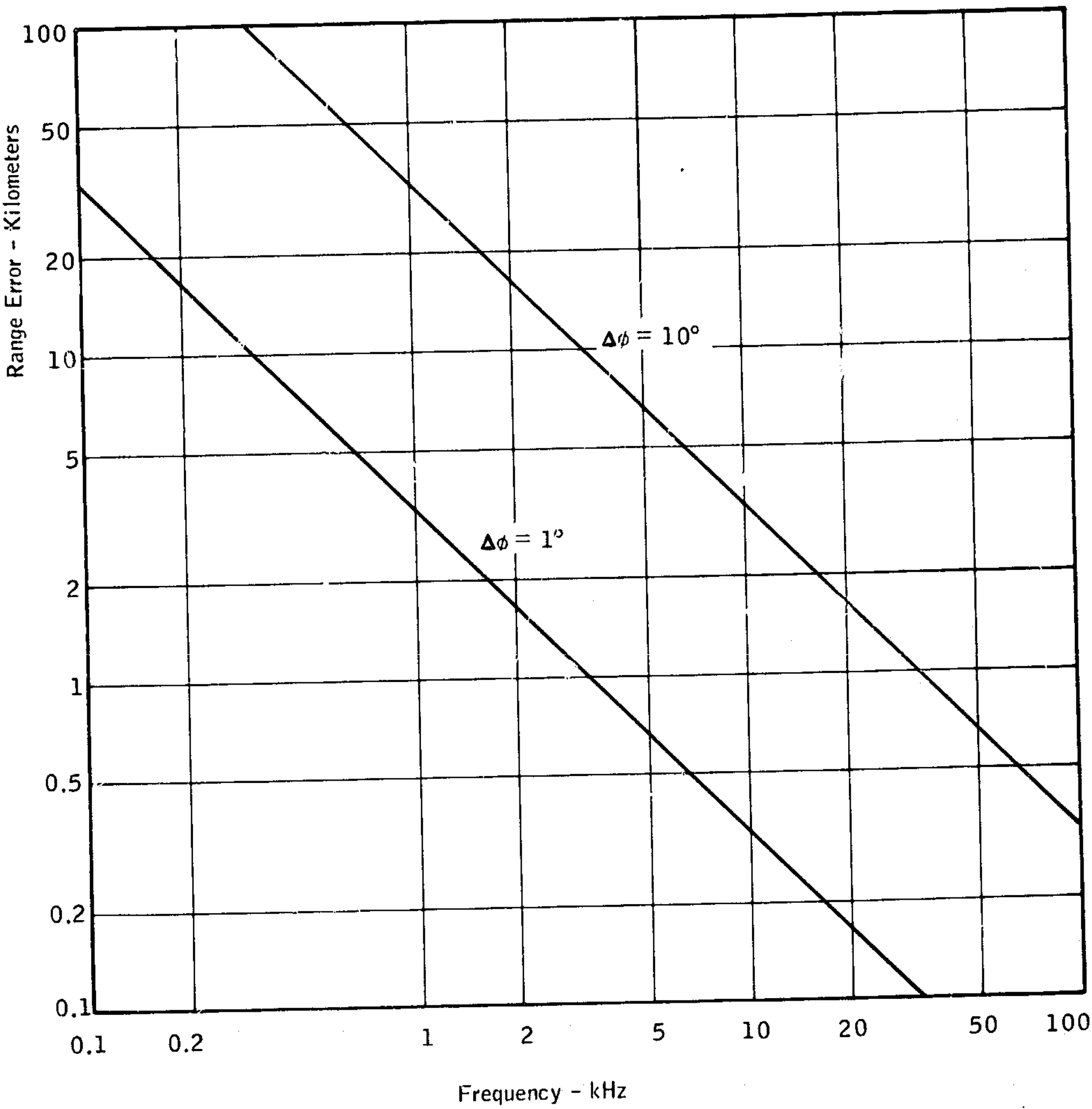


FIGURE 7. 4. 10 Range error versus sidetone frequency and phase error.

The time required for each balloon is based upon the integration necessary to give adequate phase-measurement accuracy. Preliminary investigations indicate that it is feasible to reduce this integration time from 3 min to less than 1 1/2 min. Since it is only relative phase measurements that are of interest, it is feasible to beat down the Omega VLF tones and compress them into a narrow bandwidth. Limitations on this bandwidth could be fixed by the 226-Hz sidetone frequency. The amount of bandwidth reduction would be a function of the complexity acceptable in an OPL platform. This requires further investigation. Here, a bandwidth reduction of 10 was used, in order to obtain preliminary estimates of the total VCSS bandwidth.

Based on the 226-Hz sidetone limitations, OPL data can be compressed into 250-Hz rf channels including a guard band. If the system is to have the capacity for collecting data from 200 balloons in 1/2 hour, then a total of 100 OPL channels is required. This accounts for 25, 000 Hz of rf bandwidth. This bandwidth would be utilized for 1/2 hour just prior to SRT. Since it is necessary to perform two measurements of balloon location, separated by 2 hours, in order to determine wind vectors, balloon locations will also be determined during the 1/2-hour intervals prior to 0200, 0800, 1400, and 2000.

4. 3. 3 Data Collection

Unlike balloons and floating buoys, which require the bandwidth and integration time necessary to utilize OPL, the fundamental data rate determines the time- and frequency-division multiplexing for the remaining DCP's.

From Table 7. 3. 3, it can be seen that approximately 4. 5 million bits of data are used in meteorology, of which about 4. 1 million are nonballoon data. If all the meteorological data were collected within 1/2 hour, an average single-channel bit rate of 2300 bps would be required. Longer collection times would imply correspondingly shorter data rates, but a main thrust of our effort is to provide for collection and dissemination of data within 1 hour of the synoptic interval; hence, the requirement for 1/2 hour for data collection as a first objective.

A fundamental question arising at this point is whether to multiplex by time division or frequency division, or both. Time-division multiplexing increases the required transmitted-bit rate from the DCP and requires a corresponding increase in power in order to transmit the data successfully through the satellite. The satellite power required to transmit data to the ground station will remain the same whether the data are frequency- or time-division multiplexed. However, the major objective is to simplify the ground station as much as possible.

Frequency-division multiplexing permits a lower bit rate but requires more sophisticated filtering. With frequency-division multiplexing, channel allocations have to be made, and standards of frequency and power discipline have to be imposed for the entire set of 26, 000 platforms. Utilization of frequency-division multiplexing increases system flexibility by allowing access to a number and variety of channels simultaneously. The requirements for the location of balloons, plus the need to interrogate a large number of sensors, indicate the proper solution is a combination of time- and frequency-division multiplexing. No attempt has been made to optimize the mix utilized in this report; however, some of the primary factors will be discussed.

Establishment of a uniform bit rate for all sensors is desirable, because it will permit standardization of much of the DCP electronics, resulting in economies of scale and facilitating simpler GDH schemes. The uniform bit rate should be as low as possible to minimize the DCP transmitter power required; the lower the power, the cheaper the platform. A lower limit on useful data rate occurs when the address message necessary to interrogate the DCP becomes a substantial portion of the message itself. Typical addresses for the number of platforms required will be in the order of 20 bits. Hence, at 200 bps and with 100-bit messages (appropriate for many DCP's), approximately 16 percent of the time is spent on interrogating the target. Since an rf bandwidth of 250 Hz has been allocated for OPL, a bit rate of 200-bps is selected for the standardized data rate from the other DCP's. Utilization of a nonreturn to zero (NRZ) code will enable a 200-bps rate to fit into a 250-Hz rf channel and allow for standardized channel allocation.

At a 200-bps sampling rate, and allowing 10 percent for identification of address and another 10 percent for transition times and other phase delays, a data rate of approximately 5.8×10^5 bits per hour is achievable. It can be seen that, in order to obtain all meteorological data within 1/2 hour, approximately 15 250-Hz channels are required.

While meteorological data are obtained on a global basis in 1/2-hour intervals every 6 hours, synchronized to GMT, data from hydrologic, offshore, seismic, volcanic, agricultural, and forestry platforms will be collected at a uniform rate. For all but the last two, the 6-hour synoptic-reporting-time requirement permits uniform collection. In agriculture and forestry, the users have requested that data be collected in local time, i.e., just prior to dawn, noon, and in the evening. The result of a local-time requirement is, conveniently, also a uniform data-collection rate. For example, each satellite could be allocated six time zones as the earth rotates. The prior-to-dawn data can be taken by phasing DCP interrogation to the movement of the earth's terminator as it goes from east to west beneath the satellite. This programming can be readily handled by the control-and-data-acquisition (CDA) facility on the ground.

Accordingly, the normal interrogation mode consists of the meteorological synoptic weather taking every 6 hours and is characterized by a high data load within 1/2 hour and continuous data collection from the remaining sensors, normally at a steady pace. In addition, the capability would exist to modify the interrogation program in order to permit interruptions in schedules or to provide for alarms.

At the data rate of 200 bps, and with continuous data taking, it can be seen that two 250-Hz channels can handle the agricultural and forestry data, less than one channel could handle the seismic and volcano data, less than one channel could handle the hydrologic data, and less than one channel is more than adequate for offshore platforms. The partial channels may be time-division multiplexed to reduce the total of channels allocated. In fact, it would be possible to time-division multiplex the approximately 30,000 Hz required for the balloons and meteorological platforms with all other sensors. It would then be feasible to contain all the remote platforms within 30 kHz of bandwidth. However, the Panel does not recommend that the data be squeezed into an rf bandwidth as small as theoretically possible, but rather that the system implemented have capacity to handle traffic growth.

4.3.4 A Representative Frequency- and Time-Division Multiplexing System

This section will attempt to discuss some of the factors in providing a model frequency- and time-division multiplexing scheme, and in so doing to highlight some of the tradeoffs and technology requiring further investigation.

4.3.4.1 Channel Allocation

In assigning narrow-band channels to each of the DCP's, it is important that the carrier frequency for one DCP should not drift into a channel allocated to another DCP. State-of-the-art crystal oscillators can provide one-part-per-million long-term stability; at 149 MHz this corresponds to 149-cycle drift making it practical to allocate 250-Hz rf channels. An alternative is to provide phase-lock loops in the DCP that would be locked to a frequency standard transmitted from the DCP. In this system, an interrogation tone would be put out, through the satellite, from the ground station. All DCP's would lock on to this pilot interrogation tone and displace it by some reference frequency to determine a reference corresponding to this channel location. A typical offset frequency could be the difference between 138 MHz and 149 MHz. Hence, a local oscillator, stable to one part in 10^6, would cause a drift in the order of 11 Hz.

An important design criterion for the phase-lock loop would be low cost, in order to make it practical to place on the large number of DCP's expected. It is believed that the development of such a narrow-band channel system is feasible, but the low-cost requirement is a problem for the phase-lock loop.

Another problem in frequency-division multiplexing is power stealing. If a broad-band transponder, similar to that being used in the ATS satellites, is employed in the VCS it will be possible for a high-powered DCP to dominate the transmission through the satellite. That is, if the high-powered DCP transmits a signal substantially stronger than signals of the other DCP's, then the output power allocated to it by the satellite transponder will be correspondingly higher. It is possible in this manner for the lower-power signals still to have their design-objective power densities at the satellite but to be retransmitted to the ground at an unsatisfactorily low level. It is important, in this case, to impose strict power discipline as well as frequency discipline on the DCP's to ensure that no DCP will exceed certain nominal power levels. The problem is complicated, because a large number of users, both national and international, will be using a global VCSS.

Protection from power stealing can also be obtained by channelizing the VCS platform. If each channel has its own amplifier, then each input signal could be individually gain-controlled to provide a uniform allocation of power when retransmitted to the ground. The large number of channels of information (100) required just for the balloon data makes it economically unattractive to provide individual amplifiers and gain control for each channel. A combination of power discipline and limited channelization is suggested for the model system. Typically, 10 subchannels of 250 Hz each could be assigned to one major channel of 2500 Hz. In this way the system could be segregated into a number of channels, each having 10 subchannels. Major channels would not interfere with each other then, since each would have its own automatic gain control.

4.3.4.2 Interrogation

One channel will have to be allocated for interrogation. It is proposed that the interrogation signal be treated as one of the up-link channels to be received, and transponded like any other DCP up link. Hence the interrogation traffic flow will be counter to most of the data traffic--it will be going up along with the DCP data to the satellite, and down to the platforms along with the transponded DCP data to the CDA station.

The interrogation signal may represent the basic frequency reference for the entire system. All DCP's will respond to the master interrogation signal, generated by the CDA. Each will derive its own transmission frequency and, hence, subchannel, from a self-contained synthesizer. In order to maintain a uniform system bit rate, an interrogation rate of 200 bps is desirable. This means, with an address of 20 bits, that 10 DCP's can be interrogated per second, or 600 DCP's per minute. This is adequate for interrogating the highest anticipated traffic rate, which is expected to occur for balloon location with the OPL system, when 100 balloon platforms will have to be interrogated per 1 1/2 minutes. Interrogation will be accomplished without waiting for DCP response; a continuing bit stream of interrogation addresses will be generated from the CDA through the satellite and into the DCP's.

A problem will occur in the overlap areas when one DCP will be receiving interrogation signals from two satellites. A further aspect of this problem is that the mobile platforms, i.e., the balloons and drifting buoys, will be moving from one satellite-coverage area to another; thus a need arises to "hand over" balloon control from one VCS to another. This problem can be handled by assigning an interrogation channel and frequency to each satellite. With four satellites, a total of four channels is required. One interrogation channel could contain 10 250-Hz subchannels. A balloon receive channel would have a bandwidth no greater than 250 Hz so that, once a balloon is locked to an interrogation channel, interrogation signals from another VCS would not interfere with the signals received from the VCS controlling that particular DCP. In this system, it might be necessary to program interrogation of a balloon, moving from one coverage area to another, through both VCS's to ensure that interrogation be successful. However, the balloon would normally be unable to receive more than one of the VCS's at a time.

4.3.4.3 Alarm Capability

One significant advantage of a VCSS is its potential for disaster warning. The continuous surveillance of all data-collection platforms provides for the possibility of immediate relay of danger signals. In this way natural disasters might be avoided, or, at least, appropriate warning could be provided. This alarm capability can be obtained by providing "hot lines" that will always be open and available to data-collection platforms. DCP's can be instrumented, so that if alarm situations prevail the DCP's can automatically transmit this information on the hot line. The information can be in the form of a signal indicating existence of an emergency situation, plus location or identification of the platform registering this fact, or basic data can be transmitted in the alarm channel. In the former case, the CDA can then proceed to interrogate the station issuing the distress signal and read out its data. Disaster warnings especially appropriate for the data-collection-satellite system include warnings for seismic events, volcanic eruptions, and floods.

4.3.4.4 Other Data Sources

There are other sources of data that might be relayed through a data-collection satellite. It is appropriate to mention them and to acknowledge sufficient capacity in our representative system for their inclusion.

The ocean-research vessel is a unique potential user of the data-collection satellite. Approximately 80 ocean-research vessels are now in operation and could be expected to have message lengths from 10^3 to 10^4 bits in length. Tying in of these ocean-research vessels to shore-based computers would be a useful service that could be supplied on a time-division multiplexed basis with the regular data-collection service. This type of data collection could be provided on demand, so that times of light traffic occurring during nonsynoptic intervals between meteorological samplings could be used for these intermittent loads.

Another possibility for utilization of light-traffic intervals is the dissemination of meteorological and earth-resources data. Use of VHF data dissemination, time-shared with data collection, provides the opportunity to disseminate data to small terminals and, hence, numerous users. For example, weather products could be disseminated globally in the 1/2 hour immediately subsequent to data collection and processing.

From the standpoint of economizing on VHF bandwidth, data dissemination through the VCS might appear wasteful of useful-frequency allocation. However if it turns out that nonuniform bandwidth utilization is necessary in order to obtain rapid collection of meteorological information, it may be convenient to utilize the same bandwidth, time-shared for the dissemination of the same meteorological data.

From the same standpoint, time-sharing of other functions within the allocated bandwidth may be economical. For example, production and transmission of cloud pictures from a geostationary satellite (as suggested by ESSA in its GOES study) might be a separate type of service performed by a VCS. In this case the satellite design would change radically, since it would no longer be dedicated to the data-collection mission. Such a satellite is clearly outside the scope of points-to-point missions; it would in all probability be dedicated to a single user and thus is excluded from further consideration.

4.4 Vacuum-Cleaner Data-Collecting System

In this section we shall try to describe a representative data-collection system, to demonstrate practicality for the anticipated traffic loads.

4.4.1 Channel Utilization

A 50-kHz rf bandwidth is selected, since this is sufficiently wide to handle the traffic load and allow room for growth. Radio-frequency bandwidths of this magnitude will not represent an undue demand on the existing VHF-spectrum allocation. The 50 kHz of bandwidth is broken into 20 2500-Hz channels—each channel with 10 subchannels. A total of 200 250-Hz subchannels is available. The basic system bit rate is 200 bps. The location system employed will be OPL and will require 250 Hz of rf band and 1 1/2 minutes to locate each balloon. Balloons will be located at the rate of 40 per hour. A stability of one part in 10^7 on the DCP local oscillator is assumed.

The sample channel allocation is shown in Figure 7.4.11. Channel 1 is utilized for interrogation. A total of five subchannels, to be used with five satellites, is allowed. The routing of information for this channel is from the CDA station, up through the satellite, and down to the DCP.

Channel 2 is allocated for agriculture and forestry and is also operating continuously. The routing for information here is from the DCP, through the VCS, and into the CDA. This channel will readily provide for the expected traffic load for agriculture and forestry. Essentially, one subchannel can carry the entire predicted 1975 load; however, the assignment of an individual channel provides for isolation of this particular user, preventing him from interfering with any of the other users. In addition, it permits interrogation at higher rates, if desired, or the accommodation of more DCP's.

Seismic and volcanic sensors are also assigned one individual channel; and, again, room for growth by an order of magnitude in either time- or frequency-division multiplexing is allowed. Hydrology is assigned channel 4, also operated continuously. Two channels are allowed for alarm. These hot-line channels are always open to demands for a disaster-warning signal. Channel 7 is provided for administrative traffic, which can be either CDA to DCP or vice versa. Channel 8 is spare.

Channels 9 and 10 are for the meteorological traffic and will be utilized in the intervals of 1/2 hour just prior to SRT. This also applies to channels 11 through 20 and the balloons, but the balloons are also interrogated in the 2-hour period just following the SRT's, so that wind-vector information, compiled by two position fixes, can be determined. During the periods of time in which channels 9 through 20 are not collecting the meteorological information, they can be used for data dissemination, for collecting data from ocean-research vessels, or for other applications.

This model system has considerable traffic-growth potential through the 1980 era. Approximately 75 percent of the capacity is unused.

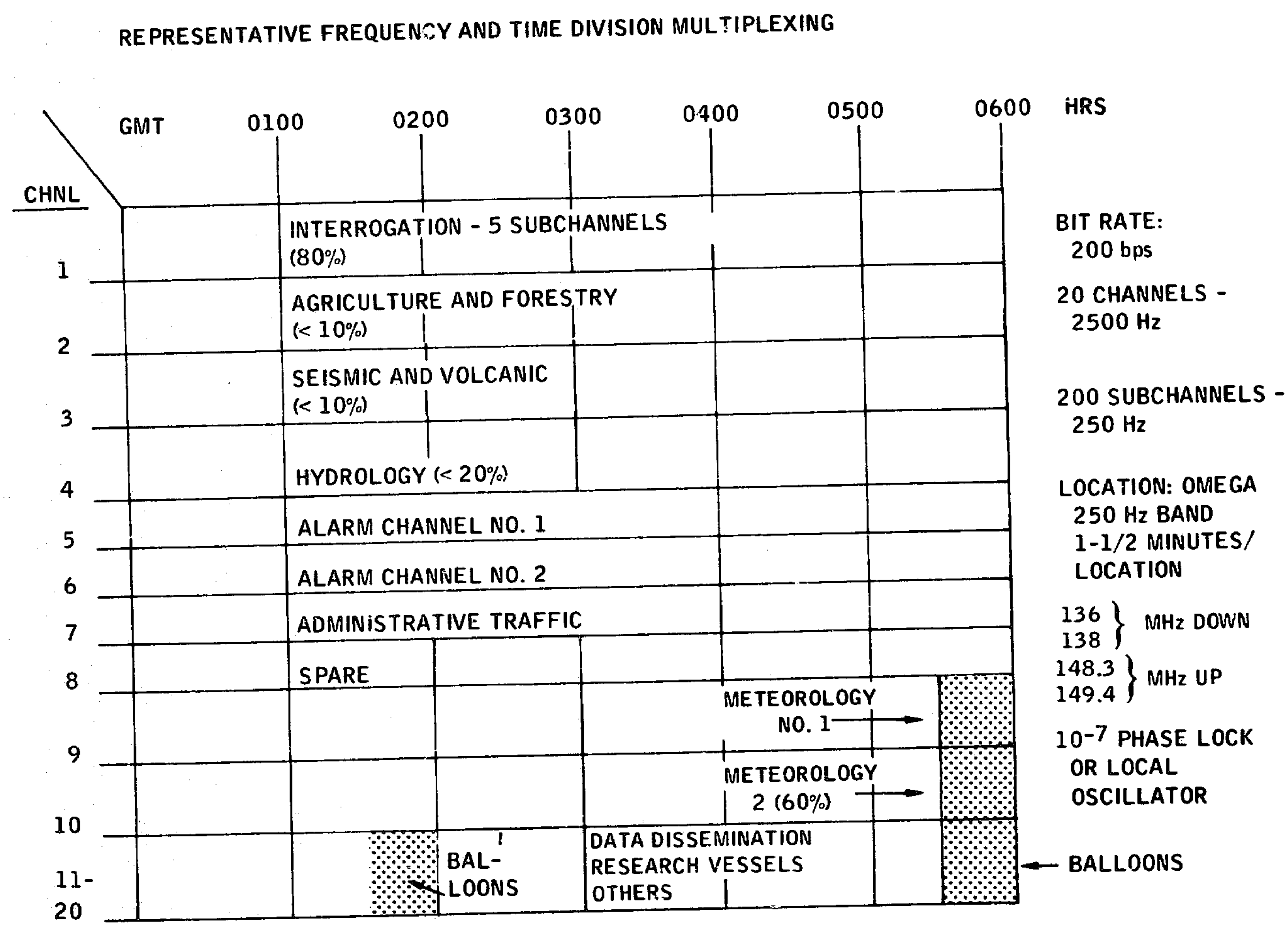


FIGURE 7. 4. 11 Sample allocation of channels.

If necessary, it would be possible to reduce the 50-kHz band width further. The question becomes one of economy of satellite utilization versus economy of frequency utilization. That is, after the cost for orbiting a data-collection satellite system is paid, it is useful to provide as many additional services as practicable and as much flexibility as possible. In terms of available VHF-spectrum allocated to VCS functions, however, 50 kHz is not extravagant; the space-telemetry bands have room left over, and substantial system growth is still accommodated.

4.4.2 Transponder Design

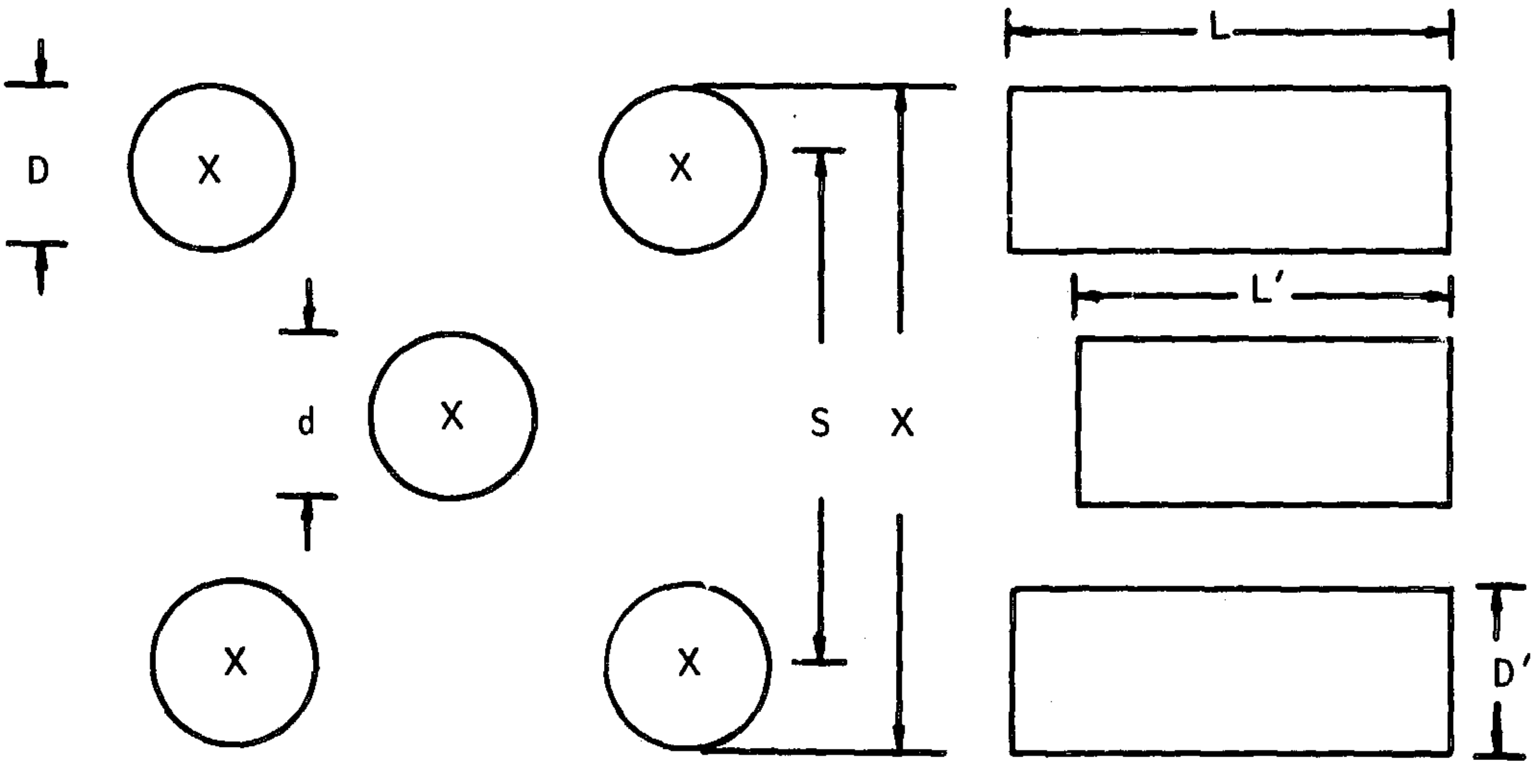
4.4.2.1 Frequency Selection

A primary objective of the design configuration will be to simplify the data-collection-platform electronics. One technique is to provide a high satellite-antenna gain. In this case a single, earth-coverage beam appears to be desirable. If an earth-coverage beam with fixed gain is provided, frequency selection becomes simplified. In this case the practical constraint is to be above 100 MHz in order to avoid ionospheric effects. A frequency allocation for space telemetry exists in the 136- to 138-MHz region, which appears to be an attractive portion of the VHF spectrum for a data-collection satellite. The problem is not in the satellite, but in providing practical, standard antennas for all DCP's which do not dominate the design of the smallest ones. This seems much easier to do at VHF than at S-band, where another space telemetry allocation exists. Once having decided to transmit downward in the VHF region, it is desirable for the up link to be closely related in order to share the same antenna. Here the 149-MHz region seems to be a good candidate.

4.4.2.2 Antenna Selection

An earth-coverage antenna minimizes the power required for DCP's to transmit 200 bps through the satellite into the CDA. With the VCS antenna half-power points at $\pm 10^{\circ}$, the corresponding antenna gain would be approximately 18 dB. The antenna dish diameter is then 25 ft. (An alternate to a parabolic dish would be a helical antenna. A typical helical array for 18-dB gain is shown in Figure 7.4.12.) In order to fit these earth-coverage antennas into a reasonable booster shroud, such as that for the Thor-Delta, it will be necessary to provide some degree of deployment. Antenna deployment is an undesirable, but not prohibitive, design requirement for either the helical or parabolic-dish antenna. In the case of a helix, compression factors of 10 to 40 percent are feasible, and swiveled and articulated structures can further reduce the undeployed dimension. Such systems are being flight-qualified now. Parabolic dishes can be folded, utilizing lightweight metallic-filament fabrics like umbrellas. Such a structure is utilized at S-band in the lunar-excursion-module (LEM) 10-ft dish. A comparable 25-ft antenna would be about 13 ft long stowed, and weigh less than 40 lb. The possibility of a lighter VHF helix with less gain was also investigated. For 173 in. length (compressed to 35 in. in the shroud) and 25 lb weight, a gain of 15 dB can be obtained. As the link calculations in the following section will demonstrate, some sacrifice in gain is acceptable if it simplifies satellite design.

	L	L′	S	X	D	D′	d
136	177″	130″	118″	184″	30″	66″	25.7″



THE CENTER HELIX IS TUNED FOR RECEIVING

FIGURE 7. 4. 12 Earth-coverage helical array.

4.4.2.3 Link Calculations

The data-collection-satellite system is characterized by low data rates. As a result, the power necessary to transmit the data is comparatively low. A table of link calculations is shown in Table 7.4.3 for the VCSS model system. Four links are established. The progression starts with an interrogation signal transmitted from the CDA to the satellite at 148.5MHz, and from the satellite to the DCP at 138 MHz. The interrogated DCP transmits its data up to the satellite at 149 MHz. The satellite, in turn, transponds the data back down at 136 MHz.

An earth-coverage satellite antenna at VHF is assumed. For this case, peak antenna gain will be 18 dB, and minimum gain at the earth's horizon will be 15 dB. For the DCP antenna, the pessimistic assumption of zero dB antenna gain is made to allow for off-axis gain loss incurred by unfavorable look angles with the fixed DCP antenna. This corresponds to the balloon platform, where omnidirectional antennas are required, since the necessary balloon-satellite geometry is not known a priori. It is assumed that, at elevation angles below 15°, balloon-antenna gain will go down rapidly. On the other hand, fixed platforms may be able to use pointed antennas with higher gain: perhaps as much as 10 dB for the larger, fixed DCP's. In order to provide uniform power at the satellite, fixed-platform transmitters would have to radiate correspondingly less power to prevent power stealing in the satellite transponder. All antennas, ground and satellite, will be circularly polarized. Polarization losses of 1.2 dB are assumed for the pessimistic case of a 15° elevation angle with the balloons.

Table 7.4.3 indicates that no particular problems are expected in establishing good data links between the various platforms. A nominal transmitter power of 5 W was assumed for the platforms. With it, 26 dB carrier-to-noise (C/N) ratio is obtainable within the 250-Hz subchannel, and 16 dB in the 2500-Hz channels. This more than adequate carrier-to-noise ratio indicates the possibility of reducing the transmitter power below 5 W. Our investigations showed that substantial cost and complexity differences were not to be expected in the range of powers between 1 and 5 W in the transmitter. Hence, this is not too sensitive a parameter. On the other hand, the possibility definitely exists for reducing antenna gain, if it were desired. This may be useful, since it is apparent that deployable antennas will be required on the VCS's in order to obtain earth coverage at 138 MHz.

In the case of the down link from the satellite to the CDA, a 22 dB, eight-element CDA antenna and 20 W of transmitted power from the VCS provide a satisfactory link. Carrier-to-noise ratios of 16.6 dB are expected. Four dB of degradation could be accommodated while still retaining extremely low bit-error rates.

The interrogation up link is more than adequate. A good signal-to-noise ratio in this link is useful from the standpoint of avoiding interference with the interrogation roll call. The interrogation down link would utilize 1 W of power (its share of the 20 W of transmitter power put into the 20 channels). This is satisfactory for initial interrogation beacon lock-on and for receiving the interrogation coded signal with error rates below one part in 10^5.

TABLE 7.4.3

LINK CALCULATIONS

Link calculations

148.5-MHz up link - CDA to satellite (command)

Radiated power (5 W nominal)	7 dBW
Antenna gain	14 dB
Polarization loss	1.2 dB
Path loss	167.9 dB
Cable loss	3.0 dB
Satellite antenna gain (minimum)	15.0 dB
Receiver noise density (1150° K)	-198.0 dBW/Hz
Bandwidth (2.5 kHz)	34.0 dB
Carrier to noise ratio (C/N)	27.9 dB

138-MHz down link - satellite to platform (interrogation)

Radiated power	0 dB
Satellite gain (minimum)	15 dB
Polarization loss	1.2 dB
Path loss	167 dB
Ground station gain	0.0 dB (balloons)
Cable loss	1.0 dB
Receiver noise density (1400° K)	-197.1 dBW/Hz
Bandwidth (2500 Hz for interrogation lock on, 500 Hz for signal)	34.0 dB (lock on) 27.0 dB (signal)
C/N (lock on)	8.9 dB
C/N (signal)	15.9 dB

149-MHz up link - platform to satellite (DCP response)

Radiated power (5W nominal)	7.0 dBW
Platform gain (>15° elevation)	0.0 dB
Polarization loss	1.2 dB
Path loss	167.9 dB

TABLE 7.4.3 (Continued)

149-MHz up link - platform to satellite (DCP response) (Continued)

Cable loss	1.3 dB
Satellite antenna gain (minimum)	15 dB
Receiver noise density (1150° K)	-198 dBW/Hz
Bandwidth (250 Hz)	24 dB
C/N (250 Hz)	25.6 dB
or C/N (2500 Hz)	15.6 dB

136-MHz down link - satellite to CDA (data)

Radiated power (20 W nominal)	13 dB
Satellite antenna gain (minimum)	15 dB
Polarization loss	1.2 dB
Path loss	167.0 dB
Ground station gain	22.0 dB
Cable loss	3.0 dB
Receiver noise density (2400° K)	-194.8 dBW/Hz
Bandwidth (50 kHz)	47 dB
C/N	26.6 dB

4.4.3 Satellite Design (Vacuum-Cleaner Satellite-VCS)

Having configured a representative transponder, it is now of interest to determine the implications for satellite design in order to obtain some estimate of the cost and complexity of a VCS system.

For our reference system, we will utilize four equatorial geostationary satellites. These satellites will be stationed nominally at 50° W, 140° W, 40° E, and 130° E longitude. The coverage provided by these satellites is shown in Figure 7.4.9. Fixed-platform elevation angles no lower than 5° and balloon elevation angles of no less than 15° are assumed. As a result, fixed-platform coverage to 70° latitude is obtained. Balloon coverage to 60° latitude is obtained, with some small segments below 60° in which balloons will not be located. If higher-latitude coverage were desired, some of the systems discussed earlier would have to be implemented. This system was chosen in the absence of a specific justification for higher-latitude coverage.

Placement of the satellites in the Western Hemisphere is based upon obtaining dual coverage over the continental United States. These satellites will be directly over the Pacific and the Atlantic, respectively, and hence will obtain good coverage from balloon platforms. The Eastern Hemisphere satellites are phased to be 90° apart, and cover Europe and Africa at 40° E longitude, and Asia and Australia at 130° E longitude.

It is of interest to size and cost the spacecraft roughly in order to obtain data for cost-effectiveness trades. As a reference, we will utilize relations derived by the Panel on Broadcasting. That group derived the following relationship for satellite weight:

$$W = \frac{0.34\ (\text{power}) + 167 + W_c + \text{antenna weight}}{0.77}$$

where: power = total spacecraft power required
W_c = weight of the communication system
antenna weight = weight of the antenna system

The figure of 167 lb is the weight necessary for the attitude control, thermal control, telemetry, tracking, and command, etc. It was estimated that a typical overhead power for satellite operations would be in the order of 60 W plus the power necessary for the communication subsystem. For a 20-W transmitter with 50 percent efficiency, roughly 40 W of prime power is required. It is estimated that the receiver portion of the transponder will require 5 W. Hence, the total satellite power is approximately 105 W.

It is estimated that a complete transponder, including transmitter and receiver, 20-channel amplifiers, and associated electronics, can be built to weigh less than 10 lb. Allowing for redundancy, the total weight of the communication system will be 20 lb. It is estimated that a high-gain VHF antenna for the system could be built for between 25 lb (for a 15 dB helix) and 30 lb for a deployed dish of the same gain. Utilizing the formula derived by the Panel on Broadcasting, the total system weight is about 340 lb. Since this estimate was based on pessimistic assumptions, it is safe to say that a VCS can be constructed to weigh less than 350 lb.

The satellite itself as described herein would be quite simple. No especially difficult requirements would be imposed upon any of the subsystems. A 20-W transponder is within the state of the art, a 40-W VHF transponder already having been flight-tested successfully on the ATS. The challenge in the satellite design will be the high-gain VHF antenna. However, the objective of obtaining minimum earth angle from the VHF antenna is not a "hard" requirement, since plenty of margin still exists within the link. This permits some reduction from 18-dB gain in order to simplify antenna design. A 9-dB VHF antenna has been successfully tested on the ATS as an example of the state of the art.

A DSV-3N (TE-364-3) Thor-Delta configuration can lift into transfer orbit a 706-lb payload, consisting of a 353-lb satellite payload and a 353-lb SVM-2 apogee motor (utilized on INTELSAT-III). The SVM-2 will then transfer the satellite payload into geostationary position.

A potential booster development is the DSV-2N/uprated Delta TE-364-3 combination. The uprated Delta is a hydrogen-oxygen second stage (sometimes called HOSS). This combination, along with the TE-364 apogee engine, is capable of injecting 795 lb into geostationary orbit. If this development is successfully completed by the time the VCS system is deployed, multiple launches of two VCS's per Thor-Delta launch vehicle will be feasible, and the launch costs will be halved. With $7 million allocated to spacecraft R&D, the present launch cost of $5 million per VCS, and an estimated cost of $15 million for four flight VCS's and one spare, the total cost of putting the four 5-year satellites of the VCS system into orbit will be about $47 million.

4.4.4 Command and Data-Acquisition Stations

It will be necessary to develop a command and data-acquisition (CDA) station for the VCSS. The function of the CDA will be to command and control the satellite subsystem, to provide the interrogation signals through the VCS and into the DCP's, to receive the data from the DCP's, to locate the mobile platforms, such as balloons, to record the information received from the DCP's, and finally, to transmit the raw data acquired to the center proposed for the systems for remote-sensing information and distribution. In turn, the center will provide information on interrogation programs to be utilized.

It is anticipated that a normal interrogation program will be utilized most of the time. This program will provide for the orderly gathering of data, either synoptically or locally. Provisions for program changes will be provided for special situations, where modifications of the interrogation program will become necessary for either research or operational reasons. The means for handling alarm or on-demand traffic will be included in the CDA.

In order to monitor the balloons properly, the CDA will do position computation. Referring to the distribution of VCS's shown in Figure 7.4.9, it can be seen that one CDA will be able to control and interrogate two VCS's, and hence will have control over platforms along 210° of the equator. One station, located in the central United States, will cover both Western Hemisphere satellites. However, for a global system, there is a need for another station in the Eastern Hemisphere. This could be located in central Europe or Asia. Contact between the two CDA's on opposite sides of the earth could be maintained through conventional satellite communications or, with slightly more complexity, by time-division multiplexing through the data-collecting satellites themselves. Another possibility is local hopping, in which two slave ground stations support the master CDA, and interrogation signals for the two Eastern Hemisphere satellites are relayed through the VCS's, through the slave stations, back into the second set of VCS's, and into the platforms. This double hopping will increase the traffic through the Western Hemisphere VCS's by a factor of 2, but will centralize all satellite control.

The best solution for an optimum configuration of CDA's is based upon political as well as technical factors. Questions of how a global meteorological and earth-resources system would be handled on the international level will influence the decisions on which technique to utilize. Either of the proposed approaches represents a technically feasible solution.

Assuming the two-CDA configuration, it is estimated that the 4-year systems cost for CDA would be approximately $27 million. Hence, the total cost of operating both the CDA's and the VCS's for 4 years will be approximately $74 million. Additional costs may be required for further systems management of the entire data-collection satellite, control, and data-acquisition facility. It is not clear at this time if that would be a separate function handled through a center such as proposed by the Panel on Systems for Remote-Sensing Information and Distribution, or an independent function. In the latter case, it is still believed that the entire program could be run for less than $100 million, which is at least an order of magnitude lower cost than that for conventional communications techniques for performing the data-collection function. A summary of VCSS parameters is given in Table 7.4.4.

TABLE 7.4.4

A REPRESENTATIVE DATA-COLLECTING-SATELLITE SYSTEM--1975

Minimum data-collection platform: 5 W; 0 dB ($<15^{\circ}$ off antenna pattern axis)

Four geostationary data-collecting relay satellites (DCRS):

Balloon coverage: $<60^{\circ}$ N and S latitude

Other: $<70^{\circ}$ N and S latitude

Two command-and-data-acquisition (CDA) stations

VHF channelized transponder--50 kHz

148.5 MHz, CDA to VCS; 138 MHz, VCS to DCP; 149.2 MHz, DCP to VCS; 136 MHz, VCS to ground

20 channels, with 10 subchannels each; 2500 Hz each channel

20-W transmitter

Earth-coverage, 18-dB gain, VHF antenna

Weight in orbit: <350 lb

Power: 105 W

Launch vehicle: Thor-Delta

Estimated 4-year cost:

R&D	$ 7 million
Satellites (four orbited plus spare)	15 million
Launch vehicle and launching pad (five* at $5 million)	25 million
CDA plus maintenance and management	27 million
	$74 million

*One spare.

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5.0 WIDE-BAND DATA-COLLECTING-RELAY-SATELLITE (WBDCRS) SYSTEM

5.1 General

A wide-band data-collecting-relay-satellite system employing satellites in 24-hour orbits and capable of achieving continuous real-time recovery of imaging data from up to three earth-resources satellites (ERS) is technologically feasible by 1975. Operational ERS has been assumed as the primary relay mission for the WBDCRS. Included as secondary missions are operational Apollo applications program (AAP) data relay and ESSA meteorological data relay. This section of the study report estimates the system performance requirements imposed by the ERS mission parameters postulated in the 1968 NAS Summer Study on Space Applications, defines alternative design approaches to the problem employing high-gain, mechanically focused and electronically focused antennas in the relay satellite, presents a comparative analysis of the alternative design approaches, and identifies component and technique developments upon which deployment of such a system depends.

5.2 Requirements for WBDCRS

5.2.1 Target Characteristics and Coverage Requirements

Mission parameters assumed for a 1975 ERS system are given in Table 7.5.1.

TABLE 7.5.1

ERS MISSION PARAMETERS, 1975

Altitude and orbit shape	-	500 nautical miles (nm)circular
Inclination	-	98^{o} sun-synchronous
Stabilization	-	3-axis
Imaging geometry	-	100-nm swath, continuous
Swath center	-	Subsatellite track
Overall system resolution	-	100 feet
Number of spectral bands	-	3

With the maximum of three earth-resources satellites deployed and operating, one would be placed in a 9 a.m. orbit (i.e., the satellite will cross the equator at 9 a.m.) and two in coplanar or near coplanar orbits around noon to get complete earth observation every 18 days, allowing for redundancy of coverage and for cloud cover. It may be acceptable to constrain the two earth-resources satellites in the near-noon orbits to be coplanar and a half-orbit apart, in which case two data-relay satellites, each capable of handling two earth-resources satellites simultaneously, would suffice for continuous coverage of the three earth-resources satellites. If we consider an AAP vehicle with a data-acquiring payload as requiring channel capacity comparable to an earth-resources satellite for retrieval of mission data, it would be reasonable to adopt the requirement that each WBDCRS accommodate three target satellites simultaneously, and each target satellite be equivalent to an ERS. With this arrangement, two or more wide-band channels would be available to an AAP mission at least 50 percent of the time.

Assignment of information rates for the data-relay function derives from the image parameters given in Table 7.5.1. For the wide-band remote-sensing information system (the remote sensor and on-board signal processor, the ERS-to-WBDCRS link, the WBDCRS-to-GDH link, ground signal processing, and image reproducer to yield an overall ground resolution of 100 ft, the product of the modulation transfer functions (MTF) of all the elements must be equivalent to a 2-MHz information bandwidth if the pictorial information is flowing continuously and no auxiliary data are included. The basic 2-MHz baseband rate stems from the average of 4×10^6 picture elements per second for the system. Allowance of a 20 percent gap in the actual data flow is reasonable in order to accommodate scanner and recorder flyback, synchronization information, attitude-determination data, and miscellaneous data, bringing the actual baseband rate to 2.5 MHz.

The WBDCRS system, if implemented, would represent by far the largest investment in the total earth-resources information system, by virtue of the ERS-to-WBDCRS link. Taking the actual picture element rate of 7.2×10^6 per second for the return-beam vidicon (RBV) camera proposed for the ERS, a baseband video requirement of 4 MHz appears to be an economical compromise between high-frequency degradation and transparency for the critical link.

Current estimates of the best output peak-to-peak (p-p) signal to rms noise ratio of the RBV are 37dB, corresponding to an rms signal-to-noise (S/N) ratio of 28dB. Allowing for a 5dB improvement in signal-to-noise ratio performance in RBV technology for ERS satellites launched within the lifetime of the WBDCRS, and allocating a maximum S/N degradation of 1dB to the WBDCRS for the up link and down link combined, yields a combined rms S/N requirement of 40dB for the WBDCRS. This can be met by assigning 41dB and 47dB requirements to the up link and down link, respectively. The disparity in S/N performance allocation between the up and down links is consonant with the relative expense and difficulty of the up link and is close to the most economical allocation. Overpowering the down link with respect to the up link yields the secondary benefit of desensitizing the effect of degradation of the relay satellite's effective radiated power (ERP) upon the performance of the down link. For example, a 2dB reduction in down link power output caused by aging of the power subsystem and the transmitter power amplifier will erode the combined S/N ratio of the communications relay system by only 0.5dB.

With the noise budget assigned above, an imaging sensor capable of a peak-to-peak (p-p) signal to rms noise ratio of 42 dB will result in a 41.2—dB S(p-p)/N(rms) at the output of the ground receiver demodulator for the worst-case geometry of the system. This is 2 dB better than quality rating 1.5—"Excellent"—of the Television Allocations Study Organization (TASO). In comparable TV-quality studies performed by RCA, 95 percent of the viewers rated such pictures as "fine" or better.

The objective of 30-ft ground resolution in each of seven spectral bands stated for the 1980 ERS, with all other mission parameters affecting the communications system unchanged from the 1975 ERS, introduces an information-bandwidth performance requirement of 104 MHz for the WBDCRS.

5.2.2 Link Parameters

5.2.2.1 The Up Link

As a first step in the assignment of communications parameters to the terminals of the WBDCRS system, a modulation scheme will be defined. The up link, with its 41-dB rms S/N requirement necessitates an ERP-aperture product in excess of 71.5 dB above 1 watt-ft^2. This is the overriding technical problem for the system: it makes the utilization of signal energy available to the up-link receiver the principal factor in choosing the modulation scheme. This leads to a choice between pulse-code modulation (PCM) and wide-band frequency modulation (FM), which are clearly superior to other modulation schemes while being closely competitive with each other. The second most important criterion affecting this choice is the cost of implementation of the modulation and demodulation elements of the system. For the picture-quality requirements adopted for the total information system, seven-bit quantization and sampling at a rate of 2.5 samples per Hz of information bandwidth will be required of the ERS PCM encoding elements. This leads to a PCM data rate in excess of 100 Mbits per sec for the return-beam vidicon (7.2×10^6 picture elements per sec or a minimum information bandwidth of 3.6 MHz). At these data rates, the functions of analog-to-digital conversion in the ERS spacecraft and recording and decommutation of raw mission data in the ground station would all strain the logic-device and recording technology of the early 1970's and, if feasible, would be very costly. The analogous problems with wide-band FM reside with achieving composite linearity of better than 1 percent in the modulation and demodulation processes. This requirement, although difficult for the modulation rates and deviations dictated by this application, is within grasp, employing microwave varactors that are available today. Aside from the feasibility question, FM also enjoys a sizable advantage over PCM with respect to the simplicity and low cost of the modulation and demodulation elements. Finally, FM enjoys the advantage of having its critical signal-processing component, the demodulator, at the ground station.

Although spectrum allocation does not pose a problem in the ERS-to-WBDCRS link, it is of serious concern with the down link. In the interest of conserving spectrum in the down link, it would be highly desirable to obviate the need to demodulate and remodulate in the relay satellite. Aside from its possible unreliability, such an arrangement introduces additional sources of quantization noise with PCM and nonlinearities with FM. Again, FM is significantly better than PCM. As will be shown in the following discussion, a 30-MHz allocation for each ERS satellite is sufficient to meet all the channel requirements of the WBDCRS. Even by allowing a rather optimistic one bit per Hz of rf bandwidth, PCM would necessitate more than 100 MHz of allocation for each ERS being simultaneously serviced by a relay satellite. In view of the foregoing considerations, wide-band FM is the clear modulation choice.

A carrier-to-noise ratio (C/N) of 15 dB assures a margin above threshold (the C/N above which the processing gain available with FM systems is realized) of at least 5 dB. FM systems employing feedback demodulators, with extreme linearity in both the modulation and demodulation process, have been demonstrated with threshold levels below 7 dB C/N. Use of a modulation index (m) of 2.5 will yield an improvement in output S/N (rms) of 17.3 dB. In addition, preemphasis at the transmitter of the high-frequency components of the baseband signal relative to the low-frequency components and inverse weighting at the receiver yield an additional improvement in output S/N. Employing the preemphasis characteristic that is recommended in CCIR Recommendation 405 for a 4-MHz baseband signal equivalent to 525-line commercial TV signals affords a 10.2-dB improvement in S/N over an unweighted signal. The S/N requirement of 41 dB adopted for the up link is thereby realized:

	dB
Carrier-to-noise ratio	15.0
FM improvement	17.3
Preemphasis improvement	10.2
S/N (rms)	42.5
S/N margin	1.5
S/N (rms) required	41.0

The modulation index of 2.5 gives rise to an rf bandwidth of 28 MHz. Multiplexing of three ERS and two ESSA satellite channels, while allowing for appropriate guard bands at the relay satellite for transmission to the ground, can be accomplished within a 100-MHz band without demodulation in the relay satellite. The 8.4- to 8.5-GHz frequency allocation for space research under International Radio Regulations accommodates 100 MHz and is accordingly recommended for the WBDCRS-to-ground links.

The preferred design approaches to the WBDCRS, among those considered by the panel, would use a carrier frequency somewhat above 10 GHz on the critical ERS-to-WBDCRS link. With the anticipation that space-qualified tunnel-diode amplifiers or diode mixers with sufficient bandwidth and better than 5-dB noise figures could be made available in this frequency range, an effective noise temperature of 1200°K is estimated for the relay-satellite receiver. The self-noise power of the 1200°K satellite receiver over the 28-MHz rf bandwidth is -122.4 dBW, and the required signal power for a C/N of 15 dB is -107.4 dBW.

A very useful parameter which identifies the fundamental trade-offs in assessing payload penalties to the target satellite and the relay satellite is the product of the effective area of the target satellite antenna, the target transmitter power, and the power gain of the receiving antenna at the relay satellite ($P_T A_T$ (eff) G_R). This parameter can be termed the ERP-aperture product for the ERS-to-WBDCRS link. At a maximum range of 23,000 nautical miles (target satellite over a pole, relay satellite in the equatorial plane), the required ERP-aperture product is 66.5 dB above 1 watt-ft^2, exclusive of losses. Estimating total losses of 5 dB for scan loss, polarization loss, line and feed losses, and degradation of communications and power subsystem equipment brings the required ERP-aperture product to 71.5 dBW-ft^2. The requirements for the ERS-to-WBDCRS link are summarized in Table 7.5.2.

TABLE 7.5.2

PERFORMANCE REQUIREMENTS FOR THE ERS-TO-WBDCRS LINK

C/N	15.0 dB
Margin over threshold	5.0 dB
Modulation index	2.5
FM processing gain	17.3 dB
Preemphasis gain	10.2 dB
S/N (rms) available	42.5 dB
S/N required	41.0 dB
S/N margin	1.5 dB
N_o relay receiver	-198.0 dBW/Hz
P_{rec} required	-107.4 dBW
Losses*	5.0 dBW
Power-aperture product	71.5 dBW-ft^2

*Contributions to losses:

Scan loss	1.0 dB
Polarization	1.0 dB
Line and feed losses	1.5 dB
Power and equipment degradation	1.5 dB
	5.0 dB

5.2.2.2 The Down Link

Although the WBDCRS-to-ground link must support a 100-MHz bandwidth and a 47-dB S/N, link performance does not pose any serious technological problems when stated C/N_o at the ground receiver is 10 dB superior to the ERS-to-WBDCRS link. This stems from the high figure of merit that can be postulated for the ground-station front end. At the preferred frequency band of 8.4 to 8.5 GHz, a 40-ft-diameter antenna, with an aperture efficiency of 55 percent and a receiver effective noise temperature of 100°K, yields a figure of merit (G_A/T_{eff}) of 6×10^4 °K. Allocating a total of 10 dB for losses (atmospheric attenuation, polarization, line and feed loss, and equipment degradation) results in an ERP requirement for the WBDCRS of 47 dBW. This can be realized with a 2-ft dish having an aperture efficiency of 55 percent and a transmitter output of 30 W.

Operation on a shared basis in the 8.4- to 8.5-GHz band is recommended for the down link. This band, allocated to space research under international and FCC regulations, would be completely occupied by the down-link system. However, the field intensity resulting from the down-link transmission at the earth's surface would be more than 10 dB below the maximum level allowed for shared operations: -152 dBW/meter^2/4kHz bandwidth. A representative composition of the 100-MHz band for inclusion of the three ERS channels and two ESSA satellite channels is shown in Figure 7.5.1. The guard bands indicated are sufficiently wide to accomodate spillover as well as the worst-case doppler shift, which approximates 450 kHz. Although the doppler shifts occur in the up link, it would be highly desirable to limit the signal processing in the relay satellite to frequency translation, limiting or AGC, and the necessary frequency-division multiplexing for synthesizing the down-link spectrum of Figure 7.5.1. Under these conditions the doppler shift in the up link would be directly translated to the down link.

A second recommendation concerning the synthesis of the down-link spectrum is to employ multiple rf final amplifiers in the relay satellite rather than a single power amplifier. A single amplifier would be required to supply the entire 30-W output of the 100-MHz spectrum. The recommended approach incurs the penalty of having the frequency-divided multiplexing filter, with its attendant loss of about 1.5 dB, at the output level. However, this loss is more than offset in the single-power-amplifier approach employing traveling wave tubes (TWT) by the need to back off the output from the most efficient operating level. This need arises with TWT's because of inter-modulation products generated by the AM-to-PM conversion effect. For the WBDCRS application, with three equal, high-power carriers for the ERS bands and two low-power (one-tenth) carriers for the ESSA satellites, one could be expected to back off between 4 and 5 dB on the power output; otherwise, the S/N requirements of the link would be jeopardized. The AM-to-PM phenomenon is avoided if a TWT is driven by a single, angle-modulated carrier. Probably the most unfortunate aspect of the AM-to-PM conversion effect is that the dc input requirements are no different than if the tube were operating at its most efficient operating level. Thus, the back-off decrement reflects directly as a decrement in efficiency. Alternatives to TWT's are not envisioned to be suitable for this application by 1975. Since this problem plagues most space-communications systems employing TWT's, a serious investment in technology-development efforts seems warranted, either to develop new

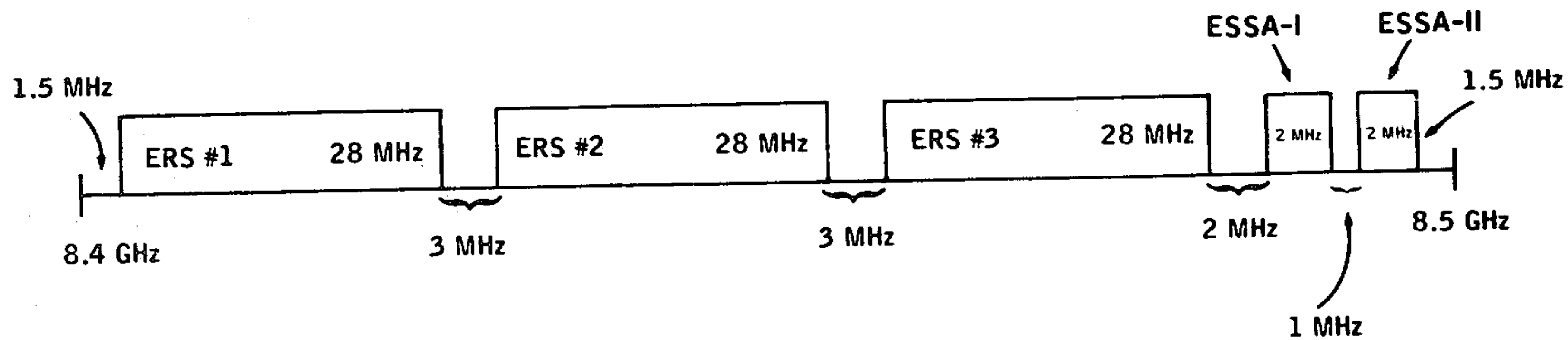

FIGURE 7.5.1 Representative channel assignments for WBDCRS down link.

devices or to effect improvements in the electron-beam technology of the TWT.

The channelized approach to the power amplifier would require a 15-W TWT for each of the wide-band channels and a single 5-W TWT for the two ESSA channels. The multiple power amplifier design affords as a side benefit a significant degree of redundancy in a critical element, so that the down link is less likely to fail catastrophically.

Table 7.5.3 is a summary of the requirements of the parameters of the WBDCRS-to-ground link.

TABLE 7.5.3

DOWN-LINK PARAMETERS

Carrier frequency	8.45	GHz
Radio-frequency bandwidth	100	MHz
Modulation index (WBFM)	2.5	
Channel capacity	Three at 4 MHz video Two at 840 kilobits per second PCM	
C/N	20	dB
Margin over threshold	>10	dB
S/N (rms)	47	dB
Ground-antenna diameter	40	feet
Ground-antenna-aperture efficiency	55	percent
Ground-receiver-noise temperature	100^{o}	K
Relay-satellite-antenna gain	32	dB (2 ft diam)
Spacecraft-power output	30	W
Losses*	10	dB

*Contributions to losses:

Atmospheric	3.5	dB
Polarization	3.0	dB
Line and feed losses	1.5	dB
Equipment degradation	2.0	dB
	10.0	dB

5.2.3 Satellite Orbits and Ground Station Locations

WBDCRS satellites placed in geostationary orbits at 10° W and 170° E longitude will:

1. Provide continuous coverage of the target satellites, including AAP spacecraft in low-altitude (200 to 300 nautical miles), low-inclination trajectories
2. Allow for ground readout stations at Rosman, N. C., and Mojave, Calif., for which the antenna-elevation angles would be greater than 5° above the horizon
3. Afford excellent immunity to multipath effects in the critical ERS-to-WBDCRS link by virtue of at least 21° between the line of sight and the earth's tangent
4. Obviate the need for a wide-band link between geostationary satellites; instead, interconnection to the systems for remote-sensing information and distribution could employ dedicated coaxial cables, microwave relay links, or point-to-point satellite service

For an operational system, a third WBDCRS satellite may be warranted for minimizing interruptions in service in the event of relay-satellite failure. The third satellite would be placed in an appropriate parking orbit in a standby mode to maximize its service life. The recommended WBDCRS system deployment is illustrated in Figure 7.5.2.

5.3 Design Approaches

5.3.1 Mechanically Focused Antennas

The design-tradeoff discussions presented in this section deal almost exclusively with the achievement of the receiving capability at the relay satellite that was developed in the preceding paragraphs. It was recognized early in the study that the wide-band link from the target satellite to the relay satellite dominates the cost of establishing and maintaining the wide-band data-collecting-relay system, and that the antenna and receiving subsystems of the relay satellite, in turn, dominate the up link. Accordingly, investigations carried out in connection with the WBDCRS concentrated heavily on phased-array receiving techniques, because of their well-known effectiveness in forming multiple beams from a common aperture.

The other communications segment of the WBDCRS that poses significant, but not comparable, technical challenge, the down link, was treated independently from the up link inasmuch as the choice of up-link approaches does not materially impact the down-link requirements or constraints. The remaining communications segments, such as command links and beacon transmitters and receivers, that may be needed for aiding spatial acquisition and tracking, represent an insignificant portion of the total system costs.

Mechanically focused and steered antenna systems were not rejected out of hand. Their two most important attributes, the economy and simplicity of the communications-receiving electronics and the relative ease with which wide-angular coverage can be provided, are not easily matched by

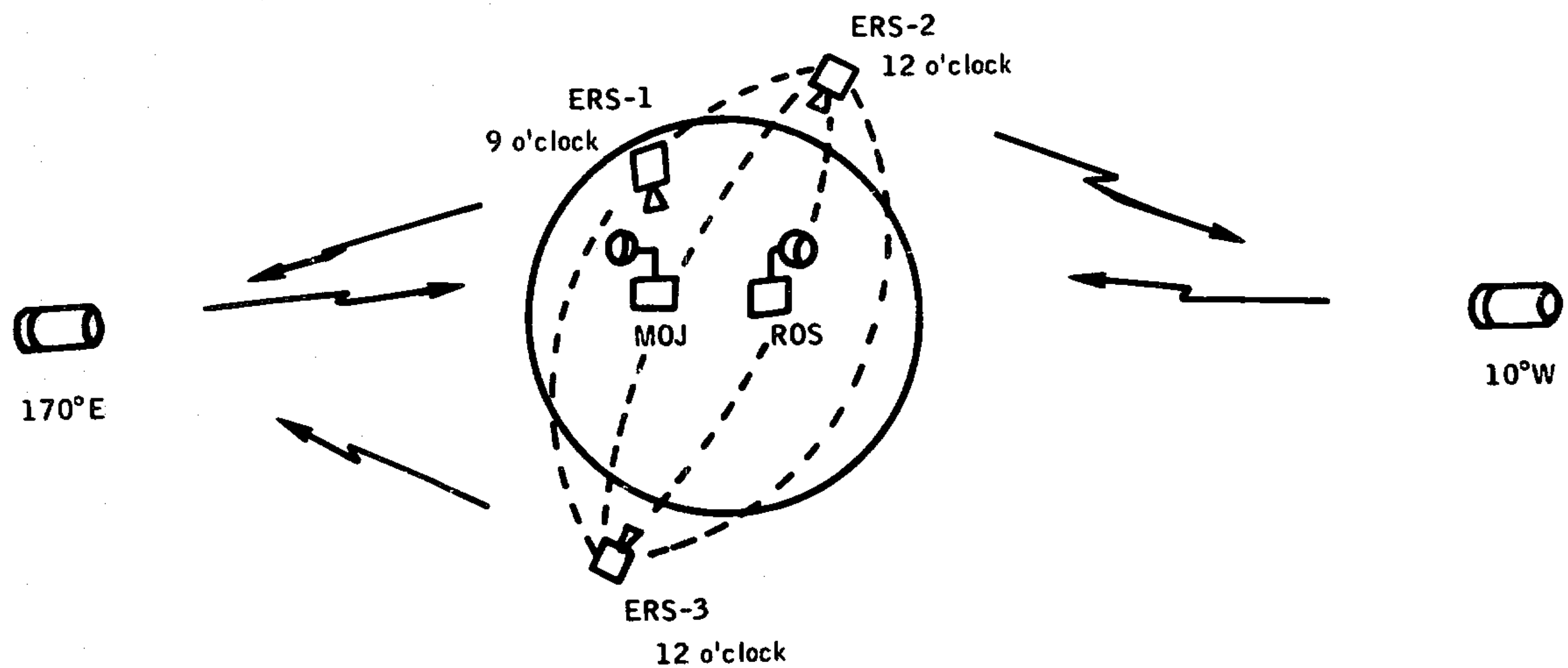

FIGURE 7.5.2 Wide-band data-relay system.

phased arrays. Indeed, the converse of these attributes represent the major disadvantages of all the phased-array approaches considered for this application. However, the serious impact of wide-angular coverage is greatly ameliorated by two factors: (1) that all the target vehicles are in low-altitude circular orbits, and (2) that a relay-satellite-to-relay-satellite link is avoided by allowing for two ground readout stations and point-to-point communications to bring the readouts to one location. For applications in which either or both ameliorating factors do not exist, the choice of phased arrays bears reexamination. The relatively high cost and complexity of the communications electronics associated with phased arrays stems from the large number of receiving modules that are needed to correlate the received energy captured by each element in the array. Generally speaking, the number of modules is proportional to the number of elements and the number of simultaneous beams, and in some array designs the number of modules proliferate at a faster rate. Recent advances in the miniaturization and the reduction of power demands of radio-frequency and intermediate-frequency components, such as phase shifters, mixers, band-pass filters, and gain blocks, have brought phased-array designs within competitive range for many spacecraft applications. The high order of redundancy afforded by the distributed arrangement of receiving modules greatly desensitizes the effect of component failures on the useful life of the communications subsystem.

The principal disadvantage of the mechanically focused antenna is its limited multibeam capability. Techniques for generating multiple beams from a common reflector, using either multiple feeds or movable feeds, exhibit a sharp selectivity between aperture efficiency and the number of beam widths contained within the total coverage volume. For the gain-coverage requirements of the WBDCRS, the attendant low aperture efficiencies could not be tolerated. In consequence, five dishes would be required for the up link, each independently steerable. The three dishes assigned to the ERS channels can be assumed to be twice the diameter of the dishes tracking the ESSA satellites. This is based on a 5-dB smaller ERP allocation to the ESSA satellites than would be allocated to the ERS satellites.

Representative terminal requirements for the ERS-to-WBDCRS links, at carrier frequencies of 10, 20, and 30 GHz, which meet the 71.5 dBW-ft^2 ERP-aperture product requirement are tabulated in Table 7.5.4. The assessment of power-aperture product to the ERS target satellite is estimated to be equally difficult in terms of payload penalty and technology development for the three carrier frequencies, based on current spacecraft and component technology. The table shows that the poorer efficiencies of rf power sources and the poorer sensitivities of receiver front ends that can be expected at 30 GHz inflict the same effective aperture on the relay satellite as for a 20-GHz link. The tighter mechanical tolerances and the greater precision required in the antenna drives are not offset by antenna size, which indicates that the optimum solution, for an operational system in 1975, lies somewhere between 10 and 20 GHz and would employ a 7-ft-diameter dish with 0.75^o beam width. A cluster of three such antennas and two 3.5-ft, 1.5^o-beam-width antennas, each independently slewed and tracked, poses an extremely difficult flight-dynamics problem. The Panel estimates that the development cost of the reaction-control system would more than offset the development costs of the

TABLE 7.5.4

UP-LINK REPRESENTATIVE TERMINAL PARAMETERS—PARABOLOIDS

PARAMETER	10 GHz	20 GHz	30 GHz
Target antenna diameter	4.5 ft	3.75 ft	3 ft
Target antenna beam width (3 dB)	1.5°	0.9°	0.75°
Target transmitter power	50 W	30 W	20 W
T_{eff} WBDCRS receiver	$1200^\circ K$	$1500^\circ K$	$1800^\circ K$
WBDCRS antenna diameter	7.5 ft	6.5 ft	6.5 ft
WBDCRS antenna beam width (3 dB)	0.9°	0.5°	0.35°

NOTES

28 MHz rf bandwidth

ERP-aperture product = 71.5 $dBW\text{-}ft^2$

All aperture efficiencies = 55 percent

phased-array technology and that the increased structural demands on the spacecraft, as well as the weight of the reaction-control system, would offset the additional weight of the receiving modules and the additional power demands of phased-array approaches. We have concluded, therefore, that the phased arrays represent a superior technology investment for this class of space-communication problem. Using today's technology, it is competitive in total system cost and offers considerable growth potential. In contrast, this application would strain the limits of effectiveness of the mechanically focused approach, while offering little growth potential.

5.3.2 Phased Arrays

Three design approaches towards the multibeam receiving array have been considered by the Panel, for the ERS-to-WBDCRS link. These are:

- Phase-shifter arrays, both the rf and i. f. type
- Switched-beam arrays
- Adaptive arrays, also termed self-focusing arrays

All the arrays considered would employ a planar structure, upon which a large number of medium-gain radiating elements are located at specific intervals. Individual control of the phases of the radiating elements, which are tapered proportionally to the coordinates of the elements in the array plane, establishes a wavefront. In the direction of wavefront propagation, the idealized array gain is the product of the number of elements and the gain of one element. The gain of an individual element depends primarily on the total scanning volume of the array. Allowing for a maximum altitude of 1000 nautical miles for the target satellites and a 1° attitude-control error in the WBDCRS satellite necessitates a 23° scan angle. The peak gain of a simple antenna with a 3 dB beam width of 23° is estimated as 17 dB, and the gain at the extreme scan angle is 14 dB.

The ERP-aperture product requirement for the ERS-to-WBDCRS link of 71.5 dBW-ft^2, which arises from the maximum slant range of 23,000 nautical miles to the ERS target, must be met at the extreme scan angle of the WBDCRS array. Assignment of the transmission parameters postulated in Table 7.5.4 for the earth-resources satellite in the region of 10 GHz results in a gain requirement of 45.1 dB for the receiving array. From these considerations, 2000 elements are nominally required in the receiving array. The 2000 elements provide an idealized gain of 47 dB, including an allowance of 1.9 dB for gain degradations due to mutual coupling losses, phase errors, and receiver mismatches. For convenience, 2048 elements are assumed, since corporate-feed methods and some beam-forming techniques naturally lend themselves to designs in which the numbers of input-output ports are integer powers of two.

With the ESSA meteorological satellites, the received power at the array antenna can be 11.5 dB less than with the earth-resources satellite for the same carrier-to-noise ratio in a 2-MHz rf bandwidth. By allocating a power-aperture product 5.5 dB smaller to the target satellite, only the central 512 elements need be employed on the two ESSA-to-WBDCRS channels of the receiving array.

Selection of the carrier frequency for the up link should be governed, if practical, by the desirability of obviating the need to employ an erectable array structure in the relay satellite. At 11 GHz, an array area of about 85 ft^2 would be required. This is comfortably within the standard shroud cross-section of the Titan III-C launch vehicle. The 10.7- to 11.7-GHz band also affords growth potential for the 1980 ERS mission parameters and is recommended for this application.

Because adaptive arrays require a receiving module for every antenna element, and because there are important advantages in providing an rf amplifier for each antenna element with the phase-shift and switched-beam arrays (these advantages are insensitivity to losses in the beam-forming elements and graceful performance degradation as rf amplifiers fail), a tunnel-diode amplifier is recommended for each element with all the design approaches.

5.3.2.1 Phase-Shifter Arrays

A receiving array employing rf phase shifters is shown in Figure 7.5.3 and an i.f. phase-shifter array is shown in Figure 7.5.4. A total of 7168 phase shifters is needed to provide three high-gain beams and two low-gain beams simultaneously. Three-bit phase shifters permit control of the phase of each element in increments of 45°. The associated phase-quantization error of 13° introduces a gain loss of approximately 0.3 dB. A two-bit

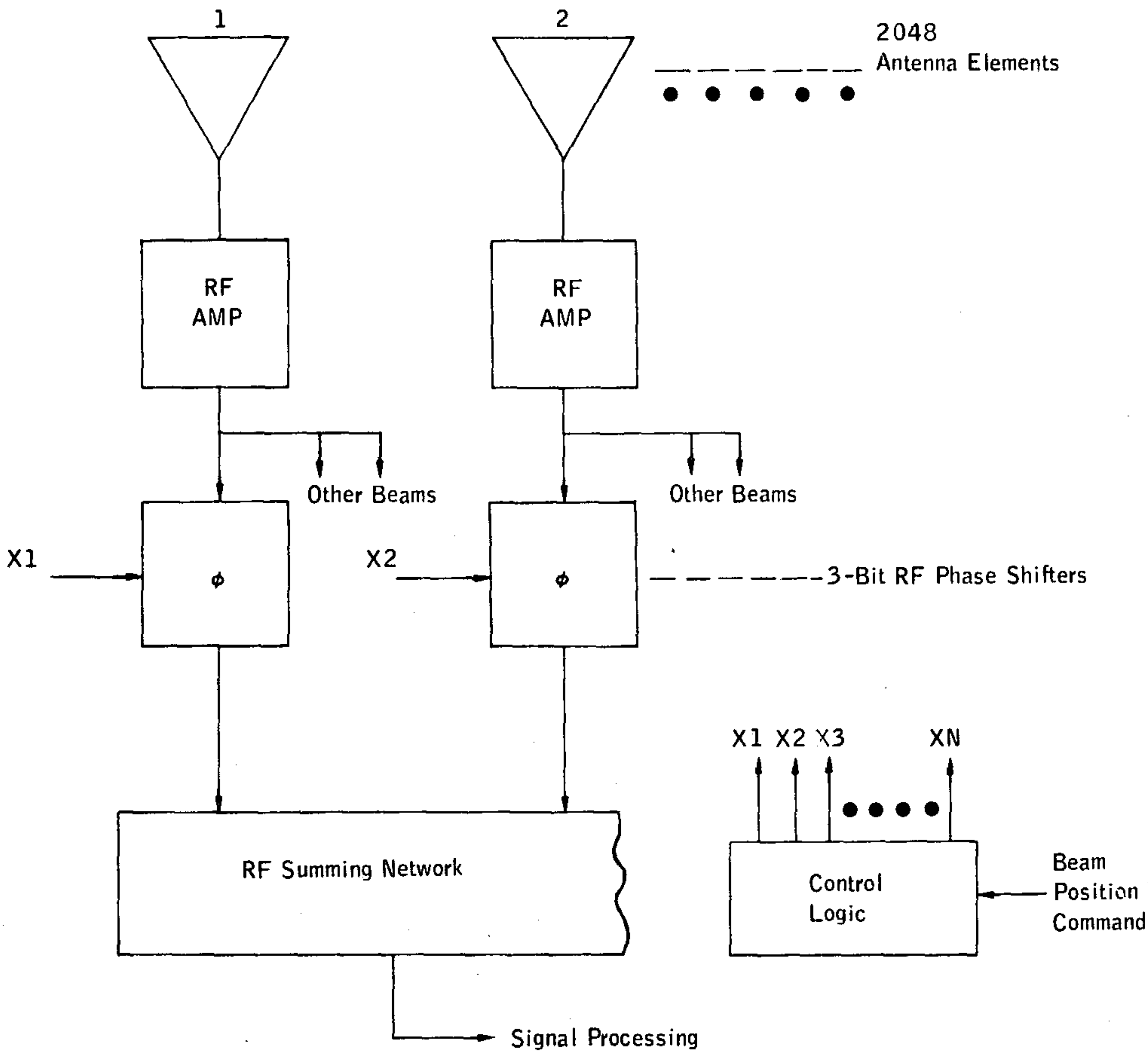

FIGURE 7. 5. 3 Radio-frequency phase-shift array.

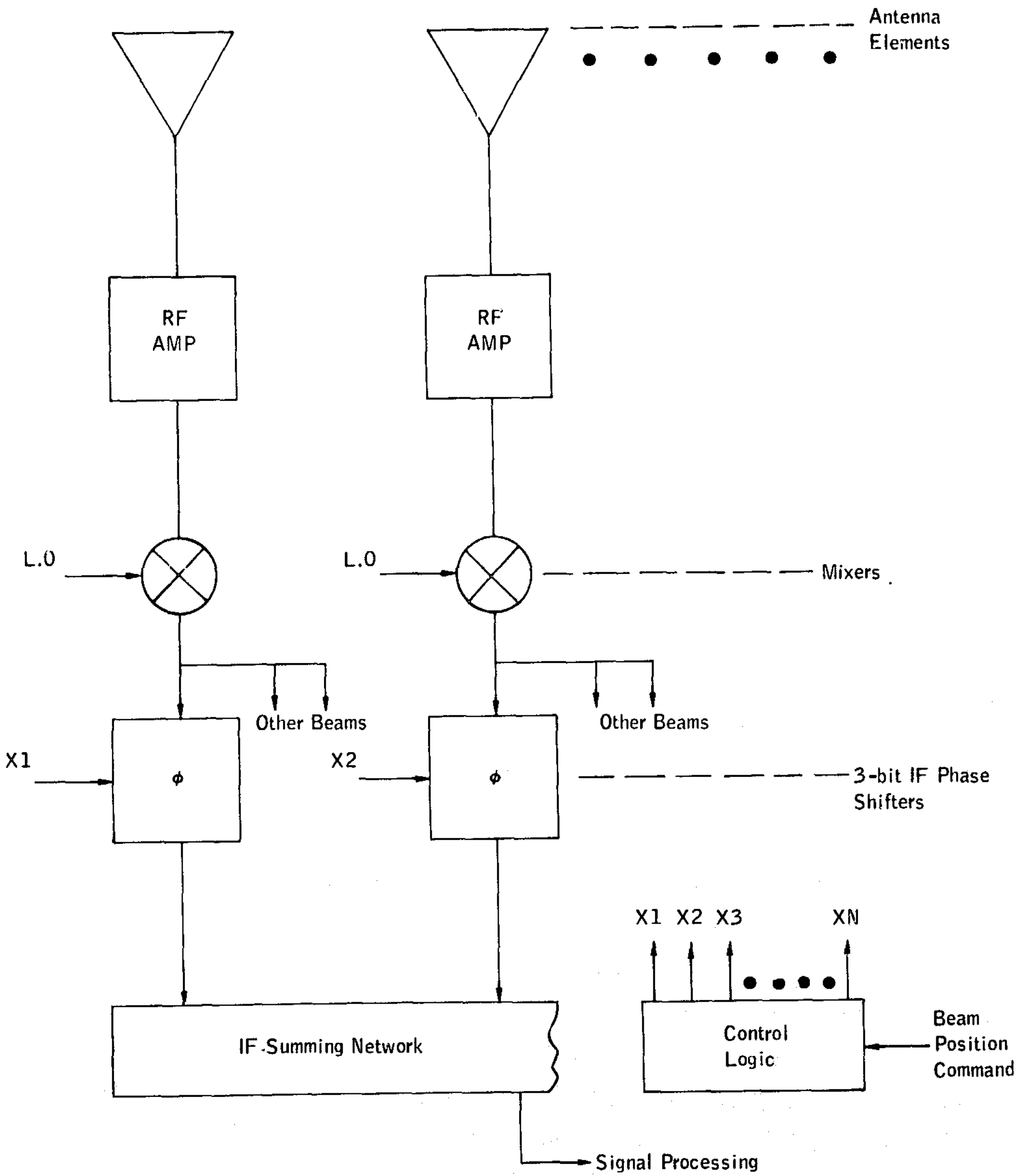

FIGURE 7.5.4 Intermediate-frequency phase-shift array.

phase shifter induces about a 0.9 dB gain loss, so its use would appear to be a false economy for this application. A hard-wired logic matrix can be employed to good advantage to convert input steering commands to individual phase-shift commands in a process which is akin to coordinate conversions. In order to maintain the array gain loss within 0.3 dB with the three-bit phase shifters, phase-shift values must be determined to a precision of six or seven bits and then rounded off. Control logic is required for each beam.

There is a tradeoff between the use of radio frequency or intermediate frequency phase shifters. Phase shifters at intermediate frequencies are inherently more economical and more amenable to miniaturization and should require far less control power for the diodes. I.f. summing networks should enjoy similar advantages. However, the use of i.f. requires the addition of 7168 down converters.

The fundamental advantages of phase-shifter arrays stem from their simplicity relative to the other array designs. This leads to:

1. The lowest rf or i.f. component count, hence the lowest recurrent cost for additional satellites
2. The lowest rf development cost
3. The lowest power demand

The disadvantages of the phase-shifter array are:

1. Of the three approaches, it is the most sensitive to mechanical distortions of the array plane. It will require the stiffest and best-insulated array structure. It may be necessary to develop exotic calibration schemes to sense the distortions. If calibration schemes are resorted to, control logic will be significantly complicated by the need to accommodate variable element coordinates. This may necessitate programmable logic rather than hard-wired logic.

2. Attitude determination must be sensed externally, since monopulse operation greatly complicates the array. Steering is inherently open loop.

3. Redundancy in the logic-control functions is not inherently available and is difficult to provide.

5.3.2.2 Switched-Beam Arrays

This class of arrays provides a multiplicity of beam ports, usually equal in number to the number of antenna elements, each of which provides a unique beam direction. A beam-forming matrix comprised of 3-dB couplers and fixed phase shifters, which are merely specific line lengths, performs the interconnection between the antenna-element ports and the beam-direction ports. The most frequently used beam-forming matrix is the Butler type. The number of elements possible with a Butler matrix is restricted to an integer power of 2, and a single beam-forming matrix is usually thought of as generating a phase taper for a linear array of elements. For a planar array of 2048 elements, an arrangement of 64 rows of elements with 32 elements in each row is contemplated, as depicted in Figure 7.5.5. If the antenna elements were to generate symmetrical beams, the array beam would have a 2:1 aspect ratio, and the array structure would exceed the shroud dimension in the Y-axis. Symmetry of the array structure can be provided by employing elements whose patterns are elliptical, twice as wide in the X-axis, and spaced at twice the interval in the X-axis. Although this approach is likely to complicate the design of the individual elements somewhat, it would appear to be warranted, in order to avoid erectable techniques and the unduly complex transmission-line problems incurred with hinged-array structures.

Beam steering with a Butler matrix is accomplished by switching to the appropriate beam port. Along either axis of the array, adjacent beams formed by adjacent ports intersect at a -4-dB level relative to the peak gain of the array. By exciting two adjacent ports, the beam-axis position is established midway between those for the beams generated with either single port excited (this is called beam interpolation), and the gain loss reduces to less than 1 dB. Along the diagonal, the potential loss could be as high as 6 dB. Interpolating by exciting a cluster of four beam ports reduces this loss to something in excess of 1 dB. To reap the benefits of beam-position interpolation, each node in the switching networks (which can be considered binary Christmas-tree arrangements of switching nodes) must be capable of splitting power between two output ports as well as directing power to either output port. This requirement adds significant complexity to the switching networks.

The switched-beam array does not appear to lend itself to economic generation of the two low-gain beams for the ESSA satellites, because an additional set of beam-forming networks would be needed for a 512-element configuration. Therefore, for this design approach, five high-gain beams are assumed. The rf component count for the beam forming and beam steering of the 32 x 64-element, five-beam array is given in Table 7.5.5.

The advantages of switched-beam arrays are:

1. Beam forming is accomplished with passive elements exclusively, which are inherently more reliable than controlled elements.
2. No additional beam-forming matrices are needed as additional beams are added. However, additional sets of switch networks are needed for each additional beam; 2047 switches/power splitters are required for each additional beam.
3. Redundancy is inherently available in the beam-forming matrices, less so in the switch networks. However, failure of a switching node will cause interruptions on a particular beam. The duration of these interruptions will generally be in excess of 1 min. This "advantage" appears to be a mixed blessing in the acquisition of real-time or wide-bandwidth data.

The disadvantages of switched-beam arrays appear rather severe for the data-collecting-relay-satellite system:

1. By far the largest number of rf components is required. How-

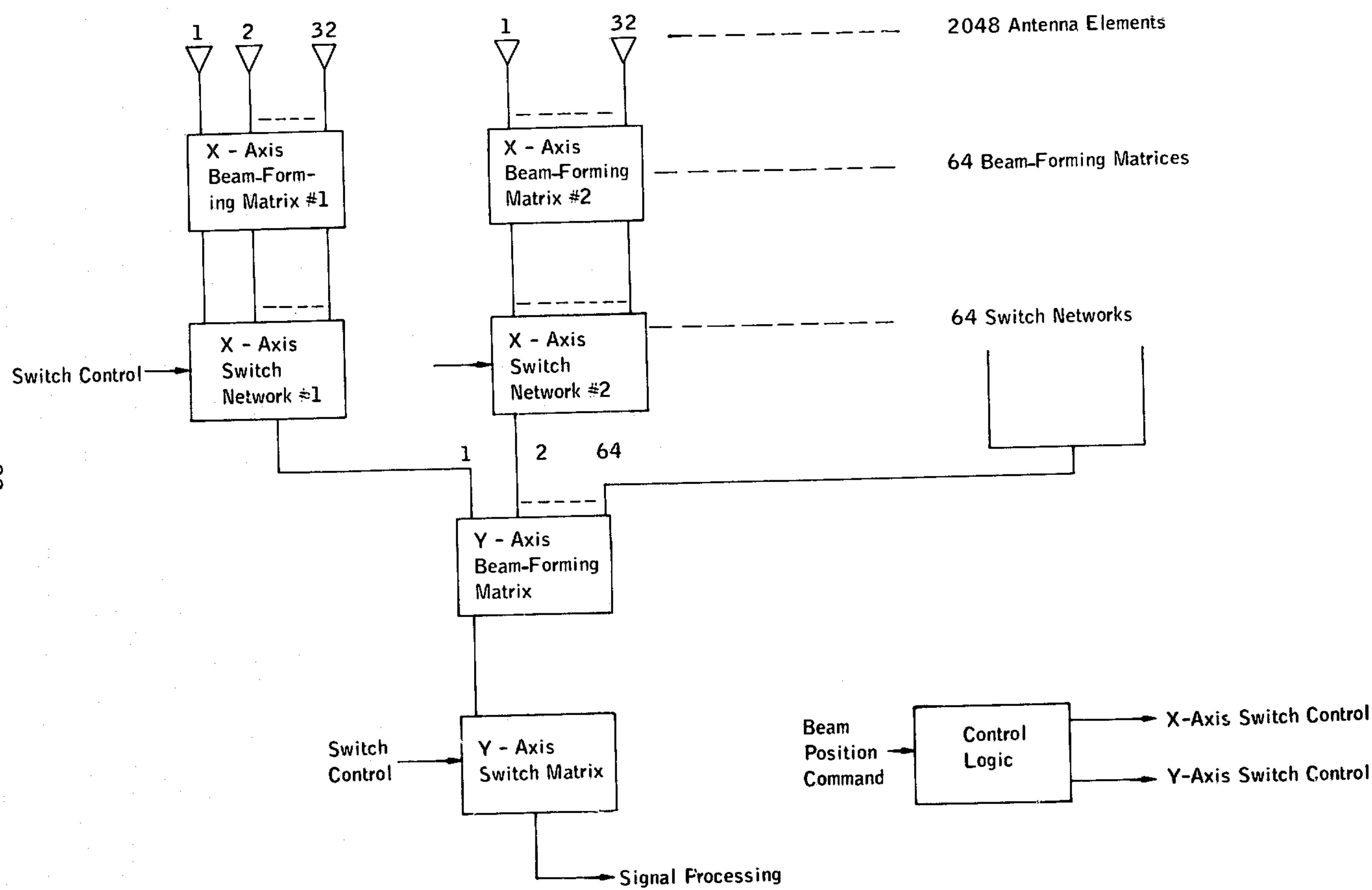

FIGURE 7.5.5 Switched-beam array.

TABLE 7.5.5

BEAM-FORMING AND BEAM-SWITCHING RF COMPONENTS

	Total Required
Beam-Forming Matrices	
32-element matrices	64
64-element matrix	1
3-dB couplers	5,120
Phase shifters (fixed-line lengths)	4,256
Switch Networks	
32-port networks	320
64-port networks	5
Switches/power splitters	10,235
Switch diodes	20,470

ever this is a receive-only array, and i.f. versions of the beam-forming and beam-switching functions could significantly ameliorate the high rf component-count problem. Development and manufacture of the hardware to accomplish these functions is easier at i.f. if the beam width can be produced, but total component count remains the same. Investigation of this alternative may be pertinent if further system studies of this type of array are undertaken.

2. Mechanical distortions introduce almost as much array gain loss as with phase-shifter arrays, and similar penalties accompany this effect.

3. Switching transients of submicrosecond duration occur on each beam every time the condition of switching networks associated with that beam is changed. These transients may cause phase-locked loops in the wide-band ground-receiver demodulators to break lock and extend the interruptions to intolerable durations. During a typical pass (one-half orbit) of a target satellite, about 100 such transients may be expected.

4. Unlike the alternative design approaches, the switched-beam array does not employ an electronic module for each antenna element. This introduces the need for much more rf cabling, with attendant higher cost and weight. Again, the i.f. beam-forming and beam-switching approach may offer relief.

5.3.2.3 Adaptive Array

The feature that characterizes this design approach to the receiving array for the WBDCRS up link is that a virtually independent receiving module is provided for each element. A typical version of a receiving module for adaptive arrays is shown in Figure 7.5.6. The qualifiers to independent operation of the modules are: Unless all modules associated with a given beam track each other in absolute phase to within 15° or 20°, significant defocusing effects begin to appear, producing gain loss; local oscillator injection at all mixers must be closely in phase.

In operation, the adaptive-array data source transmits a pilot signal, usually a tone displaced in frequency from the information spectrum, bearing a specific phase relationship to the information waveform. At each receiving module, the pilot signal is extracted, then tracked by a narrow-band, phase-locked loop to raise the S/N of the pilot signal far above unity. This tracking is essential to the demodulation process, since the pilot signal acts as the phase reference. If the pilot signal were noisy, a drastic degradation of S/N would be incurred in the coherent demodulator. Following demodulation in each module, the outputs of all elements are coherently added, and the full gain of the array is realized.

Rapid acquisition in the face of doppler shifts as high as 450 KHz and tracking-filter noise bandwidths of less than 1 KHz will probable require some form of doppler estimation for each target vehicle to be transmitted to WBDCRS from the ground station. This is not a major problem, since a frequency offset can be injected into each module, thereby, in effect, wiping out the doppler shift. Since this can be done via a common, variable-frequency oscillator, the hardware penalty is not significant.

The advantages of adaptive arrays are:

1. Adaptive arrays are the least sensitive, by far, to degradation in array gain introduced by mechanical deformation of the array structure. Knowledge of the coordinates of the radiation in the array plane is not a condition for demodulation of the information waveform; hence the term "adaptive."
2. No external means of attitude determination is required. The analogous problem of pilot-signal acquisition is far less complicated than the spatial-acquisition process necessary with competing approaches.
3. Switching transients, which may plague switched-beam designs and, to a lesser extent, may introduce problems with phase-shifter arrays, do not exist.
4. Gain variation with scan angle is caused only by unavoidable element-pattern variation from element to element and array variation in cross-section.
5. Redundancy and graceful degradation in this type of array are not contaminated by switching transients or system outages: the array and system performance are truly smooth and continuous.
6. Nonuniform element spacing can be more readily exploited

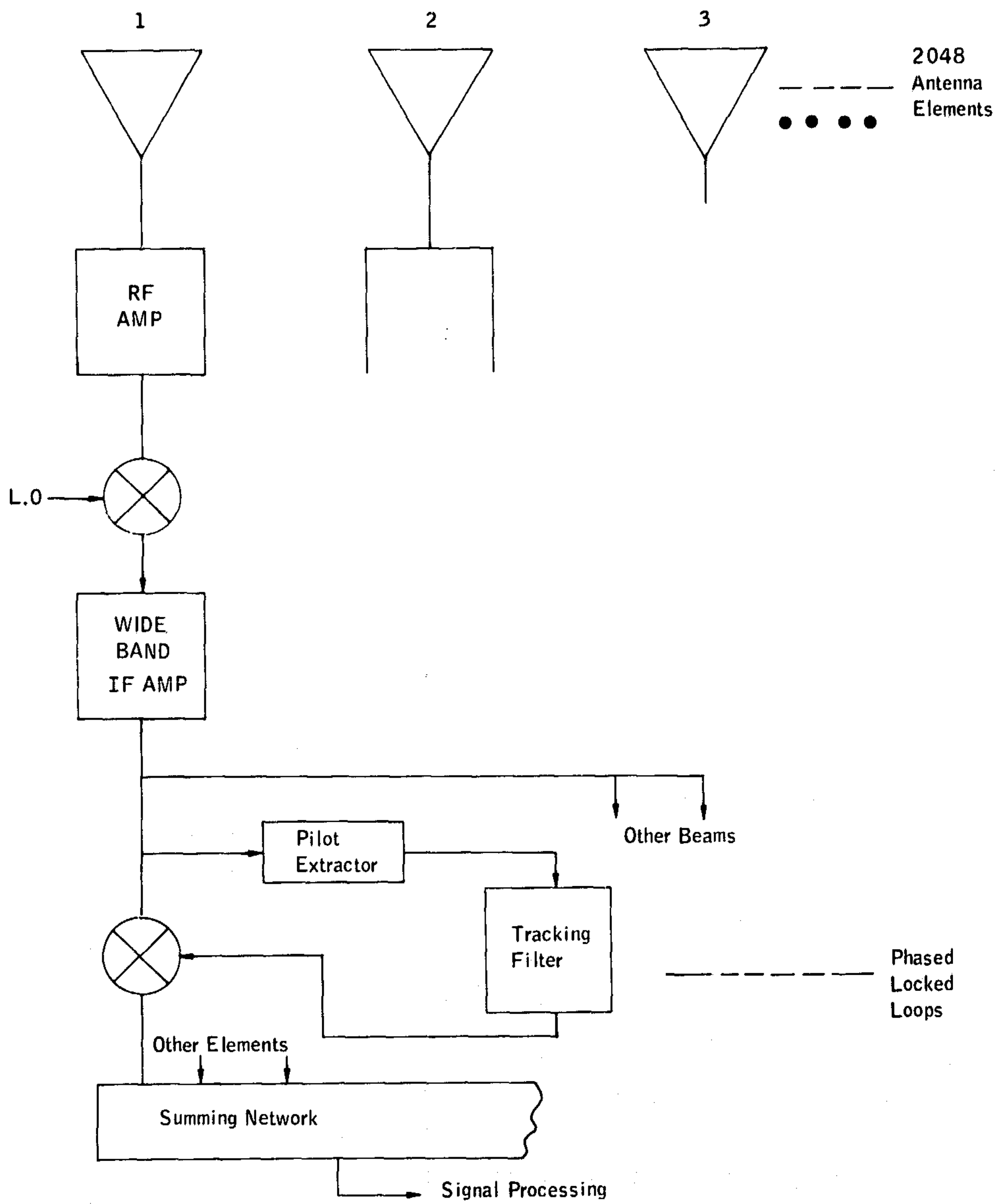

FIGURE 7.5.6 Adaptive array.

with adaptive arrays than with the competing designs. The efficacy of this design technique in reducing the number of elements required for a given array gain bears further study for this class of problem.

The disadvantages of adaptive arrays are:

1. The highest proliferation of rf/i.f. components among the three approaches. Clearly, however, the bulk of the proliferation is at i.f. It should be noted that if the i.f. beam-forming options are employed with the other two approaches, the rf component count is basically the same. Improvement in microminiaturization (and cost) of i.f. components, currently under active pursuit by several companies and by NASA, is the key to the economy of this approach.
2. With 7168 phase-locked loops and their attendant voltage-controlled oscillators operating simultaneously within the i.f. electronics packages of the array, the local radio-frequency-interference (RFI) problem is formidable. There may be noticeable weight penalties brought about by shielding or by distributed-packaging solutions.
3. Power applied to the pilot tone at the target transmitter does not contribute to the communications capacity of the channel. This problem is more serious with narrow-band adaptive arrays and can probably be kept below 5 percent of the total power for this application.
4. Acquisition of the pilot signal may be susceptible to interference from earth-based radiations. This consideration may impose the need to employ some form of pilot-signal fingerprinting rather than harmonic tones.

5.3.3 Selection of the Preferred Approach

The adaptive array is recommended on a conditional basis. Because of its clearly superior performance characteristics, it is the preferred approach. A clear recommendation must await the outcome of detailed design studies directed toward determining the feasibility of achieving the allocation of 0.5 lb and 500 mW per antenna-element-receiver module that is developed in the weight summary at the end of this section. Aside from the weight issue and its inherent performance advantages, the area of greatest development risk, the radio-frequency-interference problem, can be tested on the ground to a high degree of confidence. This is not the case with the alternative approaches, in which the item of greatest development risk, the structural and thermal integrity of the array plane, appears to be very difficult to assess in ground testing and simulation.

In the event that the weight and power allocations for the adaptive array are not achievable, the phase-shifter array, because of its potentially low weight, might become the compromise choice. This will depend upon an assessment of the actual weight differential between the two approaches in comparison with the system-operating disadvantage inherent in the phase-shifter array. The i.f. phase-shifter array appears more promising than rf phase shifters for a 1975 operational date. The rf implementation of the switched-beam approach is clearly inferior for this application to the other approaches, while the i.f. version would at best narrow the gap. The competitiveness of this approach improves only with applications requiring smaller numbers of array elements and/or a larger number of simultaneous beams.

5.3.4 Weight and Power Summary

The Panel on Broadcasting adopted the following relationship for estimating satellite weight in pounds (see Section 4.4.3 of this report):

$$W = \frac{0.34\, P_T + 167 + W_c + \text{antenna weight}}{0.77}$$

where: P_T is the total power required at the satellite

W_c is the weight of the communications system

antenna weight is the weight of the antenna system

The estimated power per element of the adaptive receiving array which allows for 3 1/2 tracking channels per element is:

	mW
Radio-frequency amplifier and mixer	10
Wide-band i.f. amplifier	140
Tracking filter and demodulators (x 3 1/2)	350
Total power per antenna element	500

Sixty watts is allocated to overhead functions such as attitude control, thermal control, telemetry, tracking, and command (TTC), and other housekeeping functions. Thirty percent efficiency is assumed for the 30-W, down-link, TWT transmitter and 10 W for the central signal-processing functions of the communications relay system. This leads to a P_T of 1194 W.

Estimating 40 lb for the down-link antenna, communications equipment, and central signal-processing hardware of the relay system yields a weight allocation for each antenna-element receiver-module of the target-to-DCRS up-link equipment of 0.5 lb. The highly cost-effective Titan III-C launch vehicle could place this 2000-lb satellite in geostationary orbit. The 2900-lb payload capability of the Titan III-C/Burner II combination allows the per-element weight allocation to increase to 0.8 lb. Thus, existing boosters can handle the adaptive-array version of WBDCRS. It appears clear that, in these circumstances, competing approaches that bring operating deficiencies into the data-collecting-relay system need not be recommended. The 1968 state of the art for antenna-element/receiver-module weight is now reported as 1.0 lb maximum with demonstrable hardware. By 1972, the year in which subsystems must be qualified to realize a 1975 launch, there seems little question this weight will be less than 0.8 lb.

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6.0 REGIONAL RECEIVING SITES FOR ERS TV

6.1 Why Use Many Sites?

The initial ERS TV system, employing three multispectral TV cameras, is designed to provide 100-ft resolution of the terrain by 1975. As the system evolves, the resolution is projected to improve to 60 ft 2 to 3 years later, and then to 30 ft in the 1980's. While this resolution is far short of what is normally considered "reconnaissance," it may well be considered "sensitive" by some of the potential ERS users. To encourage full international participation in the ERS system, and still provide protection for sovereign rights, consideration has been given to techniques which will allow only the country photographed to have access to the appropriate video information. The system has also been designed so that, either initially or as a particular country recognizes the advantages of mutually shared information, the received video may be retransmitted to the ground data-handling (GDH) center.

This section of the report discusses several techniques that have been considered to restrict the reception of ERS TV data to a particular site, the general characteristics of that site and of the link between the ERS spacecraft and the regional site, the operational discipline required in the system, and the effect of the projected resolution improvement on the system.

The conclusion of this study is that the use of regional sites (RS) is feasible but requires changes in the ERS spacecraft antenna and an additional spacecraft programmer to simplify the "hand-over" coordination between adjoining regional sites. Each regional site will be roughly the complexity of the projected ERS command-and-data-acquisition (CDA) station but will, in addition, include displays and data-interpretation and analysis facilities. Some advantage can be taken of the gain of the new spacecraft antenna to reduce the size of the antenna required at the regional site.

6.2 Techniques to Restrict Coverage to a Particular Site

Three techniques have been considered to restrict the TV coverage of a particular area to the authorized recipient of that information. They are: (1) limiting the transmitting beam of the spacecraft antenna and steering it to the proper regional site, (2) digitizing and encrypting the video with separate encryption keys for each user, and (3) organizing a "bonded" CDA staff, including representatives of all participating countries.

6.2.1 Limiting and Steering the Spacecraft Antenna Beam

Two separate techniques were considered to provide a narrow antenna beam directed only at the desired recipient: a motor-driven paraboloidal dish and a retrodirective array.

6.2.1.1 Motor-Driven Paraboloidal Reflector

There are two spacecraft-assigned frequency bands that have been considered for the regional-site problem: 2.2 GHz and 7.4 GHz. The half-cone angle of the spacecraft antenna beam has been set at 5°. From the ERS altitude of 499 nautical miles (nm), the locus of the half-power points of this antenna will describe a circle approximately 90 nm in diameter. The beam has been sized so that the received signal will be relatively insensitive to the spacecraft-attitude tolerances of ± 1° about all axes.

Assuming an aperture efficiency of 54 percent, the 2.2-GHz antenna will be 3 ft 2 in. in diameter and the 7.4-GHz antenna will be about 11 in. in diameter. Both antennas will provide a gain of 24.3 dB.

While the system could be designed to have the dish track a pilot tone generated at the RS, the system to derive the tracking information would be quite complex. The alternative is to provide a programmer on the spacecraft to drive the antenna to the proper X-Y coordinates to permit the dish to track the regional site open-loop as the spacecraft traverses the contact zone. With a 10° full beam angle and a permissible 1° spacecraft-attitude error, the maximum tracking error permitted the dish will be 1.7° in either axis, resulting in a maximum combined error of 3°. This will allow 1° to be allocated to all other errors, such as boresight error of the antenna, ephemeris errors and so on.

The motion of the antenna as it tracks and slews to a new RS will introduce additional attitude errors into the spacecraft, since momentum must be conserved in the entire system. The alternatives to this error are a very "stiff" system or momentum compensation for the antenna.

The major advantage of this form of antenna is that it is quite secure, since it can be programmed only at the CDA, and the programming "key" to the spacecraft can be protected in a variety of ways. Once properly programmed, the antenna cannot be captured by a different RS.

In spite of this advantage, it is apparent that there are severe design problems to be overcome in the vehicle dynamics and the antenna programmer. While these problems can be solved within the current state of the art, they do add complexity to the system, and the mechanical antenna appears relatively unattractive.

Rather than moving the entire dish, it is possible to steer the beam by moving only the feed and allowing the dish to remain stationary. An approach of this type is attractive, since it minimizes the impact of the antenna upon the design of the spacecraft. The required full cone angle of 120° is so great, however, that it precludes the use of a fixed dish with a movable feed.

6.2.1.2 Electrically Steered Retrodirective Array

As an alternative to a mechanically steered antenna, it is possible to design an antenna array that is steered by proper phasing of the signals driving each element of the array. In its application to the ERS spacecraft, the phasing information for the array will be derived from a pilot tone transmitted by the RS. The retrodirective array will use the information derived from the pilot tone to transmit the video back in the direction from which it received the pilot tone.

From ERS altitudes, the earth subtends a full cone angle of 123°. Thus, the 10° antenna beam must be able to be directed anywhere within a full cone angle of approximately 120° and must be directed as much as 60° away from the normal of a planar retrodirective array. Again, assuming an aperture efficiency of 54 percent, the gain of each element of the array will be 2. 8 dB to permit its half power points to form a full cone angle of 120°. The desired 10° beam corresponds to an array gain of 24. 3 dB. The difference in gain corresponds to an array of approximately 144 individual elements, which will form a 12 x 12 matrix. For the sort of gain being considered, each element will be spaced 1/2 wavelength from its neighbors in a given row. At 2. 2 GHz this spacing is about 6. 9 cm, and at 7. 4 GHz it is 2 cm. Thus, the 2. 2-GHz array is 32. 5 in. square, while the 7. 4-GHz array is 9. 5 in. square.

With an array of this type, the beam tends to distort as it goes far off axis, and, in this particular case, the gain may be down by as much as 3 dB when the beam is 60° off axis; the corresponding beam width will then be 14°.

To overcome the loss at high deflection angles, it is possible to divide the array into four subarrays, each subarray inclined 60° to the earth's radial (30° to the plane of the earth-facing surface of the spacecraft) in the form of a frustum of a pyramid, with the apex pointing toward the earth. In this way, the maximum scan angle required of each subarray is reduced to 60° full cone angle, and the gain of each element may be raised to 8. 8 dB. Only 35 elements per subarray are then required to attain the desired 10° beam (24. 3 dB gain).

If the subarrays are rectangular, the antennas will be somewhat larger than the planar array, with the 2. 2-GHz antenna becoming 44. 5 x 44. 5 x 8. 25 in., and the 7. 4-GHz antenna becoming 13 x 13 x 2. 5 in. The reason for the larger volume is that the area exposed when the apex was removed from the frustum cannot be used by the antenna, since it is in the wrong plane. In the actual design of the antenna, consideration should be given to the use of triangular matrices for the subarrays, since this will permit design of an antenna that occupies less earth-looking area than the planar array.

As noted, use of the retrodirective array requires that the RS transmit a pilot tone to acquire the array. At the spacecraft, the coherent wavefront of the pilot tone is virtually planar, since the minimum distance between the transmitter and the spacecraft is 499 nautical miles. Thus, the system is independent of small tracking errors by the RS and of the attitude errors of the spacecraft. In the former case, the curvature of the wavefront over the distances considered is so small that small displacements over the surface of the wavefront will not sensibly change the phase relationships over the surface of the array. In the latter case, attitude changes in the spacecraft result in corresponding changes in the phase of the received wavefront and are thus automatically compensated by the system.

Since the retrodirective array is electrically steered, it can be slewed from one RS to another very quickly, and with no reaction upon the spacecraft. To use the system efficiently, however, it is necessary to coordinate the entire ground environment. This can best be accomplished by using the spacecraft itself to perform the coordination. Before it acquires the video signal, an RS must be tracking the spacecraft beacon. Since the beacon antenna pattern is onmidirectional, all RS's within range will be receiving this signal simultaneously. Thus, a simple timed programmer on board the spacecraft may be used to transmit a coded signal via the beacon to turn off the pilot tone of one RS automatically and to turn on the pilot tone of the second RS. To avoid conflicts, each site will have a unique pair of on-off codes. Note that, unlike the computer or extensive memory required to control the mechanical antenna, the control programmer for the retrodirective array need store at most two time-tags to be transmitted in accordance with a spacecraft clock for each RS. Since the programmer can be loaded at each contact with the CDA, only several orbits' worth of storage of 20 to 40 words per orbit are required.

The major disadvantage of the approach just described is that the antenna could be captured by an intruding site capable of transmitting a more powerful pilot tone. Such intrusion would deny access to the data to the proper recipient. An intrusion of this type is, of course, easily recognized, and appropriate measures can be taken. In the worst case, all access to the spacecraft could be denied within range of the intruding station, thus negating a large investment on the part of the intruder.

6.2.2 Encrypting the Video

As opposed to limiting access to the spacecraft video, it is possible to transmit an encrypted signal to the entire receiving area and change encryption keys, so that only the intended RS can decrypt the video. Unique keys can be used by each site, and the spacecraft lock can be changed at the appropriate time by a programmer similar to the one described for the retrodirective array. Such a system can be made almost as secure as desired, and would satisfy the problem of limiting access to the video.

The only satisfactory encryption techniques require that the data be in digital form, and it is thus necessary to convert the analog signal from the cameras. Since the video baseband is 4 MHz, it is necessary to sample the video at an 8 million sample-per-second rate, which barely satisfies the Nyquist sampling criterion. In actual practice, the sampling must be at a somewhat greater rate, to allow the signal spectrum to be separated from the sampling spectrum with physically realizable filters and to reduce the residue sampling energy left in the signal spectrum to an acceptably low value.

To preserve the 40-dB dynamic range of the video information, it is necessary to convert each sample to at least a seven-bit signal. Thus, the 4-MHz analog signal becomes a digital signal of 56 million bits per second. Assuming the digital information is transmitted in non-return-to-zero form, with a clock signal in the spectral null at 27.5 MHz, the digital system requires a minimum of 7.5 MHz more bandwidth than the analog system and sacrifices the 12.3-dB FM improvement in signal-to-noise ratio obtained by the use of a modulation index of 1.5 in the FM system. Depending upon the bit-error-rate criterion established for the digital system, some of the 12.3 dB may be recovered, but, all other things being equal, the digital system will always operate at a signal-to-noise disadvantage in this application.

Thus, considering the state-of-the-art difficulties in designing an accurate, unattended seven-bit converter to operate at an 8 million sample-per-second rate, the need to obtain an extremely low bit-error rate on the line synchronizing signal for the TV system, and the loss in signal-to-noise ratio in the video itself, encryption techniques appear less attractive than a retro-directive array.

6.2.3 "Bonded" Ground Data-Handling Center

While not, strictly speaking, a technical solution to the problem, consideration has been given to the configuration of a GDH center designed to satisfy the security needs of the various using nations. Such a system does not require an RS and can operate completely at the GDH center itself.

Since there is no spacecraft data storage in the system, the system operates strictly in real time, and the spacecraft ephemerides provide a positive indication of the landmass being televised at any point in time. Thus the GDH center can be designed to distribute the video to one of a series of private display-recording stations strictly as a function of the spacecraft ephemeris. The receiver and distribution lines can be shielded as well as desired, and all information can be stored as privately and securely as a member-user desires. Data reduction and interpretation can be accomplished either at the GDH center or in the homeland of the member-user, with the raw image information being transmitted by whatever means a particular nation chooses.

The station operation-and-maintenance cadre would, of course, be drawn from all member nations. Ground-truth data and other collateral information can be shared to any degree that individual members desire.

The cost of admission and upkeep to a bonded GDH center can be expected to be considerably less than the cost required to build and maintain an RS. Thus, recognizing the value of ERS information, there may be compelling economic reasons for international cooperation.

6.2.4 Regional Cooperation

Since high-quality video may be obtained so long as the spacecraft is more than 5^{o} above the horizon, the unobstructed ground coverage will extend to a distance of more than 1450 nautical miles from the RS. Assuming unobstructed horizons, an area of 6.7×10^{6} square miles will be accessible to each RS. This area clearly exceeds the land area of most nations that might be interested in participating in the system. Thus, in smaller nations, access to the spacecraft would be limited by the spacecraft programmer, and the

RS would be used to an extent significantly less than its inherent capability. If two nearby nations wished to participate in the system, each would have to own and maintain an RS, even though one station were technically able to service both nations. Thus, the admission-and-maintenance cost to each nation would be twice what it would be were the two nations able to operate a single RS cooperatively. Even on a small scale, then, neglecting the greater advantages of a bonded GDH, the economic benefits of cooperation are apparent. Since the benefits of the system are well defined, it is clear that the existence of the ERS system can, and should, encourage international cooperation.

6.3 The Regional Site

As noted, when the spacecraft is 5° above the horizon, as seen from a particular RS, the subpoint of the spacecraft is approximately 24.5 great-circle degrees (1450 nautical miles) from the RS. Depending upon the local topography, the range in some directions may be restricted by buildings or hills, requiring the spacecraft to rise above these obstructions and reducing the coverage in those directions. Depending upon the nature of the antenna-drive mechanism, there may also be some restrictions introduced by the gimbals, reducing the coverage still further.

In spite of these restrictions, the coverage obtained by a single RS is impressively large, greatly exceeding the land area of all but a few of the larger nations of the world. For example, an RS at Rosman, N. C., will be able to contact the spacecraft when the spacecraft subpoint is anywhere over the 48 contiguous states, except for the far western tier of states, California, Oregon, Washington, and most of Nevada. Also included will be a portion of Canada, as far east as the Gaspe Peninsula and as far north as Hudson Bay. The coverage from Rosman will include almost all of Mexico except for Baja California. It will include Cuba, Hispaniola, and Puerto Rico.

The spacecraft is to operate in a circular orbit of 499-nm altitude. The inclination of the orbit plane is to be 98.8°, to provide 0.985° per day nodal regression and assure sun-synchronous operation of the spacecraft. The nodal separation of successive orbits is about 25.7°, and thus, even an RS on the equator will, for the most part, be able to contact the spacecraft on two successive orbits each day. The selected orbit is such that the node of the same orbit number on successive days progresses westward at a rate to provide 10 percent side-to-side picture overlap at the equator. The entire cycle is repeated every 18 days, and thus, coverage of every area is repeated at least that often. As an RS is moved north or south of the equator, the side-to-side overlap on successive days increases.

The maximum duration of an orbital pass is about 14 minutes when the RS lies on the orbital subtrack. During that period, at the picture-taking interval of 25 seconds, the RS will receive perhaps 30 to 35 pictures in each of the three spectral regions. Thus, an RS on the equator will receive more than 100 pictures every day, and those located elsewhere will obtain considerably more. These numbers, of course, are the maximum that might be obtained at a given site and ignore the geopolitical factors that will reduce the number of pictures actually obtained.

6.4 RS/Spacecraft RF Link Considerations

6.4.1 General Characteristics of the Video Link

As mentioned earlier, the two frequencies being considered are 2.2 GHz and 7.4 GHz. The video baseband of the cameras is 4 MHz, and a frequency modulation system will be used. A receiver with a 20-MHz i.f. bandwidth is being designed for the STADAN stations. Using this full bandwidth and the 4-MHz baseband, we may apply Carson's rule to determine the permissible deviation. Carson's rule states:

$$B_{i.f.} = 2(f_m + \Delta f_{rf})$$

where: $B_{i.f.}$ = i.f. bandwidth
f_m = video baseband
Δf_{rf} = deviation

This empirical rule determines the bandwidth necessary to transmit an FM signal with less than approximately 1 percent harmonic distortion. Applying this rule yields a peak rf deviation of 6 MHz. Knowing the FM deviation, the signal-to-noise ratio (S/N) may be computed from the carrier-to-noise ratio (C/N) by the expression:

$$S/N = C/N \, \frac{3}{2} \, \frac{(\Delta f_{rf})^2 \, B_{i.f.}}{(f_m)^3}$$

The "detected" S/N in the link calculation is the ratio of rms-signal to rms-noise. This can be converted to a peak-to-peak signal to rms-noise ratio by the addition of 9 dB. Since 25 percent of the total video signal is used for the sync pedestal to assure good line synchronization, the net black-to-white video to rms-noise ratio for both links is 41.8 dB.

The fact that the spacecraft transmitting beam was narrowed to restrict its coverage provides a bonus of more than 20-dB gain in the spacecraft antenna. This gain has been used in two ways. The antenna size at the RS has been set at 6.5 ft as opposed to 85-ft dish required at the CDA station with only 3 dB of gain in the spacecraft antenna. The change in antenna reduces cost of the RS by approximately $1 million. The second advantage taken of the spacecraft antenna gain was to eliminate the requirement to cool the parametric amplifier in the RS receiver. Thus, there is no need to include a cryostat in the RS. Thus, adding gain to the spacecraft antenna provides a significant reduction in the cost of the RS and also simplifies the maintenance of the station.

The calculation for the video link is given in Table 7.6.1.

TABLE 7.6.1

VIDEO LINK

	FREQUENCY	
	2.2 GHz	7.4 GHz
Transmitter power output (10W)	+10 dBW	+10 dBW
Line & coupling losses including radio frequency band pass filters	-1.5 dB	-1.5 dB
Spacecraft antenna gain (at 60°) with beam spreading	+21.3 dB	+21.3 dB
Polarization loss	-0.5 dB	-0.5 dB
Propagation loss (499 nm altitude, 5° elevation)	-167.8 dB	-178.3 dB
Receiver noise temperature (uncooled parametric amplifier)	200° K	200° K
Sky noise temperature (5° elevation)	50° K	50° K
Side lobe noise contribution	30° K	
Total noise power (bandwidth = 20 MHz)	-130.9 dBW	-131.4 dBW
Isotropic power at input to antenna	-138.5 dBW	-149.0 dBW
Carrier-to-noise ratio required	23.0 dB	23.0 dB
Antenna gain needed	30.6 dB	40.6 dB
Antenna diameter, feet	6.5	6.1
Receiver threshold	12 dB	12 dB
Margin	11 dB	11 dB
FM improvement (Modulation index = 1.5)	12.3 dB	12.3 dB
Detected S/N (rms/rms)	35.3 dB	35.3 dB
Peak video/rms noise (with 25% sync. tip)	41.8 dB	41.8 dB

6.4.2 Pilot-Tone Link

To acquire the video information it is necessary that the RS transmit a pilot tone to the spacecraft. Table 7.6.2 is a typical link calculation

TABLE 7.6.2

PILOT-TONE LINK

Spacecraft-antenna gain	+2.8 dB
Line losses	-1.5 dB
Propagation loss (2.75 GHz) (205:256 transmit/receive ratio)	-169.7 dB
Receiver-noise temperature (assuming transistor preamplifier)	1000° K
Earth temperature	300° K
Total noise power (bandwidth = 1 kHz) (doppler tracker)	-166.3 dBW
Ground antenna gain (using 6.5-ft dish)	+32.5 dB
Required transmitter power	-30.4 dBW

showing that the required transmitter power is in the neighborhood of 1 milliwatt. This calculation has been included only to demonstrate that the transmitter required is quite small and can be offset in frequency enough to share the dish with the video receiver.

The noise temperature for transistor preamplifiers has been included in this calculation, both to maintain as low as possible a cost for the retrodirective array, and to maintain as pessimistic as possible a noise figure for the system. In spite of these assumptions, only a very small transmitter is required.

The noise bandwidth of the retrodirective-array receivers has been assumed to be 1 kHz, although much remains to be done to optimize this figure. To minimize the system data loss, the retrodirective array must acquire the pilot tone from the RS as quickly as possible, and it must do this in spite of an RS-frequency uncertainty of perhaps 150 kHz and a doppler-induced frequency shift of ± 60 kHz for a spacecraft at the ERS altitude. To maintain a small noise bandwidth, some form of frequency-acquisition-and-tracking system is necessary. Since no information is being transmitted on the pilot tone, however, there need be no allowance for bandwidth beyond the system tolerances. Thus, the requirements for retrodirective-array acquisition appear relatively modest. For example, if we consider eliminating the doppler tracker completely, and allow 150 kHz for drift in the array-control system, the total noise bandwidth is opened to 360 kHz. The equivalent noise power at the input to the receivers of the retrodirective array then becomes -140.8 dBW rather than the -166.3 dBW shown in Table 7.6.2. Even with such a system, a 1-W pilot-tone transmitter would yield a system margin of 4.9 dB.

Since the pilot-tone transmitter shares a dish with the video receiver, its power should be as low as possible to reduce distortions. It is clearly necessary to optimize the systems tradeoffs in this area, but there appear to be no real problems in the pilot-tone link.

6.4.3 Beacon Link

The last link to be considered is the beacon link from the spacecraft to the RS. This link is at 148 MHz and is used for initial acquisition and tracking of the spacecraft and, since the transmitting antenna is omni-directional, for automatically transferring the video signal from one RS to another. The RS is thus required to derive a tracking signal from the beacon and to detect and act upon a small amount of information in a coded signal, which modulates the beacon at an appropriate time.

As noted in Table 7.6.3, the 0.25-W beacon transmitter is adequate to provide a 200-Hz bandwidth for the modulation. Since the data rate need be only tens of bits per second, this bandwidth is more than adequate and the 6.5-ft dish is satisfactory to receive the beacon link.

The one problem encountered in this area is that the beam width of the 6.5-ft dish at 148 MHz is quite broad, exceeding 100°. Thus, it may be difficult to track the spacecraft precisely enough to acquire the relatively narrow beam of the video transmission. It may be necessary to aid the tracking system by driving the dish with a set of azimuth-elevation coordinates

TABLE 7.6.3

BEACON LINK

Transmitter power (0.25W)	24 dBM
Spacecraft-antenna gain	-11.5 dB
Path loss (148 MHz)	-144.2 dB
Polarization loss	-3.0 dB
Ground-antenna gain (6.5-ft dish at 148 MHz)	+6.5 dB
Intermediate-frequency noise density in 1 Hz ($T = 1000^{\circ}$ K)	-168.4 dBM
Bandwidth ratio (200 Hz)	+23 dB
Carrier-to-noise ratio	17.2 dB
FM threshold	12.0 dB
Margin	5.2 dB

derived from the spacecraft ephemeris. Once the video is acquired, that signal may be used for tracking.

6.5 Operational Routing Required at Regional Site

In a system as complex as the one being considered, with a large number of ground stations requiring sequential service, cooperative operation of the total ground environment is essential to obtaining good system performance. It is necessary to establish a sound set of station-operating procedures and to train the station operators in following these procedures in detail. By using the spacecraft beacon to perform station hand-over, the environment has to a small degree been automated. Successful system performance will still depend largely on the RS operators performing in accordance with procedures. Very generally, the operating procedures will be as outlined below:

1. Based upon the published ephemerides for the ERS spacecraft, the RS antenna must be slewed to the proper azimuth to await the spacecraft rising over the horizon.

2. Based upon both the published ephemerides and the beacon signal received from the spacecraft, the tracking drive of the antenna pedestal can be engaged.

3. As soon as the spacecraft video coverage crosses into the domain of the particular RS in question, the spacecraft will transmit a unique turn-on signal to the RS.

4. When it decodes its own turn-on signal, the RS will automatically begin to transmit its own pilot tone.

5. When the spacecraft retrodirectional array locks on to the pilot tone, it will direct its video transmission at the RS transmitting the pilot tone.

6. As the spacecraft traverses the domain of the particular RS, the RS will continue to transmit its pilot tone, and the RS antenna and the retrodirective array will continue to track each other. The particular RS will continue to be the sole recipient of the video.

7. As the spacecraft crosses the far boundary of the RS's domain, the spacecraft transmits, via the beacon, a unique turn-off signal to the RS and transmits a unique turn-on signal to the next RS in turn, and the process is repeated.

6.6 Information Sharing

In the RS system as described, there is nothing either to require or to preclude information sharing between RS's or between an RS and the GDH center. As noted earlier, there is an economic incentive to early planning for information sharing, since such sharing may well include sharing of the RS itself.

The fact that the video information is not required at the GDH center in real time immensely simplifies the problem of sharing between an RS and the center. At any time an RS decides to participate in the information pool, it need only make arrangements to ship hard copy of the data it receives by the best available method, probably local mail service. Thus, the cost increment to participate in the GDH center is trivial.

6.7 System Growth with Improved Resolution

As noted in Section 6.1, the system resolution is expected to improve from 100 ft to 60 ft by 1977-78, and to 30 ft in the 1980's. In addition, the sensing system will change from three multispectral return-beam vidicons (RBV's) to a seven-channel scanning radiometer. Although the radiometer has yet to be designed, the bandwidth requirements are so large that the sensing system should include techniques to reduce the dead time of a normal radiometer (the time the sensor is scanning off the earth and is not producing a useful signal). To examine the communications link for the growth versions of the ERS system, we will assume that the system dead time will be about 10 percent of the total scan period. During the dead time, the system will transmit all required calibration and synchronizing signals.

Since the radiometer channels will probably be read out in parallel, rather than serially as were the three RBV's, the baseband spectrum for the seven radiometer channels will be assumed to be frequency multiplexed for transmission to the RS. An allowance of 10 percent of the total spectrum will be made for guard bands in the frequency multiplexed system. With these assumptions, a total baseband of 29 MHz is required for the 60-ft resolution, and 115 MHz is required for 30-ft resolution.

Comparing these basebands with the original requirement of 4 MHz, the system will lose 8.6 dB in carrier-to-noise ratio (and the same amount in signal-to-noise ratio) if only the receiver at the RS is changed to accommodate the new baseband of 29 MHz. The system will lose an additional 6 dB when the resolution is changed to 30 ft. While the system would still operate in the 1977-78 time scale, its dynamic range would be degraded. In the 1980's, the system would be below the receiver threshold.

The required system margin can be recovered in a variety of ways. For example, for the 60-ft resolution, both the spacecraft antenna and the modulation index can be changed. If the spacecraft-antenna beam were reduced from 10° to 5°, 6 dB more gain would be added to the system. The number of elements in the array would increase from 144 to 576, and its linear dimensions would double. For X-band, however, the array would still only be 19 in. square.

As noted earlier, the retrodirective array is self-compensating for spacecraft-attitude errors, so system tolerances are not tightened by reducing the beamwidth. The additional 2.6 dB required can readily be picked up by increasing the deviation of the transmitted signal.

The required modulation index can be determined by the equation:

$$S/N \text{ improvement } (I) = 3m^2 (m+1)$$

To find the new modulation index (m) it is first necessary to determine the total S/N improvement required in the 60-ft system. This is the sum of the improvement in the original system (12.3 dB), the improvement still required in the 60-ft system (2.6 dB), and the improvement required to compensate for the loss in C/N resulting from increasing the bandwidth (1 dB). The total required S/N improvement of 15 dB sets the new modulation index at 1.9. Since the baseband is 29 MHz, and the rf deviation required is the product of the baseband and the modulation index, the new deviation is 55 MHz. Again, applying Carson's rule, the required rf bandwidth is 168 MHz.

Referring to Table 7.6.1, we find that the 60-ft system gained 6 dB at the spacecraft antenna and lost 9.3 dB in noise power (the ratio of the new bandwidth, 168 MHz, to the old bandwidth, 20 MHz). Thus, the 60-ft system has lost 3.3 dB in C/N. The margin for the 60-ft system is still 7.7 dB, however, and system operation will be unimpaired.

When the resolution is improved to 30 ft, an additional 6 dB must be found. The power of the spacecraft transmitter might be increased, but, since the duty cycle of the transmitter is 100 percent during the daylight portion of the orbit, raising its power by 6 dB (40-W transmitter) will place a severe burden on the spacecraft.

Perhaps the most straightforward way of recovering the carrier-to-noise ratio is simply to double the diameter of the RS antenna, from 6.5 to 13 ft.

Maintaining the modulation index at 1.9, the 30-ft system will require 666 MHz of RF bandwidth, and the increase in noise bandwidth will just be compensated by the increase in RS antenna gain. The other parameters in Table 7.6.1 will be essentially unchanged.

Obviously, this brief discussion of system growth has not considered the severe problems of spectral allocations or rf equipment design. The purpose of this section was only to show the effect of the projected system growth.

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7.0 DIRECT/DELAYED ERS SYSTEM READOUT FOR GLOBAL LAND COVERAGE

7.1 Summary

The ERS spacecraft, carrying a video tape recorder, as originally conceived, has been investigated to determine its ability to obtain complete coverage of the earth's landmasses during the 18-day coverage cycle of the system. The ground environment assumed for this system consists of three command-and-data-acquisition (CDA) sites: Rosman, N. C.; Fairbanks, Alaska; and Mojave, Calif.

By eliminating the redundancy in system coverage and by using Fairbanks and Mojave sequentially on some of the same orbits, it is possible, with two spacecraft, to obtain global landmass coverage at 100-ft resolution every 18 days.

A number of simplifying assumptions have been made in this analysis. However, where possible, the assumptions have been pessimistic. The results show sufficient margin that the system is believed quite feasible. Indeed, the results show that, of the 48.9 million square nautical miles ($\overline{nm}^2$) which must be stored and transmitted by the system in 18 days, a single spacecraft could transmit 48.0 million $\overline{nm}^2$. Thus, a system with two spacecraft should also be capable of televising a portion of the earth's wet surface in addition to the landmasses.

7.2 Redundancy of Coverage

The ERS return-beam vidicon (RBV) camera system is designed to provide TV coverage in 100 nautical-mile (nm) swaths. The orbital parameters have been chosen so that there is, at the equator, approximately 10 percent side-to-side overlap between pictures taken on the same orbit number on successive days. In approximately 18 days, the coverage is complete, and the cycle is repeated. Obviously a system which provides complete coverage at the equator, provides redundant coverage north and south of the equator. At 35° N or S latitude, the redundancy is complete, and each point would be imaged twice in 18 days. At 60°N or S latitude, the redundancy is doubled, and each point closer than 60° to the poles would be imaged four times during the 18 days.

To make effective use of the capacity of the recorder, it is necessary to program the system to eliminate this redundancy. Since the spacecraft does not pass over the same area except at 18-day intervals, however, coverage must be stored (a) on every orbit over land between 35° N and 35° S latitude, (b) on one of each pair of orbits on successive days (adjacent swaths) between latitudes 35° and 60°, and (c) on one out of every four adjacent swaths every

4 days N or S of 60°. In addition, most of the daylight contacts at both Rosman and Mojave must be used for direct readout of local data, precluding the playback of stored information. Proper and efficient programming of the system thus presents an interesting topological problem, which has not been undertaken at this time.

The tape recorder planned for the system will record in one direction and play back its information in the reverse direction. It thus operates on a last-in-first-out basis. Because system programming will, at times, require the spacecraft to collect more information than can be played back in the next few orbits, some data may be stored for perhaps 6 to 12 hours before being collected by a CDA. Since the data are not perishable, this prolonged storage presents no problems.

The maximum length of tape required on the recorder is a function of the manner in which the system is programmed, and thus has not been addressed at this time.

7.3 Ground-Station-Contact Time

Figure 7.7.1 is an idealized plot of CDA-contact time with the spacecraft, as a function of the ascending node of the spacecraft orbit. The plot is idealized, since it assumes the spacecraft is visible at each CDA so long as it is more than 5° above the horizon.

Several facts can be deduced from this plot. The minimum useful contact time for the system is assumed to be 5 minutes. It is thus apparent that, except for a small band, the orbits contacted by Mojave are the same orbits contacted by either Rosman or Alaska. Mojave does, however, fulfil two functions. For orbits with ascending nodes (AN) between 110° W and 140° W, it extends the contact time with the spacecraft beyond that which would be obtained at either Alaska or Rosman. In addition, many orbits with the same AN are contacted sequentially by Mojave and then by Alaska, so that the total contact time is the sum of both. It is on these passes that the CDA station must operate cooperatively to maximize the data transfer.

Both Rosman and Mojave are at approximately 35° N latitude, while Alaska is at 65° N latitude. Thus, only about 75 percent of the daylight passes at either Rosman or Mojave are needed to transmit real-time data during the 18-day period. The remaining 25 percent of the passes may be used for transmitting stored data. In addition, all descending passes over these two stations may be used for transmitting stored data, since the local terrain will be in darkness. At Alaska, only one daylight pass in four is needed for real-time coverage, and the remaining 75 percent of the daylight passes may be used for stored data. The coverage at Alaska is, of course, seasonal, and full coverage of the local terrain cannot be obtained near the time of the winter solstice. The contact curve for Alaska shows both ascending and descending passes, while the curves of Rosman and Mojave show only ascending passes. Thus, the total contact time for the latter two CDA's is twice that shown on the curves. At Rosman and Mojave, 5/8 of the total contact time may be used to transmit stored data; at Alaska, 7/8 of the total contact time may be so used.

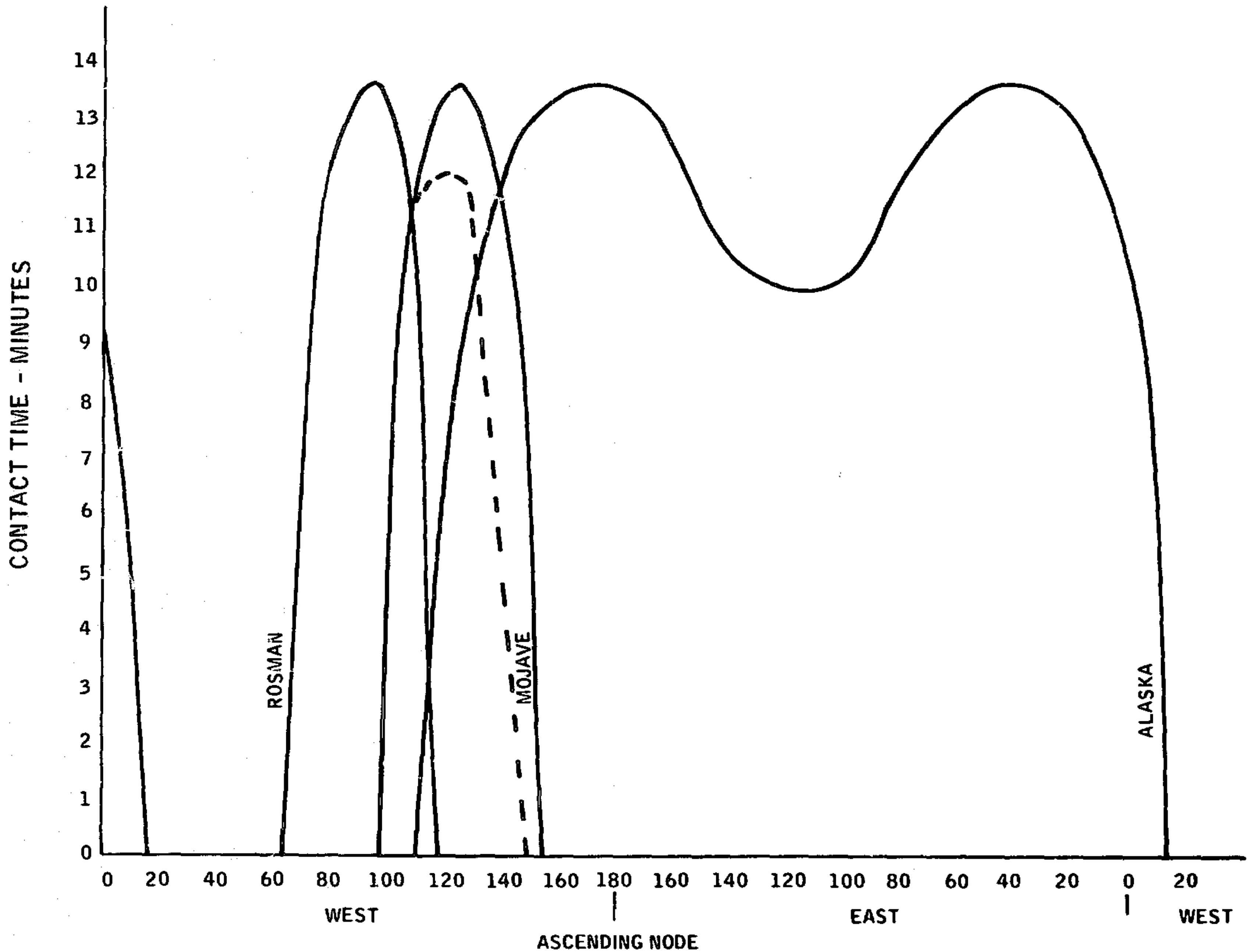

FIGURE 7.7.1 Contact time versus ascending node for Rosman and Mojave, both nodes for Alaska, all idealized.

Since the spacecraft completes almost exactly 14 orbits per day, it will complete 252 orbits in the 18-day period. Of this total, eliminating the overlap between stations, Rosman will have useful contact with 58 orbits, Mojave with 53 orbits, and Alaska with 168 orbits. The Rosman site will contact the spacecraft when the AN of the orbit is east of 110° W longitude, and the Mojave site when the AN is west of that point. Orbits west of about 115° W longitude AN will be contacted sequentially by Mojave and Alaska. Useful data will be obtained at both sites, but the useful contact at Mojave will be restricted to that shown below the dashed curve in Figure 7.7.1.

As noted earlier, simply considering redundancy, most of the contact at each station is available to read out stored data. Actually the time for stored data is even greater than has been shown, since most of the direct contact at each site is over water rather than land. To maintain conservatism in the calculations, no allowance will be made for this fact. The assumption is particularly conservative with respect to Mojave, which is required to obtain direct land coverage only of that portion of the United States and Mexico west of about 105° W. From the contact curves, the average contact at Rosman will be about 11.5 minutes, that at Mojave about 9.5 minutes, and that at Alaska about 10.5 minutes.

7.4 Coverage

Since the period of the orbit is about 6200 seconds, the velocity of the spacecraft subpoint over the earth will be about 3.45 nautical miles per second. Each swath is 100 nm wide. Thus, the average playback contact at Rosman will transmit data covering $2.38 \times 10^5\ \overline{nm}^2$, that at Mojave, an area covering $1.97 \times 10^5\ \overline{nm}^2$, and that at Alaska $2.17 \times 10^5\ \overline{nm}^2$. At Rosman, during the 18-day period, there will be 58 contacts with the spacecraft of greater than 5 minutes duration. Of these contacts, 62.5 percent may be used exclusively for the transmission of stored data. Thus, Rosman will obtain a total coverage of 8.6 million $\overline{nm}^2$ of stored ground coverage. In the same manner, Mojave will obtain 6.5 million $\overline{nm}^2$, and Alaska will obtain 32.9 million $\overline{nm}^2$, yielding a total of 48 million $\overline{nm}^2$ of stored ground coverage obtained by the three CDA's from the one spacecraft.

The total land area of the earth is roughly 36.8 million $\overline{nm}^2$. Of that area, the real-time coverage obtained by the spacecraft of the 48 contiguous states of the United States, of Alaska, Canada, and Mexico is 4.2 million $\overline{nm}^2$. This leaves 32.6 million $\overline{nm}^2$ to be obtained via the data-storage system. Even though the system has been designed to minimize redundant coverage, the convergence of adjacent swaths creates 50 percent redundancy before one of the swaths can be eliminated. To obtain the required 32.6 million $\overline{nm}^2$, it is necessary to transmit a total of 48.9 million $\overline{nm}^2$, virtually the same as the projected 18-day capability of the system. Clearly the answer to the question of performing the projected task with a single spacecraft lies within the many simplifying approximations made and must await a more rigorous analysis. The projected ERS system, however, does not have a single spacecraft. It has three spacecraft, two of which are in noon orbits with their AN's separated by about 52 minutes. The two noon spacecraft will double the projected coverage obtained with a single spacecraft and, because they are half an orbit apart, will not introduce scheduling problems at the CDA's. There is thus little question that the earth's total land surface can be imaged every 18 days at 100-ft resolution by employing these two spacecraft with video recorders, and CDA's at Rosman, Mojave, and Alaska.

7.5 Video Tape Recorder Product Improvement

The video tape recorder envisioned for direct-delayed readout in the ERS is an adaptation of a recorder developed on the Apollo program. That recorder now has tape capacity for 1/2-hour continuous recording at 4-MHz video bandwidth. A version modified expressly for the ERS mission has been under test to determine life and wear characteristics. The principal problems encountered in tape recorders are associated with the head-tape interface, materials and their long-term behavior in the recorder-case atmosphere, bearing materials and design, lubricants, and drive designs. A product-development program concentrated on these areas could be expected to improve understanding of the properties of the materials involved, to generate design procedures based on this heightened understanding and on the newly established data derived in the program, to increase the capacity of the recorder in storage and in bandwidth, and to produce a product-improved design of longer life and greater reliability.

The ERS model recorder under test has been subjected to a continuous wear-and-performance test of 2000 passes, end-to-end. At four passes per hour, this is a 500-hour continuous-wear test. The tape, coated for recording on both sides, was bearing against the same head for the full duration of the test. The recorder was run at 3/2 ERS-system speed, so that wear was accelerated by a factor of 2.25 over that expected at ERS-system speed. At 500 hours, the recorder was still meeting its performance specifications, but the heads on the bearing side of the tape were showing signs of gap erosion.

In view of the difficulties experienced in the development of new tape recorders, it would be premature to draw conclusions of great comfort from these results. The promise of reliability and increased storage capacity is clearly there, however. It would seem prudent to support product development now, since the relative increment to the ERS mission cost is low and the potential for cost-effectiveness is high. A large sum to plan for this technology is $5 million; quite possibly the cost would be less.

But, for growth beyond the initial ERS capability, it is not clear that magnetic recording is the answer. A planned program in data-storage technology, embracing magnetic, dielectric, and electro-optical storage techniques, is recommended to cope with the growth in data implied by the assumed increases in ERS ground resolution. The Panel considers that $10 to $15 million over a 5-year period is appropriate. Concurrently, a comparable sum needs to be planned to support the highly linear, wide-band signal processing, transmission, and reception technologies that will be needed at microwave frequencies to cope with the increased bandwidths accompanying increases in resolution.

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8.0 COST ANALYSIS

Three distinct systems are considered in this section. First to be considered is a system of data collection and relay from low-orbiting satellites dominated by the earth-resources remote-sensing data requirements. The data-collection and relay function of this system can be performed in at least four different ways. Second, consideration is given to the vacuum-cleaner-satellite system (VCSS), employing a form of data-collecting relay satellite (DCRS), which collects data from sensing platforms located on or near the earth. Finally, a system is hypothecated and priced which performs the same function as the VCSS without the aid of satellites, using a combination of microwave, land lines, aircraft, horseback and on-foot global data collection and relay.

8.1 Hypothetical Systems

8.1.1 The Earth-Resources Satellite (ERS)

8.1.1.1 Configuration I

This consists of three sun-synchronous, remote-sensing satellites in near-polar orbit, spaced at appropriate intervals; two geosynchronous, relay satellites; and three ground stations. The relay satellites must transmit a wide band of frequencies and are discussed earlier under the wide-band DCRS. Full coverage of the earth (land and ocean) is provided on a real-time basis at one to three central points. A 4-year operational time frame is hypothesized. Total cost of this system for 4 years is $310 million.

8.1.1.2 Configuration II

This consists of three sun-synchronous, remote-sensing satellites in near-polar orbit, spaced at appropriate intervals, and 120 ground stations. Data are transmitted directly to the ground stations without relay by a DCRS. Except for the China and U. S. S. R. landmass, complete real-time coverage of the earth (land and ocean) is provided, on a regional basis only, at each of the 120 ground stations. Again, a 4-year operational time frame is used. Total cost of this system for 4 years is $1132 million.

8.1.1.3 Configuration III

This is the same as Configuration II above, except that it provides only 36 ground stations. This system provides coverage of the earth's land and near-landmass (excepting China and U. S. S. R.) and limited ocean coverage,* on a regional basis only, at each of the 36 separate ground stations. Over a 4-year operational time frame, the total cost of this system is $237 million.

8.1.1.4 Configuration IV

This system consists of three sun-synchronous, remote-sensing, near-polar orbiters, spaced at appropriate intervals, and three ground stations. Full land and near-land, and limited ocean, coverage is provided on an individual direct/delayed readout basis at each of the three stations. Total cost for a 4-year operational time frame is $193 million.

8.1.1.5 Summary

In summary, the following tabulation reflects several relevant considerations.

Configuration	4-Yr Cost ($ million)	Coverage	Readout
I	310	Full land and ocean	3 central points
II	1132	Full land and ocean, except China and U.S.S.R.	120 regional points
III	237	Land, near-land, and limited-ocean, except China and U.S.S.R.*	36 regional points
IV	193	Land, near-land, and limited-ocean*	3 central points (direct/delayed)

Unless full ocean coverage throughout the world warrants the differential cost, Configuration IV is the most cost-effective. Configuration IV also has the substantial advantage over Configuration III of collecting data at three rather than 36 separate locations, since data collected at the latter complex would probably be transported at least once weekly to a central point for processing and dissemination. On the other hand, sovereign nations or multinational groups desiring control over acquisition and dissemination of information concerning their particular areas obtain it directly with Configuration III.

The Panel selected ERS Configuration IV as optimum at this time.

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*"Near-land" refers to that water coverage given automatically as land coverage near water is obtained. "Limited-ocean" denotes a category of coverage in which otherwise unused satellite capacity is programmed to cover a part of the open ocean.

8.1.2 Vacuum-Cleaner-Satellite System (VCSS)

This system provides for the relay of data from sensing devices (such as hydrologic river gauges, ocean buoys, and meteorologic balloons) located on or near the earth. Although it is designed to handle approximately 26,000 data-collecting transmitting platforms, it requires a relatively narrow band of frequencies, compared to the DCRS in Configuration I. Only one configuration was considered. It consists of four geosynchronous spacecraft, in orbit simultaneously, each having an expected life of 5 years, and two command-control data-acquisition stations.

8.1.3 Conventional Equivalent of the Vacuum-Cleaner-Satellite System (VCSS)

Some of the data that the VCSS is designed to collect are currently being collected by other means. A quick survey of some of these means is made in Section 8.3.

8.2 System Costs

8.2.1 General Considerations

Cost estimates were based on the following considerations:

1. Primary objectives of the cost-effectiveness methodology were to identify the major cost components of the system hypothesized by each technical panel and to maintain consistent coverage and treatment of these cost components among the several technical panels. Hopefully, the pursuit of this objective served to make more comparable the system costs presented for each panel.

2. Costs were estimated only to the detail deemed necessary to permit program comparisons and evaluations on a consistent basis.

3. This costing process reflects neither the extensive nor the intensive tradeoff analyses that might be considered for each system. Furthermore, costs (and quantifiable benefits) were not discounted, nor was the impact of inflation specifically addressed, in view of the approximate nature of the estimates. In short, although costing was performed within a relatively consistent framework, the dollar quantities (like the system configured) must be viewed as approximate.

4. Generally, the elements included in the costing procedure were incremental costs only, i.e., those costs that would be incurred by implementing the hypothetical satellite system. It is important to note, however, that the estimates presented do not include the following major cost items, that undoubtedly would be incurred because of implementation of a particular system:

a. Costs incurred by user agencies for education or extensive training and upgrading of personnel and procedures

b. Costs of analysis and interpretation (e. g., photographic interpretation) of the data received by user agencies

c. Any costs incurred by individuals or organizations "downstream" from the user agencies, e. g., costs to a farmer to revise his farming methods or to replace machinery due to new information provided by the satellite system

5. The primary functional categories were divided into collecting data from space, and processing and distributing these data to user agencies:

a. Space-segment costs

(1) Spacecraft (satellite) and sensors

(2) Launch (launch vehicle, launching-pad costs)

(3) Ground system (in general, ground stations, communication links, and tracking used to monitor, track, and control the satellite)

(4) System management and administration of the space system

b. Processing-and-distribution-segment costs

(1) Spectral-signature analysis and ground truth

(2) Ground system (in general, ground stations, communication links, and tracking needed to read out imagery and other information collected)

(3) Processing (equipment for processing, and organizing collected data into a form suitable to the user agencies, and distributing the data)

(4) System management and administration of the processing-and-distribution segment

(5) Platform equipment, such as buoys, balloons, and various types of ground collection-transmitter stations

8.2.2 Specific Considerations

8.2.2.1 Configuration I—Wide-Band DCRS

Cost estimates are made under the following assumptions:

1. Time frame: 3 years R&D followed by 4 years proto-operational

2. Spacecraft (satellite)

a. Three near-polar orbiting, sun-synchronous, sensing satellites at 500-mile altitude, spaced at appropriate intervals. Satellite life is 1 year. A total of 15 is required (12 plus three spares). Each satellite contains three cameras and control equipment, 5-ft, X-band 11-GHz antenna, and peripheral equipment; and is priced at $4 million.

b. Geosynchronous, wide-band, data-relay satellite (DCRS) with 4- to 5-year life, costing $10 million. Two in orbit at all times with one spare.

3. Launch vehicles

a. Thor-Delta type vehicle is used to launch the near-polar orbiting sensing satellites. The launch vehicle is priced at $3 million. Launching-pad operational costs are $2 million.

TABLE 7.8.1

COSTING ESTIMATES FOR CONFIGURATION I
(MILLIONS OF DOLLARS)

	Research and Development	Initial Investment in Capital-Like Equipment	Operations and Maintenance	Total
SPACE SEGMENT				
Spacecraft (satellite and sensors)—near-polar	14	60		74
Launch (vehicles, pad costs) near-polar orbit		45	30	75
Spacecraft—geosynchronous	32	30		62
Launch—geosynchronous		27	18	45
Ground system (station, network, tracking)		15	24	39
Systems management			15	15
TOTAL - SPACE SEGMENT	46	177	87	310

b. An Atlas-Centaur type vehicle is used to launch in geosynchronous orbit. The launch vehicle is priced at $9 million. Launching-pad operational costs are $6 million.

4. Contingencies

a. Spare satellites and launching vehicles are included as indicated above. Launching costs for the spare vehicles are included in the total.

5. Other

a. Total earth (land and ocean) coverage.

b. Real-time data at from one to three central points.

c. Three ground stations, at $5 million per station are provided. Annual operating costs are $2.0 million per station.

d. Research and development includes R&D, test, and integration of prototype spacecraft.

8.2.2.2 Configuration II—Direct Regional Readout (Local Option)

Cost estimates are made under the following assumptions:

1. Time frame: 3 years R&D followed by 4 years proto-operational

2. Spacecraft (satellite)

a. Three near-polar orbiting, sun-synchronous, sensing satellites at 500-mile altitude spaced at appropriate intervals. Satellite life is 1 year. A total of 15 is required (12 plus three spares). Satellite contains three cameras and control equipment, retrodirective array, and peripheral equipment, and is priced at $4 million.

3. Launch vehicle

a. Thor-Delta type vehicle is used to launch. The launch vehicle is priced at $3 million. Launching-pad operational costs are $2 million.

4. Contingencies

a. Spare satellites and launching vehicles are included as indicated above. Launching costs for the spare vehicles are included in the total.

TABLE 7.8.2

COSTING ESTIMATES FOR CONFIGURATION II
(MILLIONS OF DOLLARS)

	Research and Development	Initial Investment in Capital-Like Equipment	Operations and Maintenance	Total
SPACE SEGMENT				
Spacecraft (satellite and sensors) - near polar	17	60		77
Launch (vehicles, pad costs) near-polar orbit		45	30	75
Ground system (station, network, tracking)		483	377	860
Systems management			120	120
TOTAL - SPACE SEGMENT	17	588	527	1132

5. Other

a. Total earth (land and ocean) coverage, excepting China and U. S. S. R. landmass.

b. Real-time data at each of 120 individual ground stations.

c. Research and development includes R&D, test, and integration of prototype spacecraft.

d. It is estimated that approximately 120 ground stations are needed, 30 on land, 70 at sea, and 20 for necessary overlap. Each ground station is priced at $0. 8 million, and each sea station at $5. 4 million. Annual operational costs are assumed to be $0. 2 million per ground station and $1. 0 million per ship station. Since these stations are small and primarily designed for data collection, operational costs for tracking and control of the satellite are increased by a total of $3 million per year. No account has been taken of the need to have more than 84 ships to maintain 84 stations at sea. The figure required is normally multiplied by three.

		$Millions
Initial Investment		
Land stations	36 x 0. 8	29
Sea stations	84 x 5. 4	454
Total		$483
Operations		
Land stations	36 x 0. 2 x 4 yrs	29
Sea stations	84 x 1. 0 x 4 yrs	336
Tracking and control	$3M x 4	12
Total		377

8. 2. 2. 3 Configuration III—Direct Regional (Local Option) Land and Near-Land

Cost estimates are made under the same assumptions as for Configuration II except:

1. Total land and near-land coverage, excepting China and U. S. S. R. landmass. Only land stations are provided.

TABLE 7. 8. 3

COSTING ESTIMATES FOR CONFIGURATION III

(MILLIONS OF DOLLARS)

	Research and Development	Initial Investment in Capital-Like Equipment	Operations and Maintenance	Total
SPACE SEGMENT				
Spacecraft (satellite and sensors)—near-polar	17	60		77
Launch (vehicles, pad costs) near-polar orbit		45	30	75
Ground system (station, network, tracking)		29	41	70
Systems management			15	15
TOTAL - SPACE SEGMENT	17	134	86	237

a. 36 stations (with overlap) at $0.8 million equals $29 million initial investment.

b. 36 x 0.2 x 4 years = $29 million

c. Tracking and control = $12 million

8.2.2.4 Configuration IV—Direct/Delayed Readout

Cost estimates are made under the following assumptions:

1. Time frame: 3 years R&D followed by 4 years proto-operational

2. Spacecraft (satellite)

a. Three near-polar orbiting, sun-synchronous, sensing satellites at 500-mile altitude, spaced at appropriate intervals. Satellite life is 1 year. A total of 12 plus three spares is required. Each satellite contains

TABLE 7.8.4

COSTING ESTIMATES FOR CONFIGURATION IV (MILLIONS OF DOLLARS)

	Research and Development	Initial Investment in Capital-Like Equipment	Operations and Maintenance	Total
SPACE SEGMENT				
Spacecraft (satellite and sensors)—near-polar	14	60		74
Launch (vehicles, pad costs) near-polar orbit		45	30	75
Ground system (station, network, tracking)		12	24	36
Systems management			8	8
TOTAL - SPACE SEGMENT	14	117	62	193

three cameras, control box, tape recorder, and peripheral equipment, but fixed S-band antenna; and is priced at $4 million.

3. Launch vehicles

a. Thor-Delta type vehicle is used to launch. The launch vehicle is priced at $3 million. Launching-pad operational costs are $2 million.

4. Contingencies

a. Spare satellites and launching vehicles are included as indicated above. Launching costs for the spare vehicles are included in the total.

5. Other

a. Total land and near-land coverage.

b. Direct/delayed readout at three ground stations.

c. Three ground stations, at $4 million each, are required. Annual operating costs are $2 million per station.

d. Research and development includes R&D and test of prototype spacecraft (in large part, tape recorder product development).

8.2.2.5 Vacuum-Cleaner-Satellite System (VCSS)

Cost estimates are made under the following assumptions:

1. Time frame: 3 years R&D followed by 4 years proto-operational

2. Spacecraft (satellite)

a. Geosynchronous, data-collecting, relay satellite (DCRS) with provisions for handling approximately 26,000 data-collecting-transmitting platforms such as ocean buoys, meteorological balloons and hydrologic gauges. Four in orbit at all times. With a 5-year life, a total of four plus one spare required. Cost of satellite, $3 million each.

3. Launch vehicles

a. Thor-Delta type vehicle. (The vacuum-cleaner satellite weighs about 350 lb.) The launch vehicle is priced at $3 million. Launching-pad operational costs are $2 million.

4. Contingencies

a. One spare satellite and launching vehicle are provided. Launching costs for the spare are assumed in the total.

TABLE 7.8.5

COSTING ESTIMATES FOR VACUUM-CLEANER-SATELLITE SYSTEM (MILLIONS OF DOLLARS)

	Research and Development	Initial Investment in Capital-Like Equipment	Operations and Maintenance	Total
SPACE SEGMENT				
Spacecraft - geosynchronous	7	15		22
Launch - geosynchronous		15	10	25
Ground system (station, network, tracking)		5	16	21
Systems management			6	6
TOTAL - SPACE SEGMENT	7	35	32	74

5. Other

a. Two ground command-control data-acquisition stations at $2.5 million each are required. Annual operations are $2 million per station.

b. Research and development is primarily on the spacecraft.

c. Total earth (land and ocean) coverage between approximately 60°N and 60°S latitude.

8.3 Conventional Equivalent of the Vacuum-Cleaner-Satellite System (VCSS)

This system is hypothecated to collect the data from the data platforms listed in Table 7.8.6 by "conventional" or "nonsatellite" means. By pricing such a system, an attempt is made to illustrate the cost-effectiveness of the vacuum-cleaner-satellite system (VCSS).

If this data collection were attempted at all by conventional means, a considerable effort would be required to determine the optimum communications mix, location of repeaters, trunking, etc. For the accuracy required for comparison purposes, a set of assumptions was made, and the resulting hypothetical system cost was determined.

TABLE 7.8.6

COMMUNICATION WITH VACUUM-CLEANER DATA PLATFORMS

HF Communications	Geographical Distribution	Number of Platforms	Reporting Interval (hr)	Message Size
Balloons	G	4500	6	100
Ships (U/A)	GO	60	6	1400
Ships (No U/A)	GO	800	6	275
Ocean-station vessels	GO	25	6	1400
Buoys, moored	GO	500	6	3000
Buoys, drifting	GO	200	6	500
Buoys, manned	GO	5	6	10,000
A/C of opportunity	G	200	6	500
Offshore platform	U*	500	6	500
		6790		
Line Communications				
Land with (U/A)	GL	500	6	1400
Land without (U/A)	GL	3600	6	225
Hydrology A	U	7300	24	200
Hydrology B	U	1100	7x24	1000
Hydrology C	U	600	30x24	1200
Seismic	GL	240	6	350
Vulcanology	GL	50	6	1800
Agriculture	N. A.	4000	6	100
Forestry	N. A.	2000	6	100
		19,390		

U/A = Upper-Atmosphere Capability
U = United States ("uniform distribution")
U* = United States (shores, lakes, estuaries)
GL = Global Land ("uniform")
GO = Global Ocean ("uniform")
N. A. = U.S. and Canada ("uniform")
G = Global Land and Ocean ("uniform")

Total 4-year costs ranged from about \$1.5 billion to \$2.1 billion. Since no costs for system management, integration, etc. were included, the estimate may be too low.

Further, a large part of the cost is sensitive to the assumption that HF communications on balloons cover only about 250,000 square miles. A figure of 2500 miles HF communication range has been published for data buoys. Thus, if something like half this range were achievable with balloons, the above total cost might be halved.

Assumptions

The following assumptions were made in arriving at the cost factors in the cost summary.

1. Assume that balloons are the limiting system consideration. For a transmitter cost of \$200 per balloon, we can communicate by balloon with a large HF station over 0.25×10^6 mi^2.

Station cost:

Land	\$
Station cost	800,000
Operating cost \$0.2 million annually for 4 years	800,000
4-year land station total (per station)	\$ 1,600,000
Ship	
Equipment and engineering	2,000,000
Ship initial investment, refurbishing, etc. at \$5,000,000	5,000,000
Annual operating cost, 4 yr @ \$1 million annually	4,000,000
4-year ship station total (per station)	\$11,000,000

2.

Global surface area	200×10^6 square miles
Continental land area	60×10^6 square miles
Oceanic area	140×10^6 square miles

3. Assume that we can communicate reliably with a balloon within an area of 250,000 square miles. All but 10 percent of the ocean can be reached from shore- and island-based stations. Ship coverage is assumed to be 10^6 square miles, at slightly lower reliability.

$$\text{Land HF stations} = \frac{60 \times 10^6 \text{ square miles}}{0.25 \times 10^6 \text{ square miles per station}} = 240$$

$$\text{Land HF stations for ocean communications (island, shores, etc.)} = \frac{140 \times 10^6 \text{ square miles}}{0.25 \times 10^6 \text{ square miles per station}} = 560$$

Ships (primarily in southern hemisphere) = 10

4. Traffic density per station—assume HF stations are used to relay data to existing cable terminations.

$$\text{Average balloon density} = \frac{5000}{200 \times 10^6 \text{ square miles}} = \frac{1}{40,000 \text{ square miles}}$$

$$\text{Station density: land} = \frac{1}{250,000 \text{ square miles}}$$

$$\text{Average } \frac{\text{balloons}}{\text{stations}} = \frac{250,000}{40,000} = 6;$$

(3 times higher for coastal stations, also 3 times higher peak for clustering; $3 \times 3 \approx 10$ factor.)

Assume peak of 60 balloons to be handled at once by each station.
60 balloons @ 450 bits per interval = 27, 000 bits per interval.

5. Assume the emplaced HF communications stations will handle the 6790 communication platforms tabulated in Table 7. 8. 6 at no incremental cost.

6. Summary of detail costs for 4-year operating period

Line of Sight (LOS) Communications Stations	Low estimate ($million)	High estimate ($million)
Land HF Stations 240[c] @ $1.6 M	384	384
Shore and island HF stations 460-560[a, c] @ $1.6 M	736	896
Connection of HF stations to commercial phone 5-10 mi average @ $1000 per mile[b] (240 + 560) x $1000 x (5-10)	4	8
Annual cable charges[d] at $50-100 million/year for 4 years	200	400
HF ships 10-20 @ $15.0 M ea.	110	220
(L.O.S.) Subtotal	$ 1434	$ 1908
Land Communications Stations		
Hydrology, Agriculture, Forestry 12,000 platforms at an average distance of 10-15 miles at $1000 per mile	120	180
Weather[e]	---	---
Seismic-volcanic, 290 platforms, average distance 30 to 100 miles @ $1000 per mile[b]	9	29
(Land) Subtotal	129	209
TOTAL[f]	$ 1563	$ 2117

(a) The lower figure assumes 100 presently existing stations could be used for ballon HF communications.

(b) $1000 per mile assumes phone lines cost $5000/mile; 20-year life of lines; 4-year portion charged to system.

(c) Based on HF repeater-station network required for 0.25×10^6 mi^2 ballon communication area.

(d) Roughly similar to Manned Space Flight Network (MSFN) communications charges.

(e) Assume already connected; no additional charge.

(f) Total does not include management, integration, installation, land, housing, or any equipment on platforms.

APPENDIX A

DATA COLLECTION FROM TERRESTRIAL AND ATMOSPHERIC ENVIRONMENTAL SENSOR PLATFORMS

Thousands of terrestrial and atmospheric sensor platforms are employed today for collecting environmental data for use in research and in warning and prediction systems. Thousands of additional sensor platforms are needed to complement and work in conjunction with the many remote-sensing systems for various specific applications described in detail in other Space Applications Summer Study reports and elsewhere.

Using chiefly inputs from other panels, the Panel on Points-to-Point Communications has identified, for the 1975 era, approximately 26,000 terrestrial and atmospheric sensor platforms from which data might most efficiently and effectively be gathered by a system of three or four geostationary data-collection-relay satellites (DCRS).

The Panel has concentrated on the task of data collection from sensor platforms used in meteorological, hydrologic, oceanographic, and geological warning and prediction systems. The Panel is acutely aware of three salient features unanswered by their brief assessment of the scope of such future systems:

1. There are obvious possibilities for tradeoffs among many of the platforms considered. Although no explicit tradeoff studies have been carried out, an effort has been made to include a "reasonably representative" number of each platform type anticipated to be in use in the 1975 era.

2. For thousands of sensor platforms in the atmosphere and at relatively remote terrestrial locations, satellite data collection and relay to one or more ground facilities appears to be most efficient. For many thousands of additional sensors--a good fraction of which are in use today--it may also be most effective to use data-collection-and-relay satellites, even though for some periods of time, it may involve duplication of some facets of other communications.

3. The 26,000 identified sensor platforms are primarily--though by no means entirely--associated with U.S. programs (of course, several of these programs have international characteristics). The basic question of satellite-channel capacity and data-collection scheduling is predicated on the assumption that two satellites in the three- or four-geostationary-DCRS system provide overlapping coverage of the United States. If additional major data-collection requirements of other countries can be identified in the future, it is highly

likely that, if desired, they can be accommodated during the less busy data-collection time intervals identified in the following discussion.

Within this framework, the Panel has undertaken to outline one out of many possible schemes for scheduling the collection of data from globally distributed sensor platforms, with most dense distribution occurring in the United States.

A. 1 Types and Numbers of Sensor Platforms Circa 1975

A highly summarized description of the 26, 000 sensor platforms anticipated for the 1975 era is shown in Table 7. A. 1.

TABLE 7. A. 1

SUMMARY OF SENSOR PLATFORM TYPES AND NUMBERS

TYPE	NUMBER	LOCATION	ASSUMPTIONS AND COMMENTS
Land weather stations	4100	Global	Includes about 1000 in U. S. /Part of WWW*
Superpressure balloons	4500	Global	Primarily over oceans
Buoys	700	Global	350 in coastal North American waters
Ships	850	Global	Most in normal shipping lanes
Aircraft-of-opportunity	200	Global	Most in normal air traffic lanes
Hydrologic	9000	U. S.	Many sites part of ESSA weather broadcast networks
Seismic and volcano	290	Global	
Agriculture	4000	U. S. /Canada/ others	Three-fourths in U. S.
Forestry	2000	U. S. /Canada/ others	Three-fourths in U. S.
TOTAL	25, 640		

*WWW—World Weather Watch.

Of the 26,000 sensor platforms identified in Table 7.A.1, approximately 16,000 would be likely to be on, over, or in the near vicinity of the North American continent, as indicated by Table 7.A.2. It is clear that the mix

TABLE 7.A.2

SENSORS ON, OVER, AND NEAR NORTH AMERICA

TYPE	NUMBER
Land weather stations	1000
Superpressure balloons*	200
Buoys	350
Ships	200
Aircraft-of-opportunity	50
Hydrologic	9000
Seismic and volcano	50
Agriculture	3500
Forestry	2000
TOTAL	16,350

*It is anticipated that very few superpressure balloons will operate over continents where there are other means of upper-air measurement.

of sensor platforms under consideration is primarily oriented toward U.S. programs. Most of the remaining 10,000 sensor platforms are associated with meteorological and oceanographic data collection and would support the World Weather Watch.

If the globally distributed land weather stations and superpressure balloons are removed from consideration, the great majority of the remaining 17,000 sensor platforms could be served by a single vacuum-cleaner DCRS located in geostationary orbit at approximately 90°W longitude. Figure 7.A.1 shows a typical coverage pattern for a single DCRS. Such a satellite might constitute the first phase of a relay satellite data-collection system, for it could provide coverage for all types of platforms and at least 60 percent of the sensor platforms under consideration.

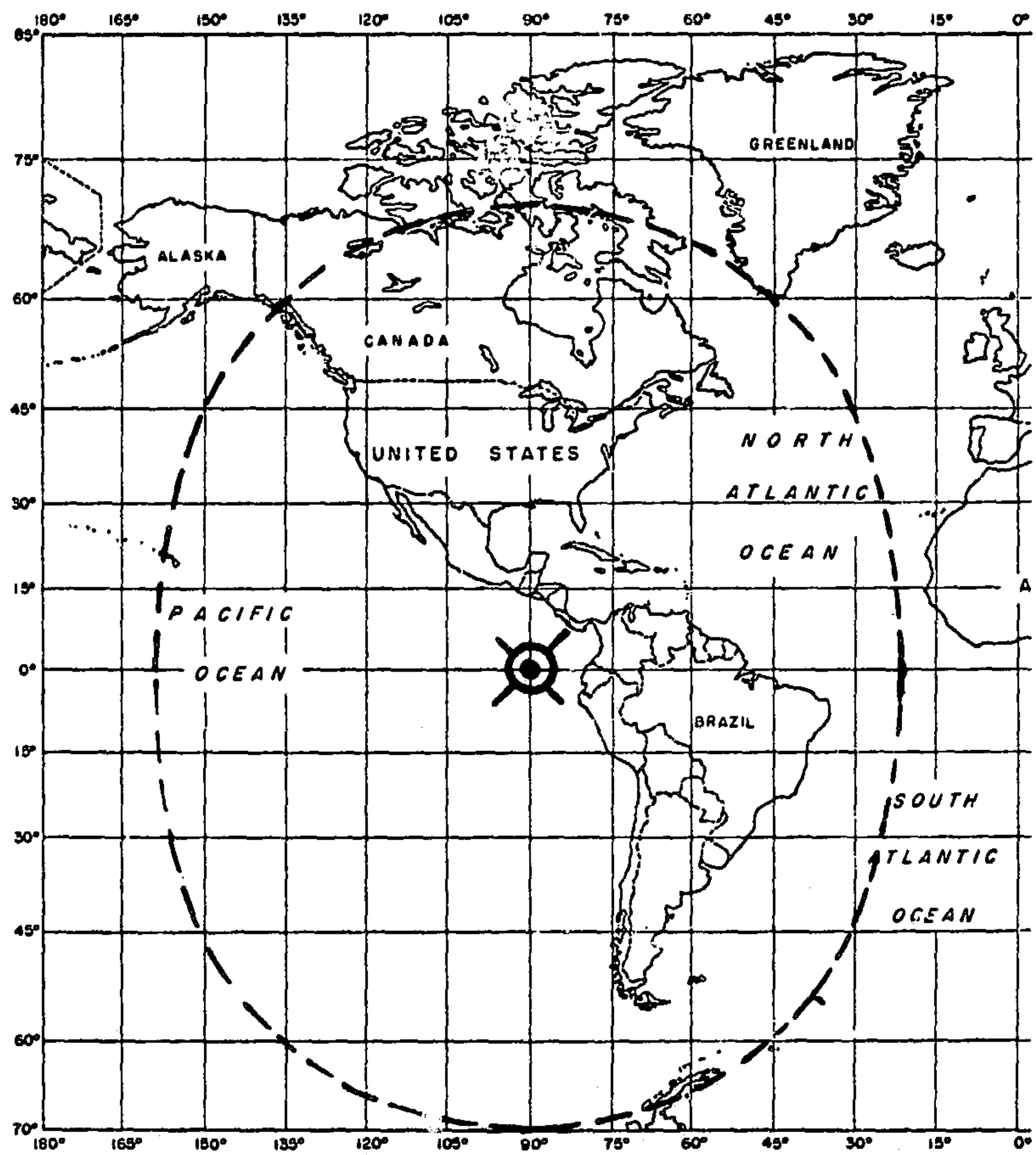

FIGURE 7.A.1 Typical coverage (140°) by a single DCRS.

A. 2 Required Data-Collection Capacity

The required data-collecting capacity and collection scheduling is a function of the number of sensor platforms within communications view of the satellite, sensor message length, the time of day the data are required (or desired), and the period within which data collection must take place. For example, meteorological data for WWW use are collected at standard times of 0000, 0600, 1200, and 1800, GMT.*

To size a typical DCRS it is assumed that data-collection subchannels of 200 bits per sec (bps) are available. Table 7. A. 3 indicates the time required to collect all categories of data from a typical "busiest region," namely that associated with the Western Hemisphere.

It is assumed that all meteorological and oceanographic data taken at 0000, 0600, 1200, and 1800, GMT, must be collected and relayed to one or more central ground terminals within 1 hour. This might be accomplished by three 200-bps channels, as shown in Figure 7. A. 2. It can be seen that one channel is required for land weather stations with upper-air (U/A) measurement capability. Another channel is required for moored buoys. All other meteorological and oceanographic data collection is accomplished by time division in a third channel.

Data collection from the offshore platforms has been scheduled to occur immediately after the meteorological data have been collected, in order to maximize the possibility of timely correlation of data processing. (If the offshore platforms also sense meteorological parameters and are needed within the 1-hour synoptic reporting interval, a fourth channel could be supplied.)

To determine further the scheduling of data collection, it is necessary to consider the "busiest time" in the "busiest region." This task is undertaken in the next section.

A. 3 "Busy Time" Data Collection Scheduling

There are data-collection requirements that are based on obtaining data before a certain local-time condition. The data-collection requirements of the remaining sensor platforms are given in Table 7. A. 4.

The meteorological synoptic reporting period between 1200-1300 GMT has the following local time equivalences in the United States:

1200 — 1300	Greenwich Mean Time
0700 — 0800	U. S. Eastern Standard Time
0600 — 0700	U. S. Central Standard Time
0500 — 0600	U. S. Mountain Standard Time
0400 — 0500	U. S. Pacific Standard Time

*Not all meteorological parameters are measured four times a day, but measurements are made at standard times, even if done only once or twice a day.

TABLE 7. A. 3

DATA-COLLECTION TIMES FOR A 200-BPS CHANNEL

PLATFORM TYPE	INFORMATION BITS/ MESSAGE	SECS (a) / MESSAGE	EXPECTED NO. OF PLATFORMS	DATA-COLLECTION TIME (a)	
				SECS	HRS (Approx)
Superpressure balloons	100	0.5(b)	1200	600	1/6
Land weather stations (U/A) (d)	1400	7.5(c)	500	3750	1-1/24
Land weather stations (No U/A)	225	1.5	1000	1500	1/2
Ships-of-opportunity (U/A)	1400	7.5	40	300	1/12
Ships-of-opportunity (No U/A)	275	1.5	400	600	1/6
Ocean station vessels	1400	7.5	11	82	
Buoys (moored)	2000	10.5	350	3670	1
Buoys (drifting)	500	3.0	100	300	1/12
Buoys (manned)	3000	15.5	5	80	
Aircraft-of-opportunity	500	3.0	140	420	1/9
Hydrologic (Class A)	200	1.5	7300	10,950	3
Hydrologic (Class B)	1000	5.5	1100	6060	1-2/3
Hydrologic (Class C)	2000	10.5	600	6300	1-3/4
Offshore platforms	500	3.0	300	900	1/4
Seismic	240	1.5	100	150	1/24
Volcano	50	0.5	30	15	
Agriculture	100	0.75	2500	1870	1/2
Forestry	100	0.75	1300	970	1/4

(a) For a 200 bps channel
(b) No acquisition time included
(c) Acquisition time of 1/4 to 1/2 sec assumed for all platforms except balloons
(d) Upper-atmosphere capability

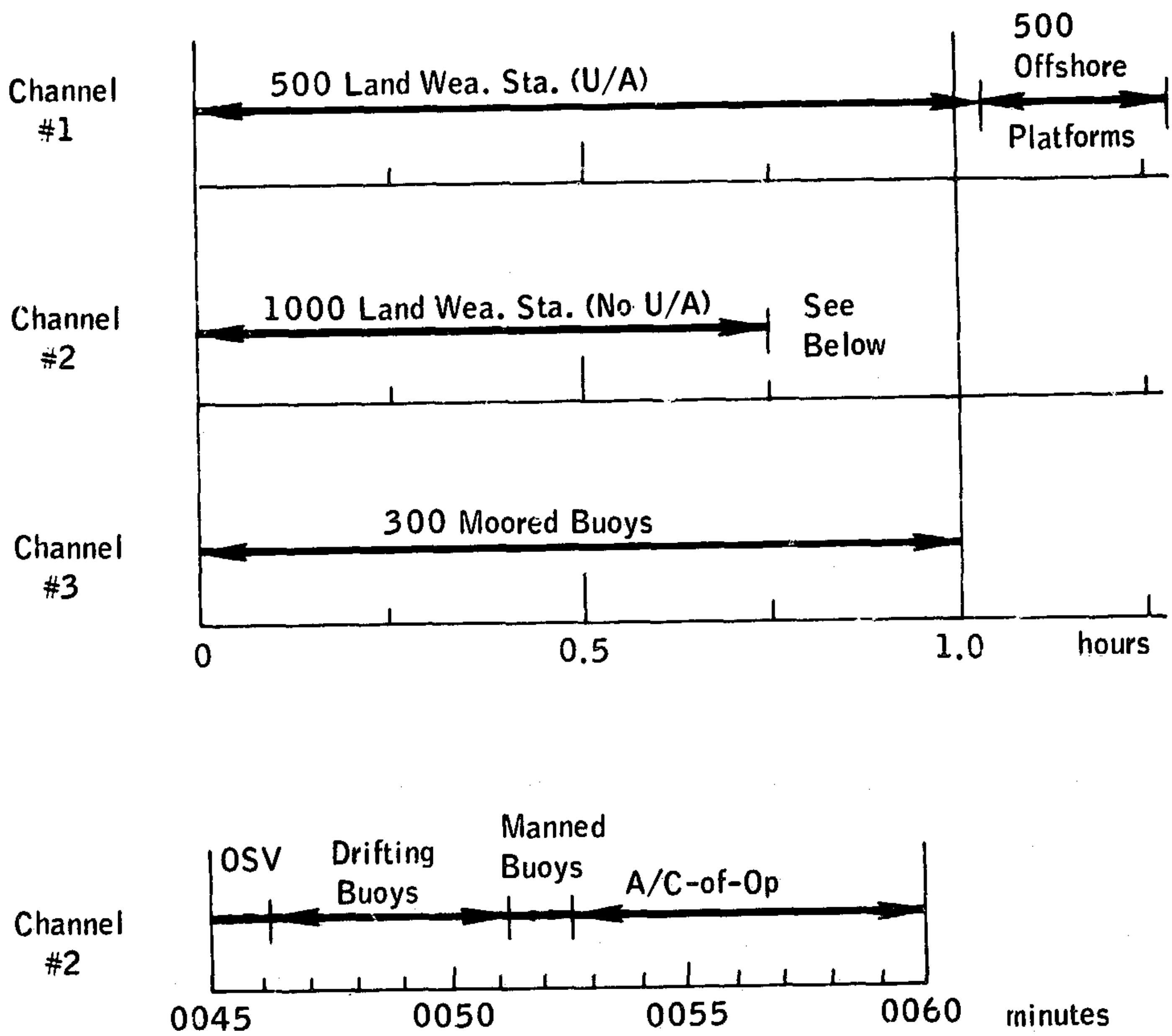

FIGURE 7. A. 2 Data-collection schedule.

TABLE 7.A.4

DATA-COLLECTION TIMES

PLATFORM TYPE	DATA-COLLECTION TIME
Hydrologic (Class A)	At least once/day—preferably before 8:00 a.m. local time
Hydrologic (Class B)	At least once/week
Hydrologic (Class C)	At least once/month
Seismic	Preferably 4 times/day
Volcano	Preferably 4 times/day
Agriculture	At least once/day—preferably before local sunrise
Forestry	At least once/day—preferably during local midafternoon

Because local sunrise occurs during this range of time, it follows that this will be the "busiest time" in the "busiest region."

In the United States, earliest local sunrise (at the summer solstice) varies from 4:13 a.m. to 4:59 a.m., at 45° N and 30° N latitudes, respectively. Latest sunrise (winter solstice) occurs at 7:35 a.m. to 6:55 a.m., at 45° N and 30° N latitudes. The general characteristic of time of local sunrise is shown in Fig. 7.A.3.

Superimposed sunrise conditions for each of the four U.S. time zones are shown in Figure 7.A.4. It is apparent that, in each time zone, some conflict occurs with the 1200-1300 GMT synoptic reporting interval. It is equally apparent, however, that by dividing up the hydrologic and agricultural data collection by time zones, it is possible to collect local hydrologic data in approximately 1 hour and local agricultural data in 1/4 hour, or less. Assuming each of these data collection needs would take place on a separate channel, the third channel could be used to collect forestry data at the same time as agricultural data for correlative purposes, if desired. (Forestry data would also be collected at local mid-afternoon time, as noted earlier.) Channel and time scheduling to achieve the characteristics described are shown in Figure 7.A.5. Agricultural and forestry data collection occupies a pre-sunrise correlated window. Hydrologic data are collected prior to 8:00 a.m., local time.

A.4 Data Collection from Remaining Sensor Platforms

The data-collection time required for seismic and volcano sensor platforms is no more than 5 minutes. Collection could take place using any of

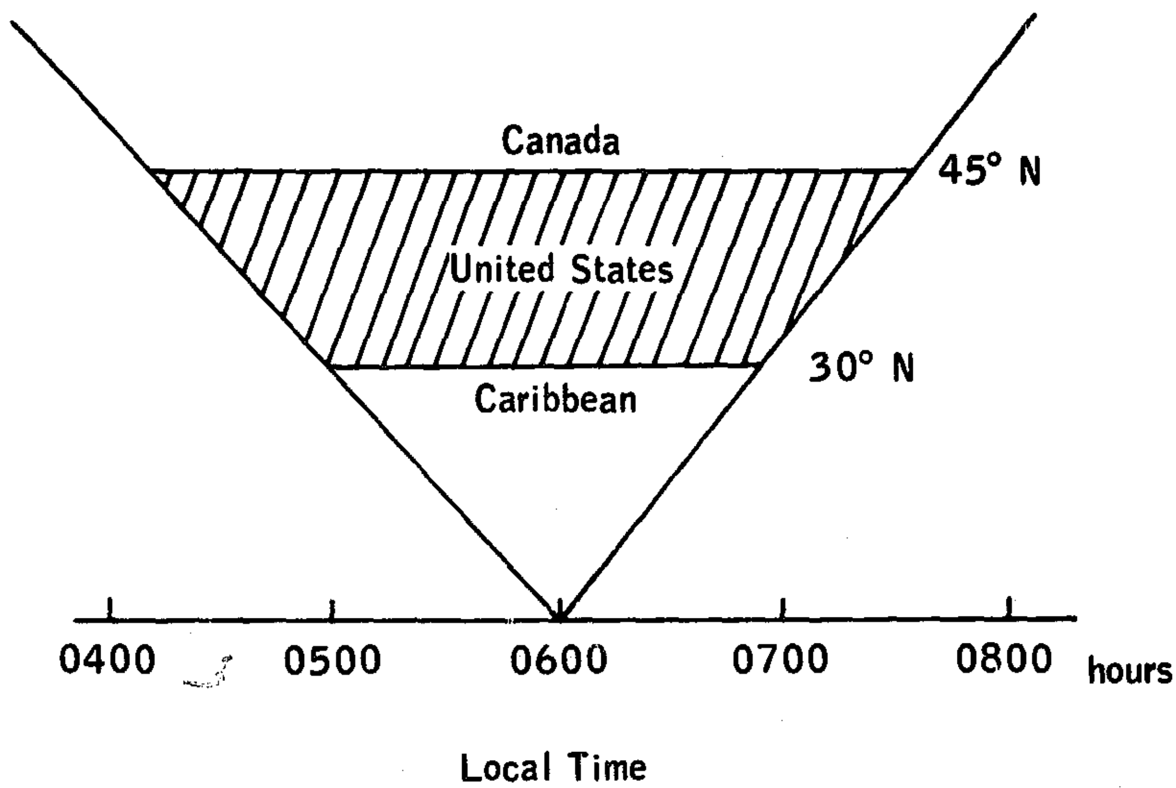

FIGURE 7.A.3 Seasonal variation of local sunrise.

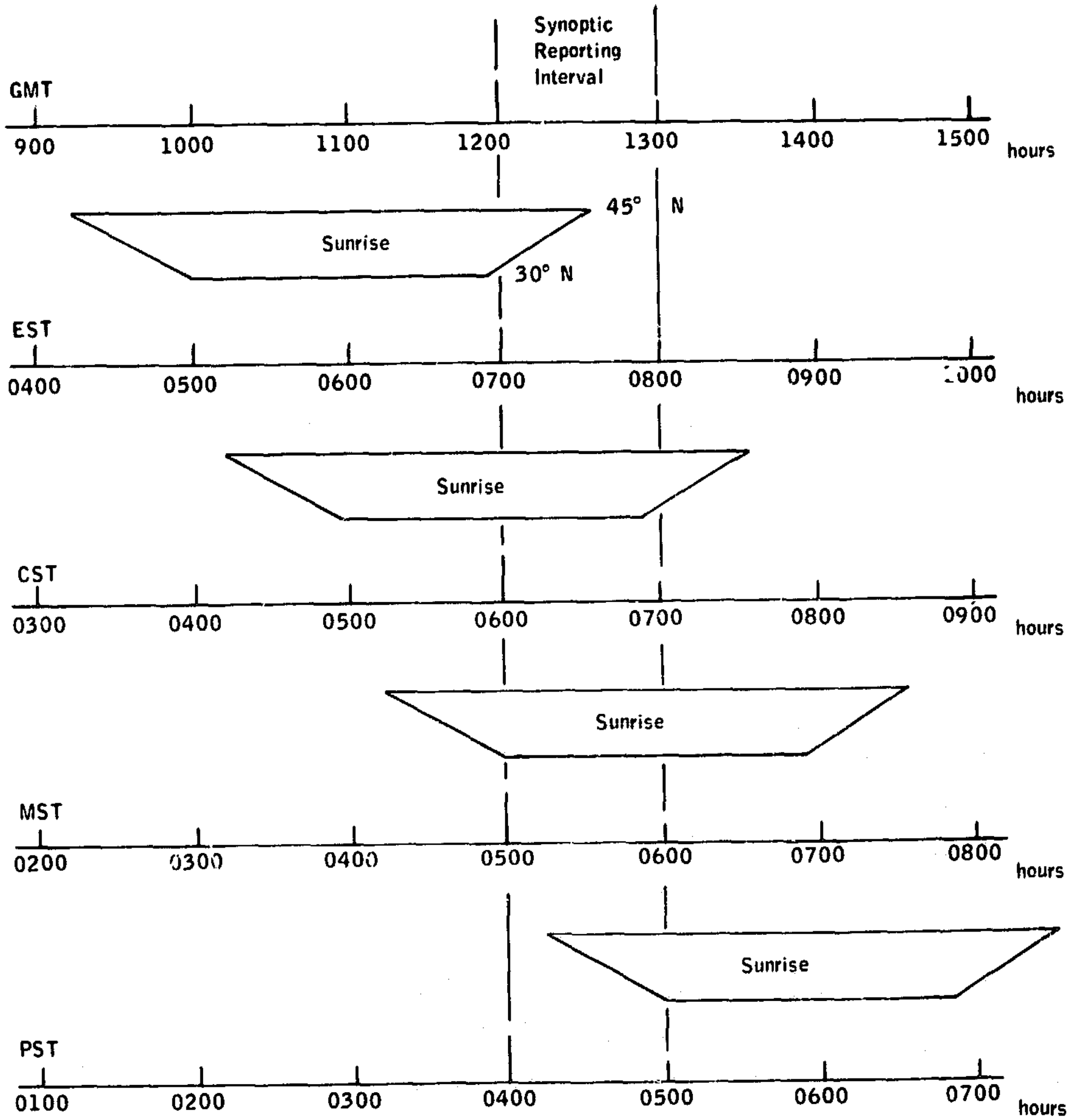

FIGURE 7. A. 4 Correlation of synoptic reporting and sunrise over the United States.

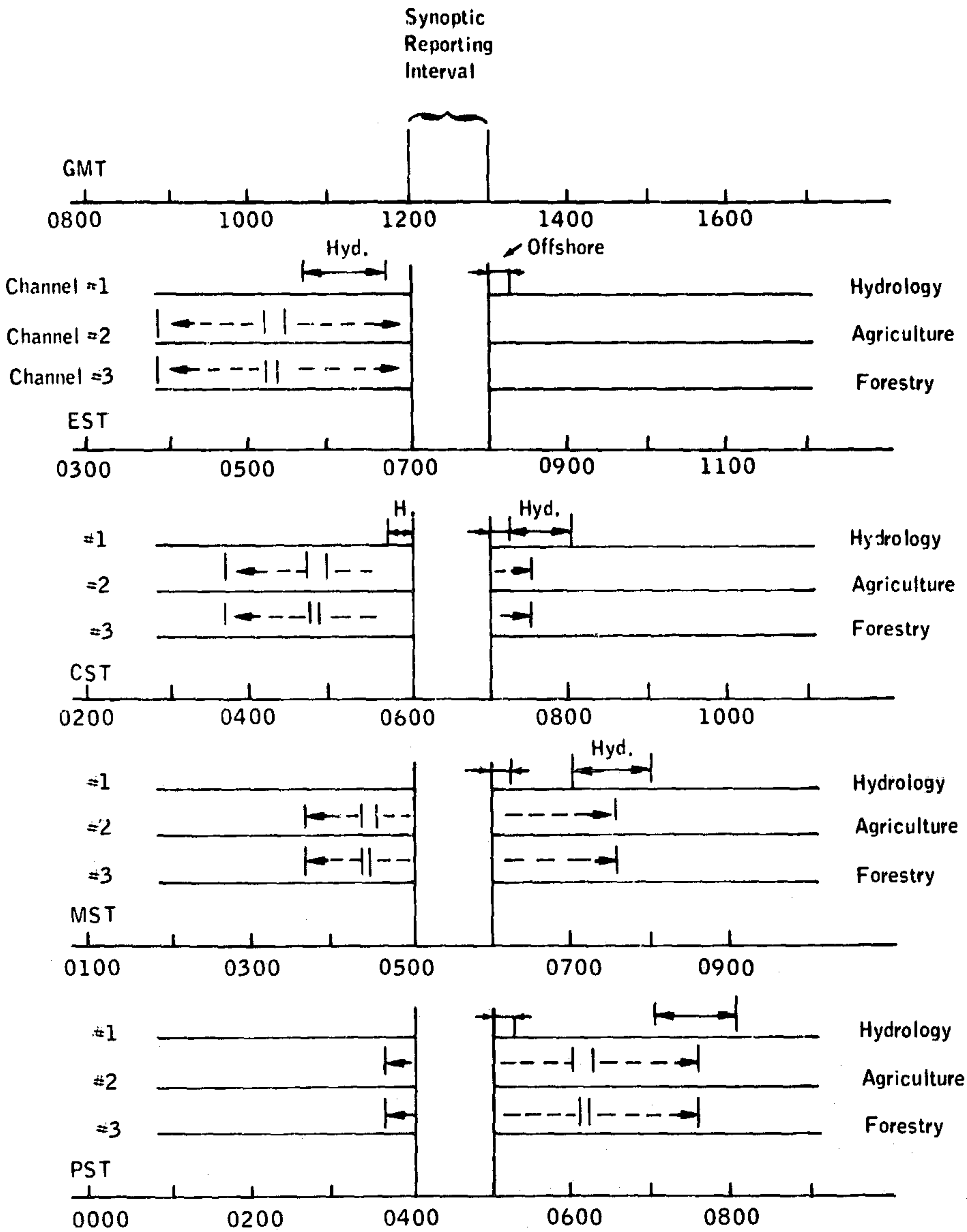

FIGURE 7.A.5 "Busiest time" schedule for collecting hydrologic, agricultural, and forestry data.

the three channels, as long as collection is not required during the time intervals already assigned.

These data could be reported within 5 to 10 minutes of the synoptic meteorological-oceanographic data (along with forestry data on Channel #3), if desired for correlative purposes.

All data collection could be carried out as often as four times daily (or more often, if desired), for none of the three channels would be in use more than approximately 2 hours out of each 6-hour synoptic reporting period.

Hydrologic Class B data (one report per week) and Hydrologic Class C data (one report per month) could be collected at any one of the many unused time intervals available on all channels.

A. 5 Location of Balloons and other Free-Moving Sensor Platforms

It has been shown elsewhere in this panel report that approximately 1. 5 minutes per 200-bps channel will probably be required to determine the location of a freely moving sensor platform such as a superpressure balloon. Assuming approximately 1200 balloons may be within view of one geostationary DCRS in a four-satellite system, an assignment of 100 channels (200 bps each) results in

$$\frac{1200 \text{ balloons}}{100 \text{ channels}} = 12 \text{ balloons per channel}$$

$$12 \text{ balloons per channel} \times 1.5 \frac{\text{min}}{\text{location}} = 18 \text{ min}$$

to locate all 1200 balloons once. To obtain an average upper-air wind measurement, each balloon must be located twice in an interval of about 0. 5 to 1. 0 hour. From the results above, it is apparent that 1200 balloons can all be located twice within a 1-hour synoptic reporting period, with a 42-minute wind-integration time between location times.

Since the data collected from each balloon can be transmitted within 1 second over a 200 bps channel, it is assumed that data collection takes place by using the location channel.

The 100 balloon-location channels would be unoccupied for at least 5 out of every 6 hours. This rather considerable data-transmission capability (20, 000 bps) could be used for collecting other data; or, possibly, a better use would be for dissemination of environmental-data products, such as facsimile pictures.

APPENDIX B

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