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LIBRA: An Inexpensive Geodetic Network Densification System

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PREFACE

The work described in this report was performed by the Mission Analysis Division of the Jet Propulsion Laboratory.

The report is organized as follows. A precis of the entire report, discussing the rationale for the study and the conclusions that were reached, is provided by the Executive Summary (Section I). The need for network densification is stated in detail in Sections II and III. The rest of the report is divided between the three major areas of activity that the proposed LIBRA System would require: hardware development, Sections IV-X (pp. 19-47); data reduction, Sections XI-XIII (pp. 48-53); and tropospheric calibrations, Section XIV (pp. 54-59). A schedule of development and estimated costs for LIBRA are presented in Section XV (pp. 59-62).

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ABSTRACT

Under a proposed system, geophysically significant measurements can be obtained of earth crustal motions using an aircraft ranging by radio to a set of transponders on the ground, which act as geodetic control points. The purpose of the system is to interpolate a geodetic network of markers closely spaced between fundamental reference points established by such techniques as radio interferometry or satellite ranging. This low-cost means of extending the accuracy of space age geodesy to local surveys provides speed and spatial resolution useful, for example, for earthquake hazards estimation. The system is called LIBRA (Locations Interposed By Ranging Aircraft).

LIBRA can be combined with an existing system, ARIES (Astronomical Radio Interferometric Earth Surveying) to provide a balanced system adequate to meet geophysical needs, and applicable to conventional surveying. Problems to be solved in connection with the system design concern the required hardware, the mathematical technique to determine station locations, and the calibration of radio ranging measurements for the effects of atmospheric time delay.

A schedule of development and estimated costs for LIBRA are presented.

I. EXECUTIVE SUMMARY

This report proposes a system by which geodesy and earth strain measurement can be performed rapidly and inexpensively to several hundred auxiliary points with respect to a few fundamental control points established by any other technique, such as radio interferometry, lunar laser ranging, or satellite geodesy. Although having applications to many geodetic problems, the work presented in this report was undertaken to augment Project ARIES in the attainment of certain geophysical goals, and can be understood only against the background of the entire ARIES effort and its rationale.

In 1972 it had become clear to the Seismological Laboratory of the California Institute of Technology and to JPL that a technique originally considered by JPL for spacecraft navigation could yield a certain kind of information that might be vital to the estimation of earthquake hazards. The technique was Very Long Baseline Interferometry (VLBI), which uses independently operating radio telescopes to determine the positions of celestial radio sources. The vitally necessary geodetic information concerned the systematic crustal movements that take place far from known faults — the "far-field strain rate," which gives a measure of how much energy is being stored in the Earth, of which a large fraction must, sooner or later, be released in earthquakes. The potential application of astronomical VLBI to geophysics lay in the fact that, once an accurate astronomical catalog of celestial sources has been compiled, and once certain astronomical parameters, such as UT1 and polar motion, are being measured with the accuracy that VLBI affords, then VLBI can be operated, so to speak, in reverse: instead of using a known baseline on Earth from which to measure the positions of celestial objects, one may use the known celestial positions to determine locations on Earth. And, if the accuracy of astronomical measurement is translated into geodesy, positions exact to centimeters may be determined over intercontinental distances. Irwin Shapiro, of MIT, pointed out the possibility of using a portable VLBI antenna to measure the relative tectonic movement of the lithospheric plates, and the group at JPL prepared to measure motions in the mushy zone of fractured continental rock between the plates, in the earthquake belt of the Pacific States, beginning in Southern California. The JPL effort was called ARIES (Astronomical Radio Interferometric Earth Surveying).

An even more immediate application of VLBI to earthquake studies was promised by certain predictions of the dilatancy-fluid diffusion model for earthquakes proposed by Amos Nur and his colleagues, but with this possibility a new problem appeared. The potential application follows from the theoretical expectation that, when rock in a region under great stress is about to rupture, it increases its volume, and so may cause the ground to rise slightly during the weeks or months before the earthquake. This small uplift might be 2 to 30 cm high and 5 to 50 km wide prior to an earthquake large enough to be destructive. The problem is cost: although the ARIES technique can establish geodetic control points with the accuracy needed to detect dilatant uplift, the probability is small that any one antenna would be in the vicinity of an earthquake large enough to test the theory in a reasonable span of time, and the number of antennas needed for an effective earthquake warning system would be prohibitively large. What is needed is a means of extending ARIES geodetic control over a large area, quickly, and economically.

The basic geophysical requirements that determine the nature of the ARIES Project can be summarized in four theses:

(1) Much detailed data must be acquired before the general theory of plate tectonics can be applied to the specific problem of earthquake hazards estimation; to gather such data is the purpose of the ARIES Project.

(2) ARIES should not be confined to the vicinity of a few major faults, because measuring motion along known faults, on the one hand, and earthquake hazards estimation, on the other, are different tasks.

(3) ARIES must be designed to test various theories of the earthquake mechanism, without depending on any one of them.

(4) If ARIES (or any similar system) is used over intercontinental distances, such as the circum-Pacific area, there must be a means of distinguishing local from global effects.

These theses are illustrated in Figs. 1 through 5, and are discussed more fully in Section II.

Corresponding to the geophysical requirements are certain system characteristics and requirements of ARIES that must be recognized in its deployment:

(1) The prime virtues of the ARIES technique over others are these: the speed with which results can be obtained; the anchoring of coordinates to an absolute frame of reference; the ability to measure three dimensions simultaneously.

(2) The purely geodetic applications of ARIES, apart from earth physics, must be included in systems planning from the outset.

(3) One pressing need is to develop an economical means of bridging the gap between ARIES and conventional geodesy; that is, to provide a fine-mesh network of ARIES control points.

These theses are illustrated in Figs. 6 through 8, and are discussed in Section III.

We therefore intercompared the various advanced geodetic techniques that are either already available or under development. Broadly speaking, all systems for determining positions that depend on ranging can be classified along three dimensions (see Fig. 9). The three dimensions are these: the type of vehicle used (such as satellite or aircraft); the type of ranging device that is used (such as radio, or laser); whether the ranging target is made active or passive (either a transponder of some kind, or a simple reflector). Each of these types of system has its special use, and a mix of many types might be desirable to satisfy the many and various requirements of the geophysical community as a whole. Nevertheless, for the purposes of earthquake hazards estimation within the framework of the ARIES Project, it is possible, from certain basic principles, to narrow the choice between competing systems. Because the network spacing is comparatively small (20 to 200 km), and since the geometry of multilateration requires that the altitude of the vehicle not be an order of magnitude greater than the station separations, an aircraft is preferable to a satellite. Because we will want to remeasure positions quickly, it should not be necessary to relocate the ground stations. Because we require an all-weather system uninhibited by clouds or smog, radio (or radar) is preferable to lasers. Because the system must be as inexpensive as possible, and because one ranging system in the vehicle is almost certain to be cheaper than many ranging systems on the ground, the ranging system should be in the vehicle. The four underlined statements form the principal conclusions to the first part of our work, and may be summarized as follows:

The optimum system to perform the ARIES Network Densification Task should be an airborne radio or radar system ranging to inexpensive markers at fixed ground sites.

An aircraft can be used to determine ground positions with centimeter accuracy by the technique of simultaneous ranging, or multilateration (Refs. 18 through 20). If as many as six stations on the ground (or, in favorable circumstances, as few as four) range simultaneously to an aircraft or satellite, taking six or more sets of ranges to the various aircraft or satellite positions, then the relative positions can be calculated by pure geometry, with no need for information concerning aircraft motion (or satellite trajectory). The simplest coordinate system to use for such a solution is illustrated in Fig. 14. If, for example, four stations range simultaneously to six aircraft positions, the 24 unknown coordinates in the system of Fig. 14 can be solved from the $6 \times 4 = 24$ range equations corresponding to the 24 measurements, barring mathematical singularities.

The simplest such system, from a theoretical point of view, would employ passive, reflecting markers on the ground and a radar ranging system aboard an aircraft. By such a system, the complexity and cost of the many ground markers is kept to a minimum, and all the complicated electronic equipment is kept to a single unit, aboard the aircraft. We therefore calculated what the basic specifications of such a system might be, as outlined in Subsection IV-B. It was shown that such a system might just barely be possible in the present state of the art, but a very-high-frequency radar would be necessary (about 40 GHz), with serious problems from attenuation and backscatter.

However, we discovered that low-powered, battery-equipped markers could be manufactured at a cost per unit not appreciably greater than large passive markers, bringing the requirements of the aircraft ranging device much closer to the specifications of commercially available equipment. It was shown that a workable minimum system using one aircraft ranging device and six active (that is, battery-powered) transponders on the ground can be built by making straightforward engineering changes to commercially available equipment. Details are given in Section IV.

The basic hardware design was outlined and specifications were defined of a hypothetical geodetic system called LIBRA (Locations Interposed By Ranging Aircraft). As the name implies, LIBRA would exist only to interpose a closely spaced network of geodetic markers between widely spaced control points established by some other technique, such as laser satellite geodesy or ARIES. A proper use of LIBRA would be to balance ARIES in a mixed system, by enabling inexpensive markers to be located

(1) In greater number than would be economical by any technique whereby measurements must be taken from manned sites.

(2) In areas inaccessible except by helicopter (or backpack), where large antennas or laser apparatus would not be practical.

Since LIBRA is designed to be used in conjunction with one or several other techniques, it determines positions in whatever frame of reference is established by the complementary technique, by a process called multilateration.

What the hardware of the final LIBRA system might look like is shown in Fig. 12, corresponding to the specifications described in Section VII. Each ground receiver is designed to respond to a range code broadcast by the positioning aircraft, to be transportable either by backpack or by helicopter, and to operate unattended for up to one year. It is anticipated that these ground markers will be transported by helicopter to their sites in most cases, that several hundred markers will be used to monitor an area about 100,000 km^2 and that manpower and overhead will be kept to a minimum by visiting and servicing (and, when desired, moving) the markers on a fixed schedule using a helicopter. A possible code-recognition device that is being developed rapidly by the electronics industry and that promises to be inexpensive and rugged is the surface acoustic wave device (SAWD), of which the principle of operation is illustrated in Fig. 13.

The mathematics of multilateration, by which positions of ground markers can be determined from a moving vehicle without prior knowledge of the location of the vehicle, is described in Section XI and illustrated in Figs. 14 through 17. The logic by which the final system might perform the tasks of conventional geodesy is shown in Fig. 15. The LIBRA system affords the same two techniques for extending geodetic control nets as conventional surveying: first, by dense coverage of an important area by a broad net; second, by linking two widely separated regions by a narrow chain. The second technique may be most appropriate for measuring motions in a narrow fault zone, the first for detecting premonitory motions prior to an earthquake over a broad area.

The single activity most crucial to the success of LIBRA is atmospheric calibration — removing the effect of atmospheric time delay from the range measurements. A brief study of the problem, and estimates of the accuracy that the final system can attain, are presented in Section XIV. LIBRA enjoys an advantage over conventional ground-to-ground ranging in that the lines of sight of LIBRA slant away from the troublesome surface layer into thinner, drier air, as illustrated in Fig. 18. Another major advantage is that the LIBRA ranging aircraft can gather meteorological data as it flies, combining ranging and calibration in a single operation.

The steps required to prove the feasibility of the LIBRA concept are outlined in Section XV, which recommends four phases of effort beyond the initial, study phase reported here:

PHASE I: Modify a commercial side-tone ranging system to attain 5 cm accuracy when data is properly calibrated; write a basic program to process LIBRA data, and perform simulation tests of an airborne system; use ARIES meteorological data (already available) to evaluate calibration techniques.

PHASE II: Use a 3-channel ranging system in the field to perform tests and demonstrations at selected ARIES sites using coplanar multilateration (described in Section XIII, and illustrated in Figs. 17a, b, and c).

PHASE III: Deploy a 6-marker system for routine support of the ARIES program. (This will reduce the number of ARIES sites to be occupied and will reduce the cost of ARIES operations.)

PHASE IV: Begin construction of a large scale LIBRA system using ground markers of advanced design.

We believe that this four-phase program, which may extend through fiscal years 1976 through 1980, will minimize costs in three important respects:

(1) The initial field tests and data acquisition can be performed using modified 3-channel commercial equipment that can be operated by contractor. (See Sections VIII and XIII.)

(2) Each phase beyond the first gathers data useful to the ARIES Project, and is completed by a logical decision point at which results can be evaluated before proceeding to the next phase.

(3) Potential users of LIBRA for conventional geodesy, such as state and federal governmental agencies, can be included in Phase IV development in a natural and logical way, via an Applications Systems Verification Test Project (ASVT).

II. GEOPHYSICAL REQUIREMENTS OF THE ARIES NETWORK DENSIFICATION TASK

The geophysical requirements for the ARIES Project, including the ARIES Network Densification Task outlined in this report, can be set forth in four basic theses.

(1) <u>Much detailed data must be acquired before the general theory of plate tectonics can be applied to the specific problem of</u>

earthquake hazards estimation; to gather such data is the purpose of the ARIES Project.

One must not try to leap from the generalizations of the plate tectonic theory directly to a program for determining earthquake hazards. The junction between the North American and the Pacific Plates is not the single line of the San Andreas Fault, but a mushy zone including the fault block mountains of Nevada to the east and the Juan de Fuca plate to the northwest. The purpose of the ARIES Project is to determine the locations of stations carefully chosen to represent local, regional, and provincial features.

A schematic diagram of what may be expected on a strike-slip fault (such as the San Andreas Fault) is illustrated in Fig. 1. Two crustal blocks slide past one another, and the fault is their surface of contact. If it were possible for the two crustal blocks to slide smoothly, then no stress would accumulate and no earthquakes would occur. In actual fact, such blocks exhibit a stick-slip behavior in which stress builds up during the sticking phase, over a period of decades, and then is released in a sudden slip, that is, an earthquake. The behavior of the blocks is very much like the motion of a bow over a violin string, on a much longer time scale. One major problem in applying existing knowledge of plate tectonics to the estimation of earthquake hazards is that conventional geological information gives only the rate of motion of the blocks (in the analogy, the speed of the bow across the violin), whereas we need to know the exact time function of stress and the frequency of slip (the quality of the music). However, that is by no means the only problem.

The San Andreas Fault is not a boundary between two rigid crustal plates, but rather it is one of numerous cracks along which southern California has been split and sheared (see Fig. 2). Seismic events occur over a wide area of the Pacific and Rocky Mountain States, with a broad spur of earthquake activity extending through Nevada as far north as Montana, far from the known boundary between the North American and Pacific plates (see Fig. 3). Concerning the fact that present theory does not account for the known distribution of earthquakes in North America, Ref. 3, p. 60, comments:

> We speak of boundary effects as though we were dealing with a unidimensional phenomenon. Actually, the tectonic effects apparently related to the western plate margin have extended inland nearly 1,000 miles in the course of geological history; in fact, tectonic activity continues locally throughout much of this broad area today. How can we relate the enormous faults, uplifts, overthrusts and tectonic depressions, the volcanic activity that has been widely present in the area since Cambrian time, the great plutonic igneous batholiths of Mesozoic and Cenozoic age, and the widespread occurrence of important mineral deposits to the phenomena occurring at the western plate margin? In particular, can the actions at a plate boundary produce deformations and extensive igneous activity as far east as the Rocky Mountains and the Black Hills? In general, the plate tectonics model provides a satisfactory explanation of the present behavior of the earth in a narrow strip along parts of the western coast, but it is apparent that much work remains to be done to understand the tectonic and petrologic history of the entire western Cordillera with its associated seismic and volcanic activity and enormously important mineral wealth.

This document goes on to recommend (p. 60):

> Extensive triangulation and leveling, together with seismic data, are beginning to provide a kinematic picture for California but, as yet, only in a very sketchy and inadequate fashion. Similar installations and connecting networks for other seismically active states, especially Nevada, Washington, Oregon, and Alaska, would vastly improve the movement picture and therefore permit us to understand better the exact nature of relative plate motions.

The precise purpose of the ARIES Project is to provide this "kinematic picture." We do not wish merely to test the existing theory, but to provide the data necessary to extend it to the phenomena it does not now describe.

But is it necessary to supplement ARIES by conventional triangulation and leveling? The economy and effectiveness of ARIES would be enormously increased if a network of geodetic control markers could be radiated out to 200 or 300 km from each ARIES position, with 1 to 4 cm accuracy, without the need either to employ slow, conventional geodetic techniques or to transport the ARIES antenna to hundreds or even thousands of sites throughout the American Southwest.

(2) ARIES should not be confined to the vicinity of a few major faults, because measuring motion along known faults, on the one hand, and earthquake hazards estimation, on the other, are entirely different tasks.

The common idea that population centers in California are menaced exclusively by the San Andreas Fault is far from the truth. Table 1 lists the damaging earthquakes that have occurred in California since 1900. This table shows that seven serious earthquakes, causing loss of life and extensive damage, have occurred in California in this century — in 1906, 1915, 1925, 1933, 1940, 1952, and 1971 — and of these, at least four occurred on faults other than the San Andreas. Furthermore, every one of these seven earthquakes occurred on a fault branch not previously recognized to be dangerous. The San Andreas Fault had been identified as early as 1893, but was not known to be a major hazard. The Santa Barbara earthquake of 1925 occurred on one of the faults of the Santa Ynez system, but it is still not known exactly which individual fault line was involved. There is a high probability that at least one very destructive earthquake will occur in California in the next 30 years on a fault now thought to be inactive.

Figure 3 illustrates the occurrence of distinctive earthquakes nationwide, and shows how numerous and various their locations have been. It is not possible to associate most of these earthquakes with active faults, at least partly because in many areas the underlying rock structure is hidden by alluvium.

The practical implication of Table 1 and of Fig. 3 for us is that ARIES must not be confined to the vicinity of the San Andreas Fault. This fact is highlighted by studies made for the Office of Emergency Preparedness and the Disaster Assistance Administration of NOAA (Refs. 5 and 6), which showed that the faults having the greatest potential for damage in California are the Newport-Inglewood Fault near Los Angeles and the Hayward Fault east of San Francisco, because of the distribution of population.

We conclude that the ARIES Network Densification task must monitor the so-called minor faults in California, especially those in populated areas, where large antennas are not readily deployed.

(3) <u>ARIES must test various theories of the earthquake mechanism, without being designed to depend on any one of them.</u>

One of the current ARIES program objectives is to obtain data of sufficient quality and quantity to test the dilatancy-fluid diffusion model of the earthquake mechanism. According to this model, the rock on a fault dilates just before rupture; that is, microscopic cracks open throughout the rock. The rock expands, and the speed with which P-waves (primary, or compressional waves) propagate through the rock is reduced. One effect of dilatancy is to reduce the fluid pressure in the pores of the rock, which strengthens the rock and postpones the earthquake. Eventually, however, water from unstressed regions diffuses into the earthquake zone, weakening the rock and triggering the earthquake. One of the observations on which the theory is founded is that the P-wave velocity has been observed to diminish and then recover before several earthquakes, presumably as cracks opened and then filled with water (Ref. 7, and see Fig. 4).

Some of the questions that must be considered before dilatant phenomena can be used with confidence as premonitory earthquake signs are these:

(a) Do the phenomena depend on the kind of rock in particular locations? If so, dilatancy would give no reliable indicator of the time or magnitude of the earthquake.

(b) Do dilatant phenomena appear on all kinds of faults — strike-slip as well as thrust faults? Several investigators (Whitcomb, Robinson, and others, Refs. 7 and 8) believe that the answer is yes, but at least one investigator (McGarr, Ref. 9) reports no change in P-wave velocity before a South African tremor believed to be associated with normal faulting.

(c) Do shallow earthquakes obey the same relationship between dilatant phenomena and earthquake time and magnitude as deep earthquakes, or is there a difference, due for example, to differences in temperature and in water and vapor pressure?

The ARIES Project is ideally suited to attack several of these questions, because of the ability of ARIES to measure positions in three dimensions, and so to detect the local uplift that is believed to result from the expansion of dilatant rock. However, a network of several hundred points must be measured frequently if a large earthquake is to be detected, especially if more than one or two data points per earthquake are to be obtained.

(4) <u>If ARIES (or any similar system) is used over intercontinental distances, such as the circum-Pacific area, then there must be a means of distinguishing local from global effects.</u>

The special situation of the Hawaiian Islands affords a case in point. Most proposals to measure continental drift by space techniques suggest a geodetic station on one of these islands. Commonly accepted theories of the origin of the islands are that either a "hot-spot" or a rising mantle plume feeds the volcanism at the surface and that the motion of the Pacific plate carries extinct volcanic islands away to the west-northwest, as a breeze carries puffs of smoke away from a fire. Dalrymple, Silver, and Wilson (Ref. 10) point out that all existing theories of the origin of the islands fail to account for several observed facts:

(a) The island volcanoes do not lie in a straight line, as they might be expected to do if they were caused simply by the passing of the Pacific plate over a motionless "hot-spot," but they lie on a broken triplet of sinusoidal arcs (see Fig. 5).

(b) Although the oldest islands in the chain are those furthest from the presently active Mt. Kilauea, the age-distance relationship is not linear.

(c) Several theories imply that all volcanic material is derived from the lithosphere, but neither the chemical variety of Hawaiian lavas nor the sequence in which they are erupted is explained.

Then is the present motion of a point on Hawaii or Maui representative of the Pacific plate? Since the mechanism that has produced (and is producing) the Islands is not clearly understood, it would be hazardous to assume that the motion of a single point on one of the younger members of the chain adequately represents the motion of the Pacific Plate. One must be especially cautious in view of the short twinkle of geological time over which a NASA project can run. Volcanism appears to occur in pulses of duration of the order of 10^4 to 10^6 years, and during any given decade there might take place local movement due to activity in the magma chamber. Furthermore, since the theoretical picture is not settled at this time, there are no clear-cut hypotheses for a VLBI experiment to test. No matter what the result of such an experiment might be, the question would arise: just what have you measured?

The four theses developed above all point to the same conclusion. It is necessary for the purposes of earth physics to lay down a fine-meshed geodetic net with a spacing of tens rather than hundreds of kilometers. Such a net could resolve some of the complexities of California's fault motion, monitor wide areas for the local uplift that may precede an earthquake, and also tie together the Hawaiian Island volcanoes, the extinct with the active, so that any motion measured by a master station could be related to the entire island chain and not just a single point. (The discussion has been worded in terms of ARIES, though it will be seen that these four theses apply equally to the lunar ranging experiment (LURE), laser ranging to satellites, or any other technique.) The basic problem, then, may be termed network densification: interpolating a fine network of geodetic control between the coarse grid laid down by ARIES. This problem arises primarily from simple economics: it would be expensive for a team of several men to take and reduce astronomical, VLBI data every 20 or 40 km.

The reasons why no existing geodetic system, or any currently under development save the one to be described in this report, is adequate to the ARIES Network Densification Task, are four in number:

(1) Ground-based geodetic systems are slow, for they depend on teams of operators moving across the countryside point by point; therefore, they provide poor time resolution of the phenomena in question.

(2) The best conventional coordinate systems are inadequate to provide a fixed framework in which to measure earth motions. Markowitz and others have shown (Ref. 11) that even astronomical zenith tubes, which in principle can measure latitudes to a precision of about 20 cm, display variations large compared to continental drift, both because of systematic error and wandering of the terrestrial poles.

(3) Although ARIES is a three-dimensional system, every ground-based system with which we could compare it or supplement it attains either horizontal or vertical control, but not both together.

(4) A serious limitation in conventional leveling is that it attains reasonable accuracy and cost only when traversing flat country. But flat country in the American Southwest typically connotes intermontane valleys filled with loosely consolidated alluvium, which may be expected to display large vertical movements depending on the amount of underground water, and which mask the important crustal movements beneath.

Nevertheless, it is not implied that techniques other than ours have nothing to offer, only that they must be supplemented. We pursue this subject further in the next section.

III. SYSTEMS REQUIREMENTS FOR THE OPTIMUM USE OF ARIES

Since several methods exist by which fine geodetic control networks are now established, it is necessary to see to what extent they can contribute to solving the network densification problem.

The fact that ARIES and the proposed ARIES network densification system are but two of the many geodetic techniques either now in use or under development makes it necessary to determine how various systems can most effectively be mixed, both for accuracy and economy. The attributes and requirements of ARIES can be stated in three theses.

(1) The prime virtues of the ARIES technique over others are these: the speed with which results can be obtained; the anchoring of coordinates to an absolute frame of reference; and the ability to measure three dimensions simultaneously (see Fig. 6).

Other techniques either presently available or under development have one or two of these advantages, but not all three. The ARIES technique, then, should be developed especially for applications requiring these advantages, and then extended to other applications as costs permit. Earth physics, especially earthquake hazards estimation, provides the most obvious application of ARIES at the present time.

The importance of these three characteristics to geodesy in Southern California may be demonstrated by the failure of first-order level lines to close. In a study of such lines, Emery Balazs of the National Geodetic Survey commented (Ref. 12):

> When an over-the-limit misclosure develops between two anchor bench marks, we usually assume that one of the bench marks has moved and we will assign a new elevation for this bench mark. But when we have consistently a four-times-over-the-limit misclosure between tidal bench marks at San Francisco and San Pedro, and similarly over-the-limit misclosures between tidal bench marks south from San Pedro all the way to San Diego, and, at the same time, tidal observations indicate no change in difference in elevation from Mean Sea Level to the tidal bench marks in question, we have a problem. This problem is very unusual and difficult to solve without upsetting the existing vertical control net in the southern half of California.

Richard Mitchell, Assistant Division Engineer of Los Angeles County, made a careful study of the problem observed by Balazs. Mitchell remarks (Ref. 12):

(a) Each running was made by a highly skilled level party that had many, many miles of completely satisfactory leveling experience.

(b) The three runnings agreed closely with each other in each section.

(c) One running was made by a second party using a different instrument and rod pair.

(d) The closure to the east of the line (the only one available to Mitchell) was materially improved by applying rod corrections that appeared negligible in the first closure test.

(e) The location of the line is in an area of great geologic complexity and of considerable seismic activity.

(f) Another link in the same loop had previously and has subsequently presented problems.

(g) Excessive divergences were encountered in running this line and are still unexplained at the present time.

The problem was apparently caused by one or a combination of the three factors corresponding to the disadvantages of conventional geodesy with respect to ARIES. Conventional leveling is slow, and was referred to a mean sea level at tidal benchmarks established from 9 years of averaging at San Pedro and 20 years at San Francisco. The tidal benchmarks at a few points along the coast furnished the only available control on the coordinate system, and the San Pedro mark is in an area made unstable by extensive harbor modifications as well as by continual pumping of water and oil. Nevertheless, conventional leveling was the only means available for attaining vertical control, since laser geodimeters and other new distance measuring equipment give horizontal control only.

The speed, the celestial orientation, and the three-dimensional capability of ARIES are of major importance to practical geodesy. The San

Pedro station mentioned above serves as a reference mark for surveying activity through the San Fernando area before and after the destructive earthquake of 1971. It is interesting to notice that the U. S. Geological Survey discovered that, between 1934 and 1938, the Red Mountain area north of Ventura rose 26 cm relative to survey stations in the south, producing a sharp inflection in first-order level lines (Ref. 13).

(2) The purely geodetic applications of ARIES, apart from earth physics, must be included in systems planning from the outset (see Fig. 7).

The charter to carry out geodetic programs lies primarily with National Oceanic and Atmospheric Administration (NOAA), not with NASA. Therefore, we are planning the ARIES Network Densification Task primarily with earth physics in mind. Nevertheless, since the ARIES data could resolve such long-standing problems in geodesy as that discussed in the previous paragraph, the practical applications of ARIES outside earth physics must be included in a systems plan.

The need to avoid duplication of effort was highlighted by the appearance of an Office of Management and Budget document (the Donelson report, Ref. 14), which recommended that civilian mapping should be unified in a single agency. This report notes that, in 1973, 28 different civilian federal agencies were engaged in land surveying, and 17 in marine charting and geodesy. A well-designed geodetic system that satisfied the needs of many users would go far toward economizing geodetic operations in the U.S., whether or not the recommendations of the Donelson report are implemented. In fact, several of the problems mentioned specifically in the Donelson report — the southward tilting of the Great Lakes area, and the rapid subsidence of the Texas and Louisiana coasts — can be resolved by a dense network of geodetic control points fixed by the ARIES technique.

(3) One pressing need is to develop an economical means of bridging the gap between ARIES and conventional geodesy; that is, to provide a fine-mesh network of ARIES control points.

Both the geophysical and the geodetic systems requirements point to this conclusion.

The geophysics of the earthquake hazards estimation task in California can best be pictured in terms of a crude physical model. Suppose melted pitch were poured into a vessel with flexible sides, and allowed to cool just enough to form a hard crust on top. Then suppose that the vessel were flexed by precisely specified forces to some new shape. The pitch beneath would flow according to the Navier-Stokes equations, and the crust above would crumble and crack. If we wrote the equations that governed the flow of the pitch beneath, we might perhaps be able to calculate the rate of cracking and average stresses built up in the crust above, in a statistical way. But we could not by such a macroscopic approach answer the question, "In the next five milliseconds, where will the crust crack?" In the same way, we cannot estimate earthquake hazards by measuring drift rates. At most, we could calculate average earthquake rates per million years. To be of practical value, the ARIES Project must address itself to the difficult task of monitoring local stresses in the Earth's crust. The crucial work of developing mathematical models of strain accumulation on California's strike-slip faults is now underway — e.g., by D. L. Turcotte at Cornell (Ref. 15). But a dense geodetic network of high accuracy will be necessary to test and parameterize the model.

Geodesy for any purpose requires the kind of absolute celestial framework that ARIES can provide; but, to be useful, this ARIES control must be available at many points, and must often be reestablished. Good temporal resolution is as important as spatial resolution. We see this from the list which S. R. Holdahl (Ref. 16) once compiled of the known causes of vertical movement of benchmarks (and see Fig. 8):

(1) Tectonic action.

(2) Decline in an artesian head due to withdrawal of water.

(3) Loading at the land surface.

(4) Oxidation of organic matter.

(5) Decline in pressure in oil zones due to removal of oil and gas.

(6) Dissolution of minerals due to irrigation or ground water flow.

The fourth cause is known to be important in the peatlands of the Sacramento area. The second cause is a plague throughout the Great Central Valley, causing subsidence rates of several centimeters per year; it may be expected wherever water is being pumped from closed or partly closed sediment-filled basins — from most of the important places where people live. All of these causes of vertical movement act locally and over short time intervals, and all of them must be geodetically monitored if they are not to corrupt our observations of the global and geological phenomena that we seek to understand. The new distance measuring equipment now under development (e.g., the multiple wavelength geodimeter, by the National Bureau of Standards) will afford horizontal control, but not vertical control. There is a gap in the spectrum of available geodetic techniques that badly needs to be filled.

IV. A CLASSIFICATION OF THE VARIOUS RANGE POSITIONING SYSTEMS

Broadly speaking, all systems for determining positions that depend on ranging can be classified along three dimensions (see Fig. 9). The three dimensions are these: the type of vehicle used (such as satellite or aircraft); the type of ranging device that is used (such as radio, or laser); and whether the ranging target is made active or passive (either a transponder of some kind, or a simple reflector). By thus sorting the very many types of possible systems in this three-dimensional array of pigeonholes, we simplify the analysis considerably, as will be seen below.

A hypothetical positioning system could be designed from a combination of any three elements selected from along the three axes; and in fact the following systems have been either built or proposed before the present study began:

A. SATELLITE SYSTEMS

1. Radio

The radio/satellite (or radio/missile) positioning systems are of three basic types. The first and most basic type uses either pulsed or continuous-wave (CW) signals to measure time of return and therefore range; in practice, what is measured is phase delay. One problem that must be overcome is "phase ambiguity." Since the wavelength of the radiation must be short to be focused toward the target at an acceptable level of signal strength, many cycles of phase shift are incurred over short distances. To avoid the ambiguity problem, many systems supplement the carrier with additional ranging frequencies. The second basic type of radio system measures phase rate, or Doppler, and integrates ("counts Doppler") to measure range change. The third basic system measures difference in phase of a signal returned from a target between two receivers to calculate a direction cosine; this is essentially radio interferometry.

a. Examples of Active Systems

DOVAP: measures Doppler at several stations to deduce positions of a cooperating missile carrying a frequency-doubling transponder; long used on the Atlantic Missile Range and at White Sands.

SECOR: uses a minimum of three ranging stations (one master and two or more slaves) to triangulate a cooperating missile or satellite; developed by the Cubic Corporation for the Atlantic Missile Range.

There are many variants of these two basic systems.

b. Examples of Passive (Receiver) Systems

DOPLOC: measures the change in Doppler of a satellite passing overhead to derive orbital parameters, designed for horizon-to-horizon tracking.

MICROLOCK: a system designed at JPL, similar to DOPLOC, to track a satellite by means of its telemetry carrier wave. It differs from DOPLOC primarily in the phase-tracking circuitry.

2. Laser

All working or proposed laser/satellite systems are "passive" in the sense that a laser is used to range a passive reflector (typically an array of retroreflectors). Thus, a basic advantage of a laser system over active radio systems is that there is no transponder delay to calibrate; therefore, very high accuracies can be obtained. There are two basic types of positioning logic, the first of which (dynamic modeling) combines range measurements taken at different times by modeling the orbit (e.g., Ref. 17), and the second (multilateration), by which simultaneous measurements are combined to solve for the relative positions of stations and satellite by geometry alone (Refs. 18, 19, 20). An advantage of multilateration is freedom from orbital modeling errors and, theoretically therefore, higher attainable accuracy. Examples follow.

SAFE:	uses dynamic modeling to calculate distances across the whole complex of California faults from Mt. Otay to Quincy. An earlier version of the system ranged to a satellite at maximum latitude, for which the effect of errors in the satellite orbital parameters could be minimized.
"3-D Multilateration":	a proposed system, outlined in Ref. 20, for detecting motion on active faults in southern California. The basic method will be used at JPL on GEOS-C data.

B. AIRCRAFT SYSTEMS

1. Radio

Most radio/aircraft systems are for navigation, and do not differ in basic principles from the radio/satellite systems described above.

a. Raydist: Example of an Active System. Variants of the Hastings-RAYDIST System are used both for navigation and for missile tracking, and rely on continuous phase-tracking to establish the phase difference between signals received at two or three stations to determine position.

b. Examples of a Passive System. By definition, passive radio/aircraft systems are radar systems. Average power requirements are minimized by pulsed instrumentation radars, which trade time as a variable to attain high signal-to-noise ratio. The phase-ambiguity problem is resolved by modulating the frequency of the pulse, for example by linearly increasing the frequency with time ("chirp radar"). One system important to this study is the coherent imaging radar system built and flown under the supervision of Walter E. Brown of JPL (Ref. 21). This system uses a wavelength of 25 cm (1215 MHz), and has a peak power of 6 kW; it employs an optical recorder to store data from which photograph-like images can be reconstructed of a landscape or seascape. The present study began by examining whether or not a modification of this system could be used for VLBI network densification; the analysis is presented in Section VI.

2. Laser

One obvious disadvantage of a laser/aircraft system is that an aircraft is an unstable platform to aim a laser from, and (because of the need to protect the pilot's eyes) is a dangerous target to aim a laser at. Nevertheless, promising possibilities of such a system were touched upon in Ref. 20.

Of course, the examples given above are by no means an exhaustive list. Some of the most promising and important techniques appear to be classified. Nevertheless, the examples are characteristic of the many types of systems with which one of the authors (Gantsweg) has acquaintance, and they illustrate an important conclusion.

The VLBI Network Densification Task imposes at least four requirements on a potential system:

(1) The network spacing, or "mesh," should be about 20 to 100 km, with the option of a mesh as small as 5 km in areas of exceptional interest. This follows from the facts that ARIES will establish a grid of points with average spacing of 100 km or so, and that

the dilatancy theory predicts uplift prior to a large earthquake over a roughly circular area 50 to 100 km in diameter.

(2) The system must be capable of remeasuring positions quickly. Premonitory earthquake signs may manifest themselves on a scale of days or weeks, not months or years (Ref. 7). Especially in the first decade or two of the ARIES project, when the primary purpose of data gathering will be to test the conflicting theories of the earthquake mechanism, good time resolution will be essential.

(3) The system should not, therefore, be limited by bad weather, or by the smog that limits conventional geodetic measurements to a few days per month in a large area of Southern California south of the Transverse Ranges. ARIES is an all-weather system, and so should be the network densification system.

(4) The system must be inexpensive. It should offer a substantial saving in cost over conventional geodesy.

When we combine these four criteria with the three-dimensional classification outlined above, we find the specifications of our proposed system outlined pretty narrowly. Because the network spacing is comparatively small (20 to 100 km), and since the geometry of multilateration requires that the altitude of the vehicle not be an order of magnitude greater than the station separations, <u>an aircraft is preferable to a satellite</u>. Because we will want to remeasure positions quickly, <u>it should not be necessary to relocate the ground stations</u>. Because we require an all-weather system uninhibited by smog, <u>radio (or radar) is preferable to lasers</u>. Because the system must be as inexpensive as possible, and because one ranging system in the vehicle is almost certain to be cheaper than many ranging systems on the ground, <u>the ranging system should be in the vehicle</u>. The four underlined statements form the principal conclusion to the first part of our work, and may be summarized as follows:

<u>The optimum system to perform the ARIES Network Densification Task should be an airborne radio or radar system ranging to inexpensive markers at fixed ground sites</u> (see Fig. 10).

V. CRITIQUE OF A PROPOSED AIRBORNE RADAR POSITIONING SYSTEM

Pursuing the logic outlined in the preceding section, we and our JPL advisors began to sketch requirements for an airborne radar system ranging to passive, inexpensive markers on the ground. At the very outset, we encountered a difficulty that is theoretically annoying, and practically fatal so far as presently available hardware is concerned. There is no way to juggle the available parameters of system power, operating frequency, and size of marker in such a way that sufficient accuracy can be achieved using markers of reasonable cost and size.

One of the most troublesome problems in a system design using a passive marker is the detection of reasonably sized targets obscured by the signal returning from the background landscape, and the most important single factor in detection is the frequency of the system. The signal-to-noise ratio is set by the "clutter," the reflection from the countryside surrounding the target, and it cannot be improved by increasing the transmitted power, since signal and "clutter" rise proportionately. The signal-to-noise ratio is improvable in only two ways, by increasing the size and efficiency of the target, and by improving the resolution of the radar, so that the smallest distinguishable area of the landscape is reduced to a minimum. This area is the product of two factors: a width, determined by the angular resolution of the radar (using a rotating antenna and a fan beam) and given by the expression

$$R \cdot \frac{\lambda}{\omega}$$

where

R = range along the ground

λ = radar wavelength

ω = width of antenna

and a breadth, determined by the time resolution of the radar and given by the expression

$$\frac{c}{b\nu} = \frac{c}{b \cdot \frac{c}{\lambda}} = \frac{\lambda}{b}$$

λ = radar wavelength

b = bandwidth factor (a decimal fraction)

The effective cross-sectional area of a Luneberg lens type ground marker (a spherical cat's eye lens at radio wavelengths, retrodirective and having high gain, therefore an attractive candidate to analyze) is given by the expression

$$4\pi r^4/\lambda^2$$

where r is the radius of the Luneberg lens.

The signal-to-noise ratio (SNR) is the effective area of the receiver divided by the effective area of the smallest resolvable element of landscape; combining the above expressions, we have the equation

$$\mathrm{SNR} = \frac{4\pi r^4 \omega b}{R\lambda^4}$$

The formula for the ranging sigma of a coherent radar system is

$$\sigma_R = \frac{c}{2B(\mathrm{SNR})^{1/2}}$$

where

$$B = \text{bandwidth}$$

$$= b \cdot \frac{c}{\lambda}$$

Substituting for our SNR, we have

$$\sigma_R = \frac{R^{1/2} \lambda^3}{4\pi^{1/2} b^{3/2} \omega^{1/2} r^2}$$

The important point to notice in all this is that the ranging sigma decreases more rapidly with the radar wavelength ($\sim \lambda^3$) than with any other factor. Notice that the λ^3 factor enters in the following way:

λ from the Luneberg sphere response

$\lambda^{1/2}$ from the range discrimination

$\lambda^{1/2}$ from the antenna beam width

λ from the bandwidth-frequency factor in σ_R.

For the present 20- or 25-cm radars already developed, the SNR is hopeless for a reasonably sized Luneberg sphere. A 3-cm radar is possible, and an 8-mm system looked very promising, at least on paper:

$R = 30 \text{ km} = 3 \cdot 10^1 \cdot 10^5 \text{ cm}$

$\lambda = 0.8 \text{ cm}$

$b = 1/10$

$\omega = 1.6 \text{ m} = 160 \text{ cm}$

$r = 9 \text{ in.} = 22.86 \text{ cm}$

then

$$\sigma_R = 0.6 \text{ cm and SNR} = 44.7$$

but if

$\lambda = 3 \text{ cm},$

$\sigma_R = 31.5 \text{ cm, with SNR} = 0.226$

At first glance these calculated parameters seem quite reasonable. Unfortunately, for a system design that ranges to a target on the ground, the background can limit the return SNR. The SNR for a return is:

$$(\mathrm{SNR}) = \frac{\text{effective area of ground marker}}{\text{area of interrogation}} = \frac{A_R}{A_I}$$

Now

$$A_R = A_m G_m$$

where

A_m = effective area of marker antenna alone

G_m = marker gain

For the case when the marker is passive, G_m = 0 dB or 1.

As pointed out above, using a passive reflector as a marker forces λ to less than 1 cm to maintain adequate SNR. Unfortunately, a radar at these small wavelengths is seriously affected by weather due to excessive two-way signal attenuation, as well as antenna design problems associated with high gain requirements and multiple access to the markers.

The requirement that the system be operable in all reasonable weather would limit the system to wavelengths longer than 3 cm. Atmospheric absorption above the 10-GHz (3-cm) region is dominated by a broad water vapor line at about 22 GHz (~ 14 mm), and a narrow O_2 line at about 60 GHz (5.0 mm) (see Fig. 11). Clouds of rain pose a serious restriction. For example, at 8-mm wavelength we could expect an attenuation of 0.3 dB/km for an instantaneous rain rate of 1 mm/h (drizzle), 1 dB/km at 3 mm/h (light rain), and 4 dB/km at 16 mm/h (moderate rain). The real problem, besides attenuation, is backscatter, which can decrease the signal-to-noise ratio to unacceptable levels. The proposed system would need a wavelength greater than 3 cm to eliminate most weather concerns, and a wavelength of 8 mm or less to attain the necessary signal-to-noise ratio — not a promising situation. Inhomogeneities in the atmosphere, from patches of air more than 100 m across, can cause rms phase variations of about 1 mm even in the best conditions, which would cause slight but inconsequential power loss to a 3-cm radar. At 8 mm, the larger inhomogeneities over sunlit desert areas may be expected to limit performance even on dry, clear days.

The conclusion to this part of our study was that an airborne radar system ranging to passive markers on the ground is marginally possible using 8 mm wavelengths; but the very great cost of developing such a high frequency system, and the sensitivity to weather, make it unpromising in the present state of the art.

VI. INTERCOMPARISON OF POTENTIAL RADIO SYSTEMS

As described in Section V, the possibility of radar ranging to passive benchmarks on the ground, such as Luneberg lenses, presents several imposing problems. The radar would have to operate at 10 to 40 GHz to discriminate the target from the landscape, at a bandwidth of 1 to 4 GHz, with a rotating fanbeam that would preclude true simultaneous ranging, and with serious restrictions in bad weather. It has been found that active, battery-powered markers may be no more expensive than Luneberg lenses; they can be manufactured to the specifications to be set forth in Section VII for less than $6000 apiece, even in small quantities.

The signal-to-noise ratio (SNR) calculations for an active system (ranging device plus transponder) are as follow. Beginning with the comparison of active versus passive marker effective area, we have

$$SNR_{passive} = \frac{\text{area of reflector}}{\text{area interrogated}} = \frac{A_r}{A_I}$$

$$SNR_{active} = \frac{\text{effective area of marker}}{\text{area interrogated}} = \frac{A_M}{A_I}$$

where

A_M = effective area of marker's antenna × gain of transponder

$A_M = A_R \times G_T$

Now

$$SNR_{active} = \frac{A_R G_T}{A_I}$$

$$\frac{SNR_{active}}{SNR_{passive}} = G_T$$

Thus, an active marker provides the advantage of turnaround gain G_T, and a carrier frequency ≤10 GHz can now be used. The ranging accuracy is not dependent upon choosing small wavelength carriers. It should be noted that when an active marker transforms to a different carrier frequency on the up link, then clutter from the downlink return is of no concern.

The conclusion is that an active marker should be used on the ground. The ranging signal sigma for coherent ranging is:

$$\sigma_R = \frac{C}{2B(SNR)^{1/2}}$$

where

$$B = b\,\frac{C}{\lambda}$$

so that

$$\sigma_R = \frac{1}{2b/\lambda\,(SNR)^{1/2}}$$

The factor $2b/\lambda$ (the factor 2 may differ slightly as a function of the modem) is denoted as the system effective bandwidth, B_e.

Thus,

$$\sigma_R = \frac{1}{B_e(SNR)^{1/2}}$$

The 1 sigma ranging accuracy is thus a function of the system design effective bandwidth B_e, and the SNR at the demodulator output. The system effective bandwidth, B_e, is a function of the type of DME modulation, and the carrier frequency. As an upper limit, B_e is to equal the carrier frequency, f_c. Due to ambiguity resolution and bandwidth problems, a practical upper limit is $1/10\ f_c$. Solving for the minimum SNR required we have:

$$(SNR)_{min} = \frac{1}{\sigma_R^2 (B_e)^2_{max}}$$

$$\sigma_R \cong 3 \text{ cm or } 10^{-10} \text{ s (LIBRA/ARIES goal)}$$

$$B_{e_{max}} = 1/10\ f_c$$

$$f_{c_{max}} = 10\ G_c \text{ (limit due to weather attenuation)}$$

$$(SNR)_{min_2} = \frac{1}{(10^{-10})^2 \left[(1/10)10^{10}\right]^2}$$

$$(SNR)_{min_2} = 100 \text{ (20 dB)}$$

We can trade SNR for B_e — i.e.:

$$B_e = 10^7$$

$$SNR \cong 60 \text{ dB}$$

$$\sigma \cong 3 \text{ cm}$$

or,

$$B_e = 10^8,$$

$$SNR = 40 \text{ dB}$$

$$\sigma \cong 3 \text{ cm}$$

If we decrease the effective bandwidth we must increase the SNR to provide a $\sigma_R = 3$ cm. We need a system that both provides a high SNR and is broadband.

Systems that satisfy these requirements (using an active marker) are of three basic equipment types: (1) pulsed, (2) side-tone range (STR), and (3) pseudo-noise (PN) code. Pulsed radars require large bandwidths and high peak powers. None surveyed can be used for our application, since their ranging accuracies were inadequate and they were designed for use with passive targets. STR is presently used in many ranging equipments, all with active markers using very high SNR to obtain high measurement accuracy. CW coded (PN) systems have been used by JPL and others very successfully. They use active markers and large bandwidths to obtain high accuracy. Unfortunately, the active correlation demodulation process is very complex; thus, equipment costs are a limiting factor. One promising avenue of investigation was the use of surface acoustic wave devices (SAWDs), also called surface wave correlators (SWC). These devices can provide inexpensive modern distance measuring equipment (refer to Section VII for details). Table 2 compares the important characteristics of a coded ranging system using active (no SWC) vs. passive (SWC) modems. Notice that both the SWC length and speed would limit its present applicability toward achieving the desired accuracy. Improvements in surface wave devices will be followed closely.

An outline of seven DME system types is given below.[1] System Type A is the passive system we considered originally. System Types E and F seem promising if surface acoustic wave devices are improved in performance. System Type G (STR) is the most promising candidate, since it is commercially available and is relatively inexpensive. Ranging accuracy is basically identical to the coded and pulsed radar systems and is easiest to implement. Practical side-tone ranging (STR) systems can provide 1- to 4-cm accuracies and are presently used for survey operations.

System Type A: coherent ranging using passive target (Luneberg lens)

Center frequency:	greater than 30 GHz.
Aircraft transmit power required (effective radiated power):	2.5 MW! note: no consideration of weather effects are accounted for.
Ultimate accuracy:	approximately 1 cm
Remarks:	a high peak power transmitter is required on the aircraft to overcome two-way path losses; weather will create additional attenuation problems; the high gain requirement of the aircraft limits multiple access to time division multiplexing (an inertial platform is required to reduce dynamic errors between samples or multiple steerable beams); the time delay variation of the target is negligible.

[1] Parametric values used for the summary are sample, realistic values.

System Type B: coherent ranging using an active target (e.g., chirp radar in aircraft with ground transponder); surface wave dispersive delay line in aircraft.

Center frequency:	1 GHz; $B_e = 100$ MHz.
Aircraft effective radiated power:	+50 dBm (100 W).
Uplink effective radiated power:	+33 dBm or 2 W when using a 27-dB gain receive antenna on the aircraft.
Ultimate accuracy:	approximately 1 cm when demodulating chirp; less than 1 cm if turnaround is carrier coherent.
Remarks:	aircraft processing gain is limited by chirp rate and dispersion; weather is not a problem; the active marker helped overcome the two-way path loss and SNR limitations of the return (System Type A); system requires a high gain antenna on the aircraft to ensure adequate output SNR of aircraft receiver; target has to be designed for minimal time delay variation.

System Type C: coherent ranging using an active target with pseudo-noise coded waveform; surface wave nondispersive delay line in the aircraft.

Center frequency:	same as System Type B.
Aircraft effective radiated power:	same as System Type B.
Uplink effective radiated power:	same as System Type B.
Accuracy:	better than chirp by a factor of 2 or 3 due to cross correlation property of code.
Remarks:	processing gain limited by code rate and length; other remarks as for System Type B.

System Type D: coherent ranging using pseudo-noise coded wave form to active target; active correlator used in the aircraft.

Center frequency:	same as System Type B.
Aircraft effective radiated power:	same as System Type B.
Uplink effective radiated power:	+33 dBm or 2 W (gain of aircraft antenna is 0 dB); processing gain = 60 dB; detection bandwidth = 100 Hz.
Accuracy:	approximately 1 cm for code demodulation; less than 1 cm if coherent turnaround.
Remarks:	processing gain = chirp rate/detection bandwidth (30 dB better than surface wave correlator); aircraft does not require a high gain antenna; simultaneous interrogation of markers can be accomplished since aircraft antenna may be omnidirectional; expensive markers are required; time delay variation of target must be minimized; code division multiplexing requires uplink power control for variable geometry; use of time division multiplexing would limit processing gain; markers need some form of identification.

System Type E: same as D with coded identification added to marker (i. e., a processing marker); identification accomplished by multiplying downlink code by demodulated pulse modulated square wave at marker (coherent detection provides accurate time synchronization); the square wave provides some processing gain against jammer input to the marker; expensive marker.

System Type F: same as D with acoustic surface wave device in the marker; downlink power is reduced by processing gain of the code

(20 to 30 dB); system accuracy is degraded by requiring a range measurement at the marker; requires further state of the art.

System Type G: side-tone ranging (STR)

Center frequency:	1 GHz; $B_e = 10^7$ Hz
Aircraft effective radiated power:	+33 dBm or 2 W
Uplink effective radiated power:	+33 dB or 2 W
Ultimate accuracy:	equivalent to chirp waveform
Remarks:	low radiated power required for both aircraft and ground marker; simultaneous interrogation of markers can be accomplished since aircraft antenna is omnidirectional; markers are inexpensive; marker identification by frequency multiplex; interference easily rejected due to narrow detection bandwidth for ranging tones; marker time delay variation must be minimized.

The RF power requirements of the aircraft and marker transmitters using the Type G configuration are calculated as shown in Table 3. The required SNR for a ranging σ_R of 0.1 ns (3 cm) is

$$\mathrm{SNR} = \frac{1}{B_e^2 \sigma_R^2}$$

$$= \frac{1}{(10^7\ 10^{-10})^2} = 10^6 \text{ or } 60 \text{ dB}$$

The required calculated radiated power for the aircraft or marker is of the order of 2 W. Allowing for multipath/fade margin, the ERP is more reasonably 10 W. For receiving and/or transmitter antenna gains larger than 0 dB, the transmitter power output is reduced accordingly.

VII. SPECIFICATIONS FOR A PRACTICAL AIRBORNE POSITIONING SYSTEM

The calculations outlined in Section VI are very promising. They indicate that the accuracy required by the ARIES Network Densification Task can be attained by modifications of existing side-tone ranging (STR) hardware, and that equipment costs should come down in the next 5 to 15 years because of improvements in acoustic surface wave devices (SAWD's). We therefore proceeded to outline the specifications of an airborne radio positioning system to be called LIBRA, such as would be required of potential contractors to obtain firm cost estimates for actual bidding.

The following is a summary of the preliminary system specifications for LIBRA (see Fig. 12):

(1) System accuracy (1 sigma): range error 1 to 4 cm. This accuracy is to be achieved following the removal of any known and measurable bias errors.

(2) System range (line of sight): 100 km.

(3) Collector: aircraft in overflight of area and in line of sight of at least six ground markers simultaneously.

(4) Collection intervals: the markers are to be powered such that the aircraft may check the marker location periodically, four times/week, one hour each, for one year, before changing batteries.

(5) Collector type: aircraft, preferably under 6,000 kg, gross. Alternate configuration: a U-2.

(6) Data collection: tape recorder (incremental) IBM compatible format. Interface buffer to convert data collected to proper format and add time code marks.

(7) Data reduction: nonreal time; not in aircraft. Status of whether data collected is valid is desirable.

(8) Downlink transmission: aircraft to markers. Frequency: 1 to 10 GHz. Bandwidth: less than ten percent of the carrier. Effective radiated power: 1 to 10 W (solid state source).

Geometric coverage: ranging to as many as six markers simultaneously, spaced up to 100 km apart. Downlink data: possible command requirements for turn on/turn off, power control, etc. Multiple access: must be able to access six markers at one time.

(9) Aircraft dynamics: velocity, 100 to 300 knots; acceleration, 3 Gs maximum; attitude, straight and level during data collection.

(10) Mechanical configuration: must fit into less than 6,000 kg gross aircraft. Easily removable for servicing. Ambient air flow provided for cooling. Must be transportable: weight, 80 kg; configuration, one 4-ft rack (standing).

Alternate configuration: must fit in U-2 pressurized compartment. Easily removable for servicing. Ambient air flow required for cooling. Must be transportable. Size: two air transport racks (standard size).

(11) Environment: 0 to 50°C. Shock/vibration compatible with commercial type aircraft.

Alternate: to be based on U-2 specifications.

(12) Power: aircraft auxiliary power unit, 115 Vac or 28 Vdc.

(13) Ground markers: inexpensive flags to be located on the ground, unattended, for up to one year. Interrogation frequency (maximum): approximately one hour per day for one year. Signal dynamic range: 60 dB; 40 dB range; 20 dB multipath. Turnaround time delay stability: less than 1.0 cm, equivalent. Receiving frequency: 1 to 10 gigacycles; bandwidth: ≤10% of the carrier. Receiving coverage: must work with collector at low elevation angles (approximately 12 deg to the horizon); azimuth coverage approximately 270 deg. Transmission frequency (uplink): a prime multiple of the downlink. Bandwidth: same as downlink. Uplink transmitter power: less than or equal to 1 W. Identification: each marker in each set of those ranging simultaneously must be identified uniquely. Mechanics:

must be transportable (manpack); weight, 20 kg; volume ≤0.04 m^3. Environment: must be able to withstand the rigors of unattended operation in all weather; must pass fungus and salt spray environments; thermal design range -25 to +75°C; shock and vibration should be consistent with transportation by a jeep vehicle and normal handling for field use. Reliability: must work unattended for up to one year. Data link: telemetry information (e.g., temperature, humidity, etc.) required from marker to aircraft. Interim unit may have separate telemetry system.

(14) Other considerations. System "on" time: must be able to collect data in 90% of area weather; moderate rain, fog, clouds shall not affect operation. Ambiguity resolution: aircraft shall resolve its position to within 15 km via onboard commercially available navigation equipment; data collected from markers shall be reduced to resolve distance to within measurement accuracy without ambiguity. Location of markers: markers are normally placed in remote areas; special cases may require location near urban areas.

VIII. A PRACTICAL SIDE-TONE RANGING (STR) SYSTEM

The question now arises: can any of the System Types A through G, outlined in Section VI, meet the specifications laid down in Section VII, at reasonable cost? We therefore examined commercially available equipment to see whether it could be improved to meet the ARIES Network Densification Task requirements, to eliminate the need to design a completely new system, which inevitably would be very expensive to construct. This approach directed us toward System Type G of Section VI (side-tone ranging, or STR) rather than to System Types E through F, which await improvements in SAWD hardware to achieve high accuracy at low cost.

The basic principle of STR is that modulation (tone) applied to a signal (carrier) that is propagated through space exhibits a phase shift that is proportional to the distance traveled and the modulation frequency. Range measurement is computed by measuring the phase delay of the tone, which has traveled between the interrogation aircraft and the responding ground marker, and by comparing this phase shift with a reference signal in the interrogator.

Phase ambiguity is resolved by the use of additional tones. To avoid "clutter" (confusing background echoes), the signal is sent by the transmitter at one carrier frequency and returned by the responder at another. The following description of a side-tone ranging system is taken by permission from Cubic Corporation's description of its Autotape, Ref. 22, and is broadly characteristic of any system that works by side-tone ranging:

> The Interrogator and Responders transmit continuously on separate frequencies. In operation, the Interrogator transmits a phase modulated ranging signal to the Responders which receive the signal and generate data and reference signals. The data signal is phase locked to the Interrogator modulation signal, and is used to determine range distance. The reference signal is phase locked to the respective data signal and used to indicate Responder internal delay time. The data and reference signals phase modulate the Responder RF carrier, are transmitted to the Interrogator which receives the Responder signal and mixes it with its phase modulated ranging signal. The resultant mixer output, when filtered, is an amplitude modulated (AM) signal, representing the signal received from the Responders. The AM signal is demodulated in the receiver and the composite data signal is filtered and passed to the Interrogator processor which computes the range to the nearest 0.01 meter. The above description describes the operation of the system using only one Responder. In actual practice, six Responders are utilized to simultaneously measure slant ranges to six remote sites. The Interrogator measures distance to the Responders by sequencing through three range tones (fine, intermediate, and coarse). The Responders automatically step through three tone pairs in sequence with the Interrogator, one pair each for fine, intermediate and coarse. Marker identification is by frequency multiplex (i.e., each marker has its own assigned RF carrier).

The Autotape System has a ranging accuracy of 50 cm if atmospheric effects are calibrated, and we know of no svstem more accurate in commercial use that which can be employed on a moving platform. (The Cubic Corporation also manufactures the Electrotape, with 1-cm ranging precision, which cannot be moved during observation.) We believe that the Autotape could be upgraded to the required accuracy for the ARIES Network Densification Task (1 to 4 cm) if the following error sources were removed.

IX. REMOVING ERROR SOURCES IN PRESENTLY AVAILABLE EQUIPMENT

The limits on the accuracy of the existing commercial Autotapes follow:

(1) Limited range resolution: the standard Autotape uses a fine modulation wavelength of 200 m (= 100 m of two-way range), and reads out to the nearest one-thousandth of a cycle to a precision of 10 cm. However, Cubic Corporation engineers assure us that the precision could be improved to 1 cm with no difficulty. (The Cubic Electrotape already has a 1-cm readout.)

(2) Temperature effects: the Autotape responder time delay variation with temperature is minimized via use of a time delay feedback loop. However, certain elements of the responder receiver outside of this loop, notably the receiver microwave filter, are temperature sensitive, producing possible errors of a few tens of centimeters over the temperature ranges of our proposed operation.

(3) Frequency standard effects: existing Autotape oscillators are stable to 3 parts per million, equivalent to 30 cm in 100 km. Our requirement for stability is to not more than 0.2 parts per million.

(4) Signal strength effects: the range measurement can change with input signal strength at the 10- to 20-cm level, primarily (according to Cubic Corporation engineers) because of the effect of varying local impedance on the receiver microwave filter.

(5) Velocity effects: these appear to be of two kinds: effects of Doppler shifts, and effects of time averaging. The bandwidth of the responder phase-locked loops is narrow (100 Hz), and a fast-moving aircraft might shift the incoming signal outside the filter bandpass. The Autotape time-averages the signal over 0.5 s, which introduces a possible source of error. If the aircraft is appreciably accelerated in turbulent ("bumpy") air, the time-average will be affected. The deduced station locations might not be affected, if there exists a mean point defining an "effective aircraft position" from which the ranges are valid. However, since there is noise on the signal, the time-average will not be exactly the same even for two nearby receivers, and will be a function of aircraft motion.

These limitations should all be greatly reducible by straightforward modifications of the basic system design. Frequency standards can be improved, the receiver microwave filter can be buffered, and signal levels from the transmitter can be increased. We believe that the following improvements could be made at minimum cost:

(1) Compensation for bias errors: these are errors associated with temperature and aging effects particularly critical in the turnaround markers. A reference subcarrier can be made part of the modulation waveform to calibrate the marker delay variations (including the RF section), in the following manner.

The marker delay is represented by τ. We interrogate the marker for each range measurement. The time rate of change of τ is negligible over the measurement interval. A range pulse inputs the marker after a delay T proportional to the range difference between the interrogator and the marker. The marker delays this pulse by τ, the marker delay. A sample of this output pulse is fed back to the marker input. The marker delays this second input pulse by τ and produces a second output pulse. The feedback loop only samples the output after the first pulse and remains open until the next interrogation interval. The marker output is now represented by a pulse pair. The first pulse of this pair represents the interrogator to marker range delay T plus the marker delay τ. The time difference between the second and first pulse represents a measure of the marker delay τ.

The interrogator, upon reception of the return pulse pair measures $T + \tau$ of the first pulse and τ, the time difference between the return pulses. It then performs

$$T + \tau - \tau = T$$

Thus the time delay is proportional to range independent of τ.

(2) Compensation for bias shift as a function of received signal level: the equipment receivers may exhibit a change in apparent bias error as the received signal is changed. Reasonably chosen geometries required for good multilateration should minimize this type of error, although the system design would still require <1 cm of shift due to approximately 20-dB expected signal variations.

(3) Elimination of range acceleration error: the use of phase lock tracking loops with narrow tracking bandwidths (100 Hz for markers and 1 Hz for aircraft interrogators) will negate range and range rate error effects for aircraft over a range of 150 to 450 km/h and ±3 g, respectively.

(4) Elimination of real-time averaging in favor of postflight digital processing: the velocity effects (and effects of system noise) with the existing equipment are significant only because the system is designed to give real-time ranges. If the signals returned from the markers were simultaneously recorded on tape and processed digitally, much longer effective integration times would be practical (e.g., 1- to 10-s samples).

(5) Use of improved quartz crystal frequency standards: the range accuracy is also dependent on the accuracy of the fine modulation frequency and the clock frequency that is used to measure the phase shift of the modulation frequency. If we use clocks

stable to within 0.1 ppm for six months, a range clock accuracy of 1 cm at a range of 100 km would be expected.

The following Table 4 summarizes the precision that can be attained by straightforward modifications to commercially available side-tone-ranging hardware.

We estimate that a side-tone ranging system could be built for $400,000 (1974), with receivers at less than $6,000 (1974) if built in quantity. Therefore an entire working system, sufficient to monitor the San Andreas Fault from San Francisco to Ft. Tejon, could be built for not more than $850,000 (1974).

The system could be made more inexpensive by fundamental improvements in receiver design, which are discussed in the next Section.

X. FUTURE IMPROVEMENTS IN RECEIVER DESIGN: USE OF SURFACE ACOUSTIC WAVE DEVICES

The simultaneous ranging employed in the multilateration technique requires that one can discriminate between markers — that is, that each marker, in a set of those ranged simultaneously, send back a signal distinguishable from all the rest. In the System Type G, such as the Autotape system outlined in Section VIII, discrimination is achieved by assigning each marker a different channel (frequency multiplexing). A more flexible, and potentially more inexpensive, design would be that of System Type F (see Section VI), in which a marker responds to a pseudo-noise coded waveform from the aircraft and responds with a uniquely coded return. The principal advantages would be these:

(1) The system would discriminate well against background noise both on uplink and downlink — a necessity in urban areas.

(2) Therefore broadcast power from the aircraft could be low — also necessary in urban areas.

(3) The number of markers ranged simultaneously need not be frozen with the ranging hardware, as with frequency multiplexing, and the system could easily be expanded.

The prime disadvantage would be the high cost of the markers, in the present state of the art. However, surface acoustic wave devices (SAWDs) are being rapidly developed for code recognition, and might dramatically reduce the costs in the next 5 to 15 years. We therefore made a careful investigation of SAWD technology, especially of the problems that must be overcome if they are to become useful for our purpose.

A SAWD is a piezoelectric transducer of electrical signals to and from Rayleigh (surface mechanical) waves on a crystal, used as a delay line. If the delay line is tapped in a pattern corresponding to a coded signal, it becomes a matched filter for that signal and can be used for code recognition; in reversed operation, it will convert a pulse back into the coded signal. Its primary advantage is simplicity. The primary disadvantages, at the present time, are limited information processing capability, high power loss, and sensitivity of time delay to temperature.

One corporation building SAWDs for ranging devices is Autonetics. The primary emphasis of this group's R&D to date is in chirp SAWDs for radar applications and bandpass filters. However, they have designed a number of tapped delay line (TDL) SAWDs. Some of the parameters of these SAWDs are listed in Table 5. These SAWDs all assume biphase modulation. In the LIBRA system, we are extremely interested in eliminating the mixing stages at the front end of the transceiver. Autonetics was not very encouraging. Present quartz SAWDs operate from 10 MHz to 600 MHz. However, aluminum nitrate SAWDs can operate from 1 to 2 GHz. Quartz suffers from greater insertion loss but has much better temperature stability. The insertion loss for tapped delay line filters using quartz with ST-X cut ranges from 50 to 60 dB. For bandpass filter applications it is typically 12 to 15 dB. The narrower the bandwidth the lower the insertion loss. Autonetics builds a bandpass filter with center frequency of 120 MHz, and 80-kHz bandwidth, and sidelobes 40 to 60 dB down. Minimum insertion loss is 6 dB. This is because at the transducer the energy propagates in two directions, thus introducing a loss of 3 dB at each transducer. Autonetics is presently building a programmable TDL SAWD at 423 MHz with a chip rate of 20 MHz. They estimate they can go as high as 40 to 50 Mchips/s with 128 taps. They have an operational programmable TDL SAWD with 128 taps at 120 MHz. Autonetics is successful in building SAWDs with peak to sidelobe ratios of 1 to 2 dB below what is theoretically feasible. They can build SAWDs with delays up to 40 μsec or possibly longer. Building two SAWDs with identical lengths does not present a serious problem, even if they have to be aligned to a nanosec (one of our requirements), but requiring a specific frequency is a problem. Thus accuracy is much more difficult than precision. For example, they attempted to design a 120-MHz SAWD with 50 taps and achieved 119.32 MHz. By further development they could probably achieve an accuracy of ±20 kHz. The difficulty seems to be in the accuracy of the laser controlled machine masks, where the tolerance is 0.25 microns for $\lambda/2$. However, the repeatability of results is very good. To establish the cost of a SAWD they need to know our maximum tolerance. The maximum number of taps today is 256 with repeatable results. Use of the same SAWD to transmit and receive is quite possible. Concerning costs and delivery times: if the masks are already available, the cost to us for a SAWD is about $300.00. The cost of a new mask varies from $500.00 to $2,000.00. Delivery time on a new mask is from 8 to 12 weeks. Therefore, a new SAWD would be about $4,000.00.

Lincoln Laboratories of MIT is working on the frontier of surface wave technology. They develop a concept, build models, some of which find their way into operational systems, and then transfer the technology to industry, and move on. They have been working with Raytheon Corp. and Hughes Aircraft Company. They would like to work with others also. The approach that Lincoln Labs has been pursuing involves the use of etched grooves or gratings in a lithium niobate ($LiNbO_3$) substrate. The reflection of surface waves from gratings in the surface are used to achieve the desired impulse response. A "herring bone" pattern is used in the surface of the substrate. This design concept is particularly useful for large time bandwidth (TBW) products. For example, devices have been built with center frequencies of 1 GHz and 1000 taps with about 50-dB insertion loss. This etched groove technique has several practical and intrinsic advantages. Unwanted reflections, velocity shifts, reradiation and dispersion inherent in interdigital transducer is avoided. Because of the processing technique these devices will eventually be cheaper. The amplitude weighting associated with each tap is a function of the depth of the groove. Using these techniques, spread factors of up to 10 k at IF frequencies of 500 to 700 MHz are attainable. To develop one tailored to our application would require 8 to 12 months. By 1977, Lincoln Labs will have perfected an etched groove technique with the use of X-ray processing for a C-band center frequency. This will use aluminum nitrate substrates. Presently Lincoln Labs generates masks with electron beams yielding 500 Å precision and is willing to teach the techniques. To obtain greater precision (up to 200 Å) requires using an HP laser technique.

The temperature sensitivity of these devices is still a problem. Quartz has a parabolic sensitivity as a function of temperature, i.e., 30 ppm over a 0 to 70°C temperature range. $LiNbO_3$ has a linear temperature sensitivity over the temperature range and is 80 ppm over 0 to 70°C. If compensation is required, then it is easier to compensate with the use of $LiNbO_3$.

An interesting device built by Lincoln Labs is a convolver. One signal enters a transducer at one end of the substrate, the other signal enters the opposite end. By using the etched groove technique they were able to build the convolver with 10-μsec delay, 70-MHz bandwidths, less than 0.5 dB amplitude ripple, 7° phase ripple, 60-dB dynamic range, and 40-dB insertion loss. It has 700 taps with the capability of going to 3000. The device performs the function of a programmable SAWD but is much simpler. To build such a device generating new masks would take 1 year. The frequency accuracies by use of the grating techniques and laser etchings are 1 part in 10^{10}. Unfortunately the temperature accuracies are 1 part in 10^6 with ovens.

The present state of the art in SAWD construction may be summarized as follows:

(1) Very excellent results are presently attainable from 50-tap, 30-μsec delay lines operating at center frequencies of 100 to 120 MHz.

(2) Single crystals are presently available that have 120 μsecs of delay. Shortly, the technology should increase enough to enable delays up to 250 μsecs.

(3) It is sensible to expect that delay lines having 500 taps should be available in the near future, and it is feasible to expect that ultimately delay lines with as many as 2000 taps will be available. The problem with the many tapped delay line is that there is difficulty in producing long crystals for long delays.

(4) At a delay of 250 μsec, a center frequency of 300 MHz, there is a 3-dB propagation loss and this loss increases as the square of the carrier frequency.

An acoustic delay line offers a number of advantages not found in the commonly used electromagnetic delay line. It is relatively more rugged than the electromagnetic line, the manufacturing processes are more adaptable to large quantity production, which would eventually result in a substantial reduction of the cost per unit, bandwidths are one of two orders of magnitude larger, and there would be virtually no maintenance adjustment because it is a solid state device. However, the acoustic delay line is incapable of supporting a steady state signal and therefore information must be impressed on a carrier or appear in a transient state. In addition, the lines are characterized by high input/output transducer losses. The key advantages that SAWDs offer to receiver design are these:

(1) Ideally suited for processing direct sequence PN waveforms in the 50 to 500-MHz range.

(2) Afford linear processing with wide dynamic ranges in excess of 100 dB.

(3) Low insertion losses (10 dB at 100 MHz).

(4) Small and lightweight.

(5) High reliability and low projected cost.

We recommend that the ARIES Network Densification System be tested and proved feasible by using the commercially available equipment of System Type G (see Section VI), but that inexpensive SAWD-type receivers be phased into use as soon as SAWDs satisfying our requirements become commercially available. We do not recommend NASA financing of SAWD development, since normal industrial evolution should eventually market devices meeting our specifications.

XI. BASIC CONCEPT OF A MULTILATERATION NET

A. MATHEMATICAL CONCEPT

The multilateration technique rests on a purely geometric concept. If a number of stations on the ground range to a number of points in the air, what information can be derived? Clearly one cannot derive the positions of either ground stations or aerial points in an absolute frame of reference. The effect on the ranges is the same, whether all the aircraft positions are moved one meter east, or all the station locations one meter west. However, it is possible to measure the positions of the stations and aerial points "with respect to each other" (a phrase defined in the next paragraph) without any <u>a priori</u> information — without having, for example, a model of an aircraft trajectory that generates the aerial points. It turns out that if, for example, an aircraft ranges from each of four aerial points to six ground stations simultaneously, the relative positions can be deduced of aircraft with respect to stations and of stations with respect to each other, provided that the configuration of stations and aircraft positions avoid certain singular patterns.

A suitable coordinate system makes the concept clear (see Fig. 14). Let the origin of coordinates be station 1, the X-axis be passed through station 2, and the XY-plane through station 3. Then the other stations and the aircraft positions are located relative to these three stations. These first three stations contribute only three unknown coordinates, and each additional station and each aircraft position contributes three additional coordinates, so that, if one has four aircraft positions and six ground stations, there are 24 unknown coordinates. There are also 24 range measurements, so that, barring mathematical singularities, one can solve for all the unknown coordinates. With fewer than six stations, however, mathematical singularities are almost impossible to avoid, as will be discussed in Section XII.

The basic concept of LIBRA is what we propose to call a <u>multilateration net</u>, which is analogous to the triangulation net of classical geodesy (see Fig. 15).

In the classical triangulation net, individual measurements of the sides of triangles are combined by the method of least squares to secure the relative positions of all the points in the network; the basic geometrical unit is the triangle. In LIBRA, the relative positions and distances of six stations on the ground are obtained at once by multilateration, and different groups of six are combined by least squares in the overall network solution; the basic unit is the group of six, which we will call the shield.

Just as classical surveys make use of triangulation chains, so LIBRA can span wide distances by shield chains, laid out along the line of flight of the aircraft. Thus, LIBRA can be used either to cover whole areas (e. g., the Los Angeles metropolitan area) or a long strip of land (e. g., the San Andreas Fault Zone). The number of stations per unit area can be varied widely, from very large, in a critical high population area where the smallest premonitory earthquake signs must not go undetected, to very small, in desert areas where only major geophysical phenomena are of interest.

B. OPERATIONAL ADVANTAGES

The advantages of LIBRA over other geodetic systems, either operational or proposed, are as follows:

(1) The ground stations need not be manned. Therefore operating costs are low. A station would be simply a rugged black box containing a transponder bolted to a concrete monument below the ground like a conventional geodetic marker.

(2) The ground stations have no moving parts. They could be manufactured cheaply and in quantity. The reason is that the radio transponder, unlike a laser, need not be aimed.

(3) A survey can be completed quickly, and repeated often. In fact, a resurvey of an important area can be performed by a single flight of the ranging aircraft, in a single morning or afternoon. This advantage may be vital in the detection of earthquake premonitory signs. Furthermore, immediately after an earthquake, important data could be secured with a time resolution attainable by no other method.

(4) Both vertical and horizontal coordinates are determined at the same time, with accuracy. Surveys performed by geodimeters on the ground are two-dimensional; they establish horizontal control only. Vertical control is certainly necessary to detect

rock dilatancy. Conventional vertical control is expensive, slow to complete, is referred to an arbitrary, wrinkled surface (the geoid), and is generally confined to nearly level land.

(5) The survey can be extended to any type of terrain — to mountains, canyons, or deserts. The only limitation is that a helicopter be able to carry the transponder and materials for a geodetic marker within backpacking distance of the desired site.

(6) Extra stations can be established easily. Stations can be relocated cheaply. It is necessary only to unbolt the transponder box from one concrete substructure and transport it to another.

XII. BASIC MATHEMATICAL REQUIREMENTS FOR A WORKABLE MULTILATERATION SYSTEM

The mathematical conditions for good multilateration geometry have been discussed by Karl Rinner (Ref. 18) and by Georges Blaha (Ref. 19), and are fully derived in Ref. 20. Here we state only the basic conclusions and the requirements that these impose on the proposed LIBRA system.

We require a system in which small errors in ranging will not result in large errors in derived station locations; such is the practical meaning of a mathematically nonsingular configuration of ground stations and aircraft positions. One may speak in terms of a mechanical analogy. In the minimum case, the six stations and four aircraft positions can be represented by six balls on the ground and four balls in the sky; the radio beams connecting the ground to the sky can be represented by thin rods. We do not want small changes in the lengths of the rods to correspond to large changes in the relative positions of the balls; that is, we do not want the mechanical model to flex easily. In short, we want a rigid system. We will use the convenient term rigid system to describe a planned configuration of station locations and aircraft trajectory that gives sensitivities — ratios of station location errors to the ranging errors that produce them — small enough to give geodetically useful results.

Several requirements are imposed on the aircraft flight plans and on the distribution of the ground markers by the mathematics of multilateration.

These requirements are summarized in the following theorem: a simultaneous ranging system can obtain no unique solution for marker coordinates if all the markers lie on a plane curve of the second order (such as an ellipse), or if all markers and aircraft ranging positions lie on a surface of the second order (such as an ellipsoid) (see Fig. 16). This theorem implies that multilateration cannot be carried out with fewer than six ground stations from an area small compared to the Earth's radius, because five points on a flat surface can always be fitted by a second-order curve. Furthermore, any number of stations will be nonrigid if they all lie on two straight lines (an X or a V), because any two straight lines are the asymptotes of a family of hyperbolas. Likewise, no solutions are possible if all stations lie in one plane and if all aircraft points lie in another plane, because two planes are the limiting boundaries of a family of second-order surfaces.

Some implications of this theorem are the following:

(1) The aircraft should vary its altitude by a large factor – e.g., by a factor of two – during data acquisition. This can be done most simply by having the aircraft overfly the markers twice, once at high altitude, and once at a much lower altitude. This requirement implies an optimum spacing between ground markers. If we use a U-2 that can fly one of the passes at an altitude of 30 km, the other flight should be performed at 15 km; since little weight is added to the solution by points at elevation angles below 12 deg, there should be a complete shield of markers in a square of about 75 km on a side. This implies that

(2) The ground markers (receivers) should be spaced fairly evenly at an average density of one every 30 km (20 miles), if the aircraft is a U-2. If an ordinary commercial business plane is used (service ceiling 10,000 m), the markers should be spaced at one every 15 km (10 miles). This is true because a minimum of six markers should be simultaneously visible from the aircraft to obtain a strong solution for relative coordinates.

(3) The aircraft should vary its ground path as well as its altitude between the two passes mentioned above. It is desirable that the aircraft fly preassigned routes calculated to give the highest

attainable accuracy, which will not be straight lines, but of which the turning radii need not be smaller than 30 km.

XIII. A SIMPLE COPLANAR MULTILATERATION TECHNIQUE FOR SYSTEM TESTS

For a complete solution of station locations in three dimensions, it is necessary to use a minimum of six stations on the ground, as discussed in the previous sections. It would be desirable (less expensive, and speedier) to test the multilateration technique using fewer stations. For example, the Cubic Autotape, for which the error sources were analyzed in Section VIII, is a three-channel instrument; time and money would be saved by performing the first modifications and experiments on this instrument. By developing the logic set forth in Ref. 20, Section XIII, under the heading "Collinear Three Station Configuration," we have invented a workable three-station technique for measuring baselines. Initial tests of LIBRA hardware, atmospheric calibration techniques, etc., should be made using this three-station technique.

The three-station technique depends on two complementary mathematical theorems, which may be combined into a single statement. It is possible to determine the relative coordinates of three ground stations by simultaneous ranging from an aircraft in two situations:

(1) The collinear case: all three stations are in a straight line. In this case, two aircraft locations are necessary (furnishing $2 \cdot 3 = 6$ sets of ranges), as shown in Fig. 17. One solves for X_2 and X_3.

(2) The coplanar case: the aircraft positions and three stations all lie in a common plane. In this case, three aircraft locations are necessary (furnishing $3 \cdot 3 = 9$ ranges), as shown in Fig. 17. One solves for X_2, X_3, and Z_3.

Both these cases are ideal. But it can be shown that, if both conditions of collinearity and coplanarity are satisfied with only moderate precision (to a few tens or a hundred meters), baseline lengths can be measured to very high precision, to within 1 cm over a 50-km baseline, hardware and atmospheric calibrations permitting.

The working system is illustrated in Fig. 17. It is expected that there will be some misalignment of aircraft and stations from the ideal collinear and coplanar cases. We have simulated numerically the performance of the system illustrated in Fig. 17. The stations are located as nearly as possible on a great circle arc on the Earth's surface, using preliminary, third-order surveying data accurate to 5 to 10 m. The curvature of the earth and local topography produce the vertical distance Z_3. The transmitter is flown in a slightly zigzag pattern through the vertical plane passing through the stations 1 and 2. The inaccuracy of the preliminary survey contributes an alignment error ΔY. The azimuth of the aircraft is determined at each station by conventional means, and the stations range at at least three instants when one of the stations determines that the aircraft is within a few tens of meters of the vertical plane. Numerical solutions were made for X_2, X_3, Z_3 as though in the coplanar case, but using ranges corrupted by the simulated displacements of station 3 and the aircraft from the ideal cases; the resulting errors in station coordinates were calculated. Representative results show that, if both conditions of collinearity of the stations and coplanarity of the retroreflector with the stations are satisfied with only moderate accuracy — a few tens or a hundred meters with 50-km station separations — the coordinate parameters can be calculated with very high accuracy — to 1 or 2 cm so far as the geometry is concerned.

All the solutions made in this study show the following characteristics:

(1) Errors in X_2, X_3, and Z_3 vary with the square of the displacement of the airplane from the plane of the stations. This proceeds from the fact that the range varies with the secant of the angle of displacement as seen from a ground station, and because $\sec \theta$ varies as $1 + \theta^2/2$ for small angles θ.

(2) If the retroreflector can be flown within ±80 m from the vertical plane of the three stations, then the distances X_2 and X_3 can be obtained to ±1 cm, and Z_3 to ±2 cm. This result holds for all baseline lengths up to 150 km, assuming that the airplane can be flown sufficiently high to be visible at elevation angles of at least 6 deg from all stations.

We conclude that coplanar multilateration provides a practical, inexpensive way to test equipment accuracy and atmospheric calibrations on known baselines in the early phases of LIBRA development.

XIV. CALIBRATION OF THE SIGNAL DELAY IN THE ATMOSPHERE

A. ADEQUACY OF CALIBRATIONS FOR THE LIBRA SYSTEM

One major disadvantage of a radio ranging system such as LIBRA compared to a laser system is that the time delay of the signal return caused by the atmosphere is more difficult to calibrate. The basic reason for this is that the water vapor has no effect at optical wavelengths, so that a laser range correction depends only on the density of the air, but, at radio wavelengths, the range correction has both a "dry component" and a "wet component" depending on the relative humidity. Therefore, temperature, pressure, and relative humidity must all be known along the signal path if the system is to attain high accuracy. Therefore, a basic question arose early in the LIBRA design activity: can the corrections for atmospheric time delay be made with sufficient accuracy to permit stations to be located within 1 to 4 cm?

The answer is yes; 1- to 4-cm accuracy is attainable. The advantages LIBRA has over other radio ranging systems are twofold:

(1) The aircraft can acquire meteorological data while it ranges. The two-pass, high- and low-altitude flight pattern required by the multilateration technique (see Section XII) is ideal for obtaining data for an atmospheric profile.

(2) The transponders can return meteorological data with the range code. Here is one benefit we accrue by using active transponders instead of passive reflectors. However, it appears to us that this refinement can be implemented in a practical way only by System Types E through G (see Section VI).

B. BASIC FORMULAS OF ATMOSPHERIC CALIBRATION

The mathematical formulas for the atmospheric calibrations are as follows:

The index of atmospheric refraction, n, is typically about 1.0003, that is, about 300 parts per million more than unity. One commonly introduces an auxiliary parameter, N, such that $N \equiv (n - 1) \cdot 10^6$; then $N \doteq 300$. The standard formula for microwave atmospheric calibration then becomes

$$N = \frac{K_1 P}{T} + \frac{K_2 e}{T^2}$$

where

T = temperature, K

P = total atmospheric pressure, N/m^2

e = partial pressure of water vapor, N/m^2

The effect of errors in the measured values of T, e, and P may be estimated by the differential form of the above equation:

$$\Delta N = \left[-\frac{K_1 P}{T^2} - \frac{2K_2 e}{T^3} \right] \Delta T + \frac{K_2}{T^2} \Delta e + \frac{K_1}{T} \Delta P$$

$$\equiv a\Delta T + b\Delta e + c\Delta P$$

For frequencies up to about 30 GHz, good approximations for the constants are

$$\left.\begin{aligned} K_1 &= 0.776 \text{ K} \cdot \text{m}^2/\text{N} \\ K_2 &= 0.0373 \cdot 10^5 \text{ K} \cdot \text{m}^2/\text{N} \end{aligned}\right\} \quad \text{Smith-Weintraub constants}$$

Let us examine a typical case. The ground level absolute humidity in the International Civil Aviation Organization (ICAO) standard atmosphere is 12.3 gm/m^3, corresponding to $e = 0.102\ N/m^2$ and relative humidity 60%, at standard pressure (= 1.013 N/m^2) and a temperature of 288K (15°C, 59°F). Then by the above formula,

$$N = 319$$

of which 273 is dry component, and 46 is wet component. Then, on a 40-km ground level baseline, there would be a 12.8-m atmospheric effect, of which fully 1.84 m would be due to humidity. If one knew T to ±1 K, P to ±0.04 N/m^2, and e to ±5% (precision attainable with common equipment), then there would be an rms error of 11.4 cm, of which 9.2-cm would be due to the uncertainty in the humidity. (The dry component, which a laser would see, would contribute 6.7 cm rms.)

The LIBRA system, however, has the advantage that the line of sight from transponder to aircraft slants up away from the surface into thinner, dryer air (see Fig. 18). The variation with altitude of the relevant parameters of the ICAO standard atmosphere is given in Table 6. An aircraft flying at an altitude of 20 km and ranging to a transponder at 40 km horizontal distance would see a delay of $\Delta R \cong 5.0$ m, of which $\Delta R_w \cong 24$ cm is due to the wet component. With the same accuracy of meteorological data, the rms ranging error is only 2.9 cm over 40 km, or 0.7 parts per million.

C.. ATMOSPHERIC MODELS TO MINIMIZE DATA TAKING

To minimize the cost of operating the system, it is important to obtain the atmospheric corrections as economically as possible, without requiring extra flying time or unusual equipment. We therefore examined to what extent a proper atmospheric model might minimize the data taking.

The lower atmosphere (troposphere) is that part of the atmosphere that is well stirred by vertical convection currents. It extends from the ground to an altitude that varies from only a few kilometers at the north pole to over 30 km at the equator. Over southern California, the height of the troposphere is typically about 10 km, so that a U-2 would fly entirely above the troposphere even during the lower pass of a two-pass data acquisition pattern (see Section XII). The difficulty in calibrating the delay of a radio signal passing through the troposphere is that a part of the delay is due to water vapor. Since the distribution of water vapor does not obey any simple equation, its contribution to the delay is difficult to model.

It is particularly troublesome at low elevation angles, where the zenith value ($\Delta R_w \sim$ 5 to 10 cm) is multiplied by a large factor. Many attempts have been made to determine the wet-component range error from measurements made at the surface. Some progress has been made, but the requirements of LIBRA will make necessary a more accurate model than any now reported in the literature. Such a model might be based on work previously undertaken at JPL for the needs of spacecraft navigation.

The distribution of water vapor in the atmosphere is difficult to determine. Theoretically, it obeys a turbulent diffusion equation with complicated boundary conditions that depend on local conditions. Empirically, P. N. Tverskoi (Ref. 23) states that the water vapor pressure in western Europe obeys an expression that we write as

$$P_w(z) = P_{ow} \exp(-az - bz^2)$$

where z is height above the ground, P_{ow} is the surface vapor pressure, and $a = 0.288\ \text{km}^{-1}$, $b = 0.0480\ \text{km}^{-2}$.

The vapor pressure distribution cannot be derived from first principles because the water vapor is not in hydrostatic equilibrium. While the dry part of the atmosphere ($\sim$ 99%) is in hydrostatic equilibrium, the partial pressure of water vapor is controlled by the local number density of water molecules. This quantity is determined by convection (wind) and need not be in hydrostatic equilibrium.

The pressure model of the above equation is empirical, and the parameters given are for Europe, but it was thought useful to compute the wet-component range error ΔR_w using this equation to test whether the form is valid. Comparison with data from various places and times could then be used to obtain the appropriate values of a and b for the American Southwest.

Radiosonde measurements of the troposphere were obtained twice daily, at 0000 and 1200 UT, during most of 1967 at Yucca Flats, Nevada. Instruments carried aloft by a balloon measured the temperature and relative humidity as a function of height (pressure). The data were numerically integrated to find the wet-component range error. Chao at JPL found that data obtained at 1200 U T (0400 local) do not give good results when used for surface predictions of ΔR_w. He points out that a temperature inversion would invalidate an assumption of linear temperature lapse. Thus, only data at 0000 UT (1600 local) were used. Two 7-week segments were found for comparison purposes. The first segment extends from April 10 to May 29; data for April 19 and May 4 and 21 are missing. The second segment extends from August 6 to September 23; data for August 9 and 18 are missing.

An exponential model of the water vapor pressure, $P_w(z) = P_{ow} \exp(-az - bz^2)$, has been shown to provide a good fit to radiosonde measurements of the wet-component tropospheric range error if a and b are functions of the surface temperature and pressure. The preliminary dependence of a and b on temperature and pressure has been deduced from 4 months of observations. When the model is applied to the 4 months' data, the rms difference between the model and data is 1.4 cm.

The accuracy of the tropospheric model is summarized in Table 7. Each month's data are given individually along with statistics of the deviations from the model. The JPL work of Thuleen and Ondrasik shows that the monthly average should provide calibrations as good as the model for the months of December through April at the Goldstone stations. Models are the most useful in the spring and fall, when tropospheric conditions fluctuate a good deal. If the April data are ignored, the model has an rms deviation from the data of 1.52 cm.

The variation of the model parameters with temperature and pressure is interesting. As the temperature increases, so does the effective scale height, from about 2.6 km at 10°C to about 4.2 km at 35°C. Such a variation is expected for a gas in thermal equilibrium under the influence of gravity. However, the measured values of H_{max} (the height at which the contributions to ΔR_w cease) show only a rough winter-summer correlation with temperature. Furthermore, the special model needed for low surface vapor pressures has by far the highest scale height, but the data show lower values of H_{max} at the times when this model applies. Thus, while the model deals well with the integrated effect of the distribution of the water vapor in the region up to ~10 km, it may not accurately model the local density of water vapor. This problem may be investigated by using the above equation in the analysis of sky temperature measurements.

The work summarized in Table 7 was performed prior to the LIBRA study, and it shows that a model can be fitted to radiosonde data with the precision required for LIBRA.

Since the LIBRA project began, we have acquired radiosonde data from Las Vegas and from Edwards Air Force Base on magnetic tape, and from El Monte Airport on TWX forms, which are now being reduced to punched cards. The first results of the current investigation seem to show that residuals of the El Monte data (LA basin) from the model will be in the 1- to 1-1/2-cm range.

The major question yet to be answered is whether the model can still be made to apply without taking extensive measurements at different altitudes — when, for example, the only available data are relative humidity at the ground receiver plus radiosonde data from points 100 km or so away. To settle this question, we will require experiments conducted in the field.

XV. RECOMMENDED SCHEDULE FOR IMPLEMENTATION OF LIBRA

A. THE BASIC STEPS TO BE TAKEN:

Three principal types of effort, indicated by the study described in this report, constitute the logical means by which to realize a practical airborne radio-ranging system (LIBRA) to bridge the gap between ARIES and conventional geodesy. Fortunately, large parts of the necessary efforts are already in progress, either as aspects of current NASA projects or as activities in commercial research and development in electronics, so that the additional cost of developing LIBRA should be small. The three areas of effort are these:

(1) <u>Assembling and Testing Ranging Hardware:</u> This can be most economically and effectively performed in two stages. Existing commercial systems of side-tone ranging can be improved to meet the standards of precision required for geophysical applications (Section VIII), but the cost per ground receiver would be too high and the time span of troublefree unmanned operation too short to make practical a network of several hundred permanent receivers to be deployed over a wide region. However,

a prototype system incorporating one master transmitter and six portable receivers would nicely complement the existing single 9-m ARIES I antenna, and would adequately support all ARIES objectives through 1977. We anticipate that by 1978 progress in commercial electronics will be such that a firm choice can be made between the possible systems enumerated in Section VI. At that time, contracts can be let to develop a final system employing reliable, low-cost ground markers by which a regional network can be measured and remeasured on a routine basis.

At that time also, the first steps can be taken to transfer this valuable geodetic tool from NASA to the appropriate user or users.

(2) Design of the Data Processing Subsystem: Large parts of the computer software necessary for LIBRA are already being developed by NASA-JPL for processing laser ranging measurements to artificial satellites by the multilateration technique. It remains only to formulate the mathematical problem of network propagation, solving for the relative coordinates of a large number of ground markers when only a few are observed at one time. The prototype LIBRA recording hardware should be designed so that the data record formats are compatible with what will be required in the final system. The basic version of the computer program should be written as soon as possible, to permit an exact comparison of the various options among meteorological calibration techniques described in the next paragraph.

(3) Optimizing the Meteorological Calibration Technique: We described in Section XIV the progress made so far in modeling the atmospheric time delay, especially the troublesome part of the delay due to water vapor. Three promising techniques, by which the contribution of the atmosphere to ranging error may

be minimized, can readily be examined without undertaking expensive new research:

(a) Meteorological data is now being taken routinely to calibrate ARIES data. The principal measurements are by radiometer, and a testing program is now underway to verify the radiometer data by specially instrumented aircraft and by radiosonde. When the basic version of the LIBRA computer program described in the last paragraph has been written, the effectiveness of the model atmosphere described in Section XIV can be tested by simulating realistic range data sets from a LIBRA aircraft; these sets would be obtained under the conditions of these ARIES observations.

(b) Remote sensing from satellites now provides such useful information as atmospheric temperature profiles in regions where conventional measurements are not available, and the precision and spatial resolution of the data will be much improved by the time advanced ARIES antennas are widely deployed. The troublesome problem described in Section XIV of ascertaining whether a thermal inversion is present, and if so, determining the several parameters needed to model it, could be completely solved by fitting a temperature profile available from a satellite to boundary conditions measured at the ground markers and along the flight path of the LIBRA aircraft. Computer simulations are necessary to determine the accuracy attainable by this technique.

(c) Any information about the aircraft velocity implies some information about the atmospheric time delay, since the difference between the real and the measured range rate to any marker is just the rate of change of the time delay, unless other sources of error are present. If the aircraft were equipped with accurate inertial navigation, the atmospheric parameters could be solved for along with the true relative station coordinates. Computer simulation of the performance of this technique will determine whether and when this technique becomes more effective than (a) or (b).

This trade-off analysis requires no data not already available or about to be available from other programs.

B. A MILESTONE SCHEDULE FOR LIBRA DEVELOPMENT

We believe that the LIBRA effort described above can be carried out according to Table 8.

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Table 1. Twentieth century destructive earthquakes in California

Place	Date	Richter magnitude	Fault	Fatalities, if reported	Damage, if estimated
Stone Canyon	2 March 1901	?	San Andreas		
Los Alamos	27 July 1902	?	Santa Ynez?		
San Francisco	18 April 1906	8.3	San Andreas	>600	~ $350 million
San Bernardino	19 Sept 1907	6	San Andreas		
Cold Water Canyon	15 May 1910	6.0	Elsinore		
Imperial Valley	25 June 1915	6-1/4	Imperial? San Jacinto?	~ 6	
Tejon Pass	22 Oct 1916	6	San Andreas		
San Jacinto	21 April 1918	6.8	San Jacinto		
Cholame Valley	10 March 1922	6-1/4	San Andreas		
Santa Barbara	29 June 1925	6.3	Mesa?	~ 20	~ $6 million
Lompoc	4 Nov 1927	7.5	Santa Ynez?		
Long Beach	10 March 1933	6.3	Newport-Inglewood	102	~ $41 million
Parkfield	6 June 1934	6	San Andreas		
Imperial Valley	18 May 1940	7.1	Imperial	7	
Tehachapi	21 July 1952	7.7	White Wolf	12	~ $5 million
Daley City	22 March 1957	5.3	San Andreas	0	~ $1 million
Hollister	8 April 1961	5.6	San Andreas	0	$250,000
San Fernando	9 Feb 1971	6.3	Sierra Madre	58[a]	$505 million[a]
Point Mugu	21 Feb 1973	6.0	Santa Monica?	0	minor

[a] According to Ref. 4.

Table 2. Correlation process parametric comparison[a]

Parameter	Active	Passive (surface wave correlator)
Maximum processing gain	10^7	10^3
Minimum detection bandwidth	1 Hz	$\frac{1}{\text{SWC length}} \times N$ N = number of coherent integrations allowed without platform movement
Maximum code rate	3×10^8 Hz	7.5×10^7 Hz (at 300 MHz)
Synchronization and track	Algorithm in software or hardware required	Automatic; inherent within correlator
SNR	Up to 40 dB greater or a given radiated power	Limited by length of correlator
Cost	High cost/complexity	Very low-cost potential

[a]Practical present-day limits.

Table 3. Marker/aircraft transmitter output calculation

	Parameter	Calculated value	Defined as
a.	Required SNR	60 dB	
b.	Detection bandwidth	0 dB (1 Hz)	
c.	Carrier to noise spectral density (C/N_0)	60 dB	(a + b)
d.	Noise spectral density (N_0)	-174 dBm/Hz	$(K \cdot T)$[a]
e.	Receiver noise figure (F)	10 dB	
f.	System noise (N)	-164 dBm/Hz	(d + e)
g.	Minimum received signal power (S)	-104 dBm	(f - c)
h.	Path loss[b] (I_S)	137 dB	
i.	Transmitter power[c] (ERP)	33 dBm or 2 W	(g - h)

[a]K = Boltzmann's constant.
T = Temperature in Kelvins.

[b]I_S = 37 + 20 log 1000 MHz + 20 log 100 NMI = 137.

[c]Receiver gain (G_R) = transmitter gain (G_T) = 0 dB.

Table 4. Precision of modified commercial side-tone-ranging hardware

Source	Expected error	Remarks
Quantization	1 cm	Can be quantized to even finer levels.
Bias due to age and temperature	1 cm	Dependent upon modulation and design of equipments.
Bias shift	1 cm	Can limit further because of geometry and, if need be, link power control
Dynamic error	—	Use PLL (2nd order) and limit velocity and acceleration to 250 km/h and ±3 g
Clock error	1 cm	1 part in 10^7 over six months

Table 5. Autonetics tapped delay line surface acoustic wave devices

f_0, MHz	No. of taps	Insertion loss, db	Chip rate, MHz
63	63	50	5.25
120	50	50	5
64.52	40	59	5.376
124.28	255	64	12.4
70	50	60	5
70	100	60	10
31	up to 170	?	6.25 to 1.25
120.9	64	?	?
120.9	128	?	?

Table 6. Values of the constants for the ICAO Standard Atmosphere and 60% relative humidity

Altitude, km	N	T, ^{o}C	P, $\times 10^5$ N/m^2	e, $\times 10^5$ N/m^2	a, K - 1	b, $\times 10^5$ N/m^2	c, $(\times 10^5$ N/m$^2)^{-1}$
0	319	15.0	1,013	10.2	-1.27	4.34	0.27
1	277	8.2	893	6.5	-1.09	4.72	0.28
3	216	-4.5	701	2.6	-0.86	5.17	0.29
10	92	-50.3	262	0.04	-0.50	7.52	0.30
20	20	-56.5	55	0	-0.09	7.96	0.35
50	0.2	9.5	0.8	0	-0.0008	4.67	0.27

$$\Delta N = a\Delta T + b\Delta e + c\Delta P$$

$$N = (n - 1) \cdot 10^6 - 1$$

where

n = atmospheric index of refraction

T = temperature

e = water vapor partial pressure

P = total atmospheric pressure

Table 7. Summary of fit of model to radiosonde data

Data (1967)	Average ΔR_w, cm	Rms from average	Bias[a], cm	Rms from model	Number of days	Temperature range, °C
April	3.55	0.76	-0.22	0.72	20	1-20
May	6.20	2.19	-0.06	1.32	27	12-32
August	11.8	1.88	-0.02	1.51	24	31-37
September	10.8	3.60	+0.05	1.73	23	20-32
All	—	—	-0.06	1.40	94	—
All, except April	—	—	-0.03	1.52	74	—

[a]Bias = observed - computed.

Table 8. LIBRA milestone schedule

Fiscal Year	Funding	Activities
1976	$350,000	Modify a commercial side-tone ranging system to attain 5 cm accuracy when data is properly calibrated. Write basic program to process LIBRA data, and perform simulation tests. Use ARIES meteorological data to evaluate calibration techniques.
1977	$375,000	Use a 3-channel ranging system in the field to perform tests and demonstrations at selected ARIES sites using coplanar multilateration.
1978	$450,000	Deploy a 6-marker system for routine support of the ARIES program. (This will reduce the number of ARIES sites to be occupied and will reduce the cost of ARIES operations.)
1979-1980	$500,000 – $800,000[a]	Begin construction of Phase II LIBRA system using ground markers of advanced design, especially planned for use by one or more user agencies. Arrange for transfer of operations from NASA to designated user or users.

[a]Adjusted for inflation.

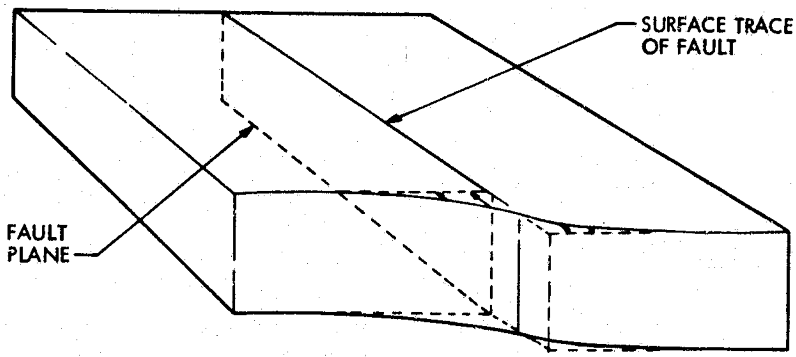


Fig. 1. Idealized plate boundary deformation. The boundary between two plates might exhibit this idealized pattern of deformation under shearing stress, if the boundary were a single vertical plane surface between two uniform rock masses. The real, more complicated situation is indicated in Fig. 2.

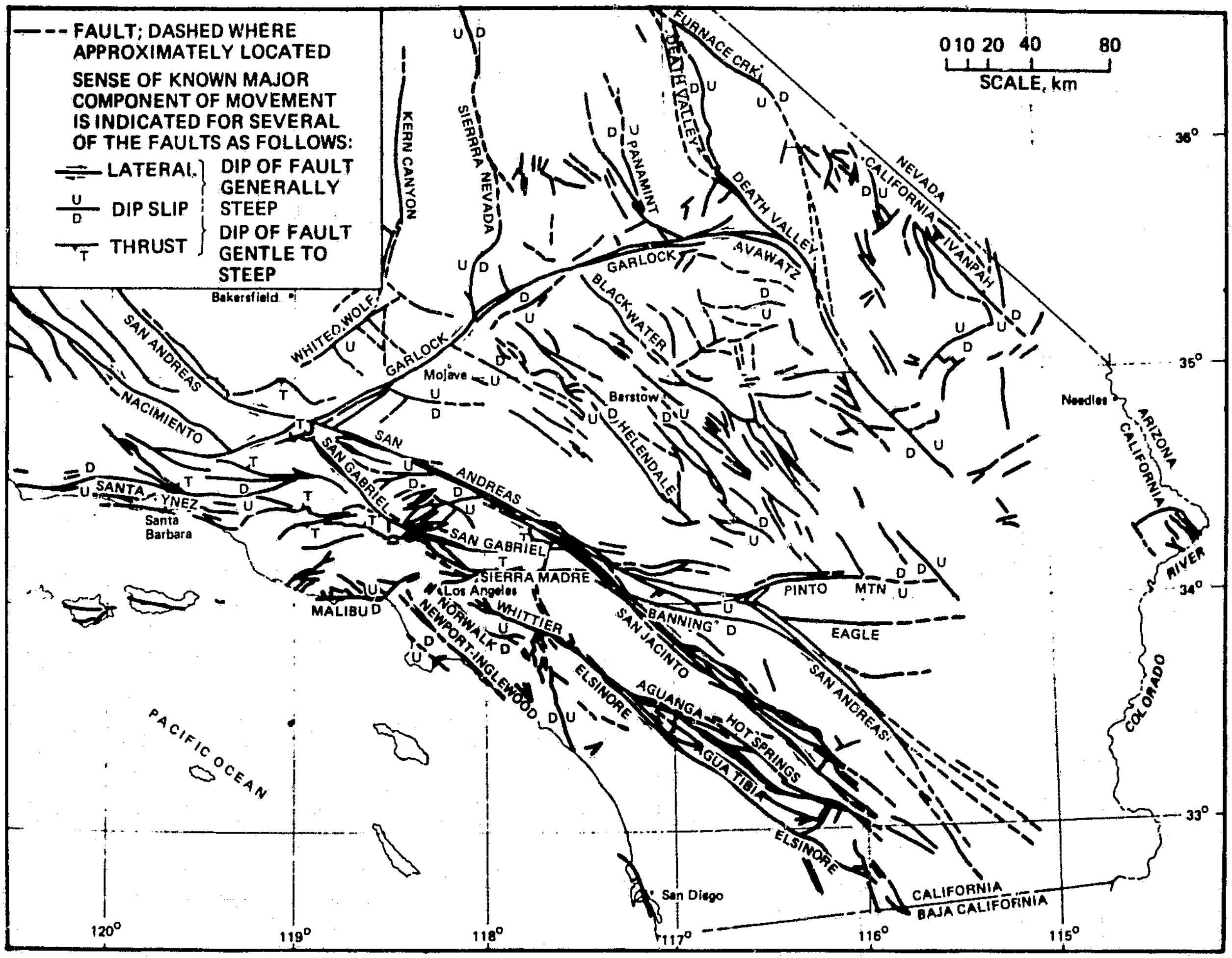


Fig. 2. Major faults in Southern California. The real boundary between the North American and Pacific Plates, in Southern California, is this broad fractured zone. The three-dimensional structure is largely unknown. This figure illustrates the need for a dense network of control points in earthquake hazards estimation. (From Ref. 1.)

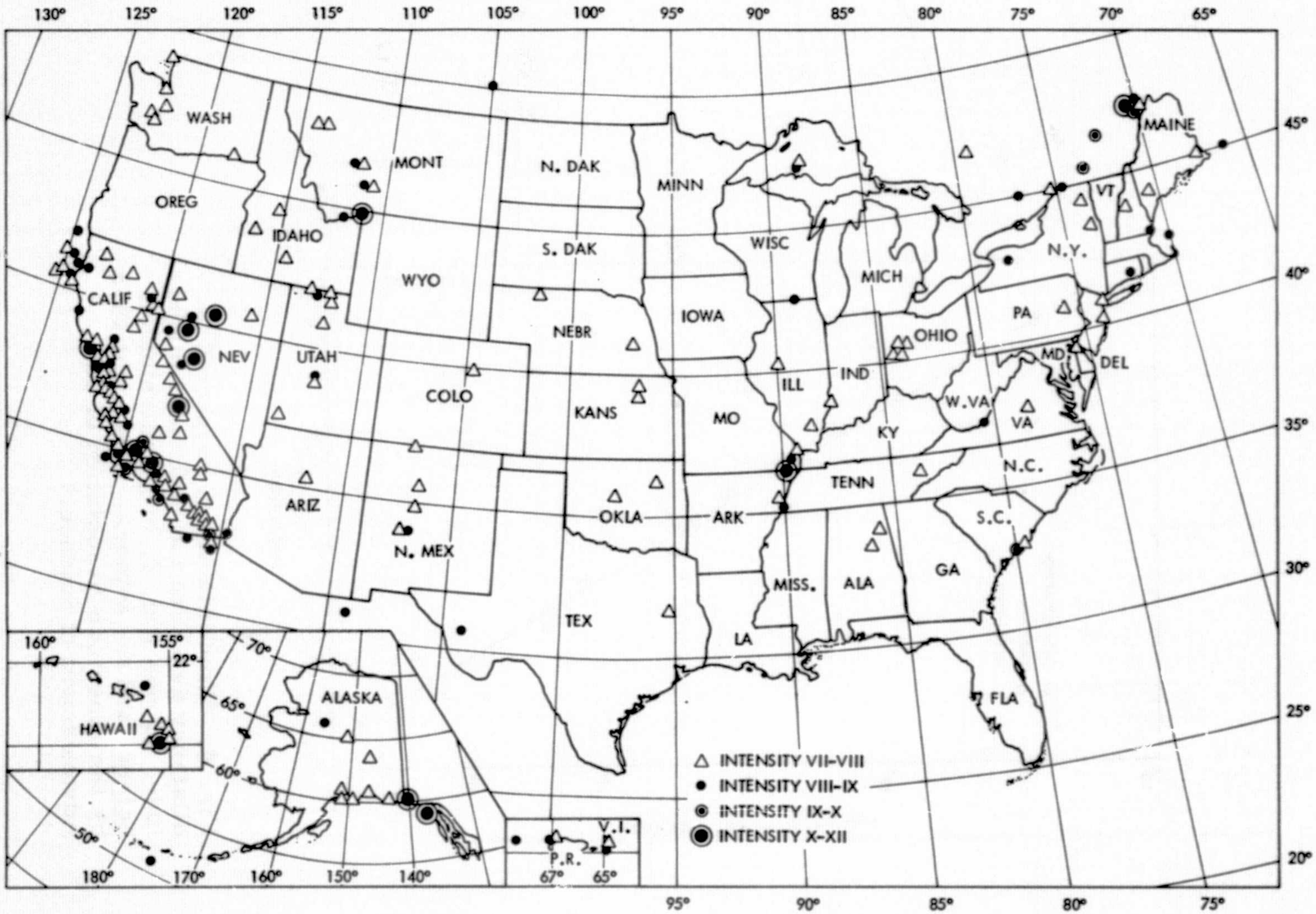
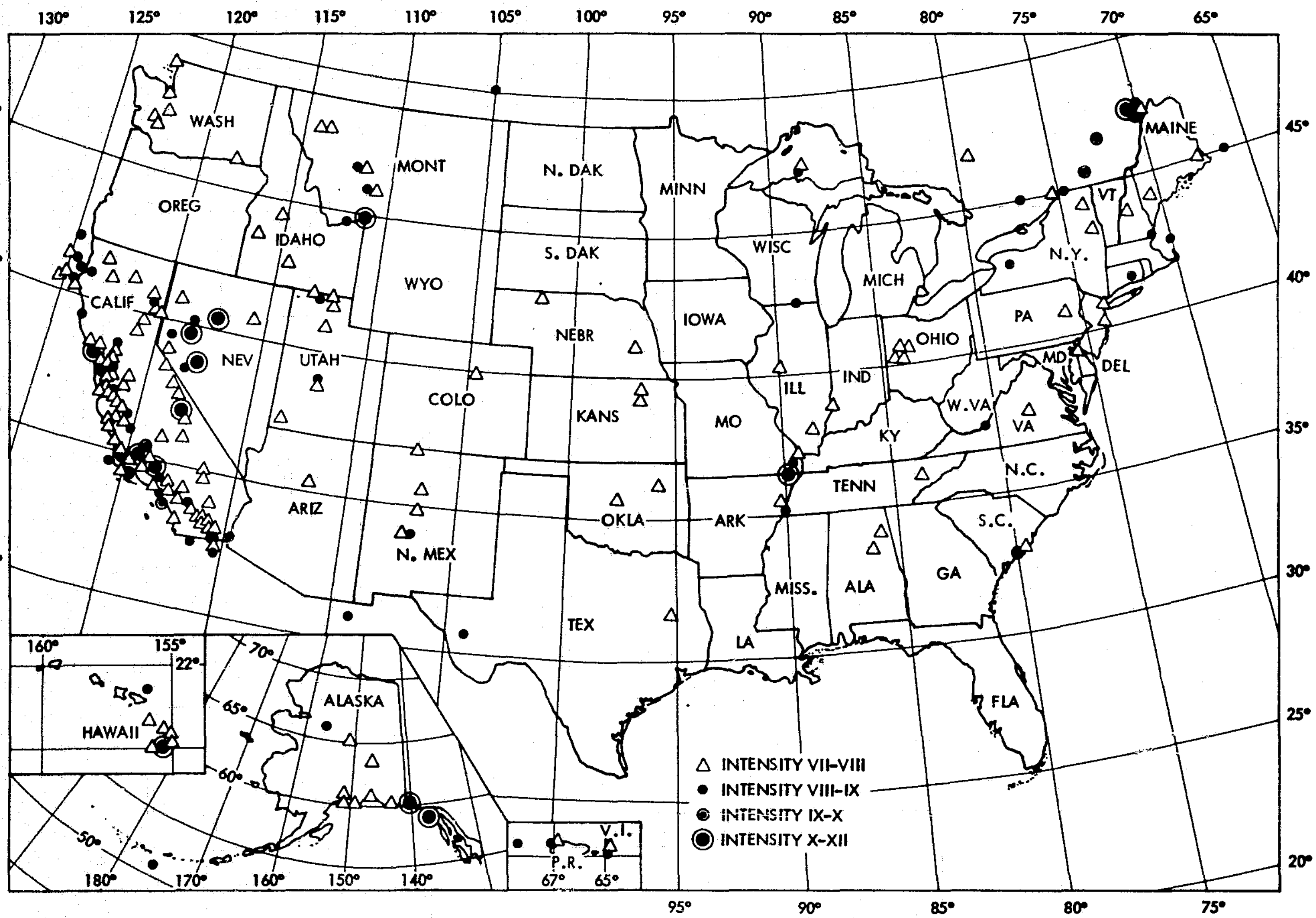


Fig. 3. Earthquake distribution in the United States. Shown are the locations of earthquakes large enough to cause appreciable structural damage (VII and higher on the Modified Mercalli scale) up to 1970. Clearly, the potential field of ARIES Project operations is not confined to the Pacific States. (Adapted from a map issued by the National Oceanic and Atmospheric Administration Environmental Data Service, Ref. 2.)



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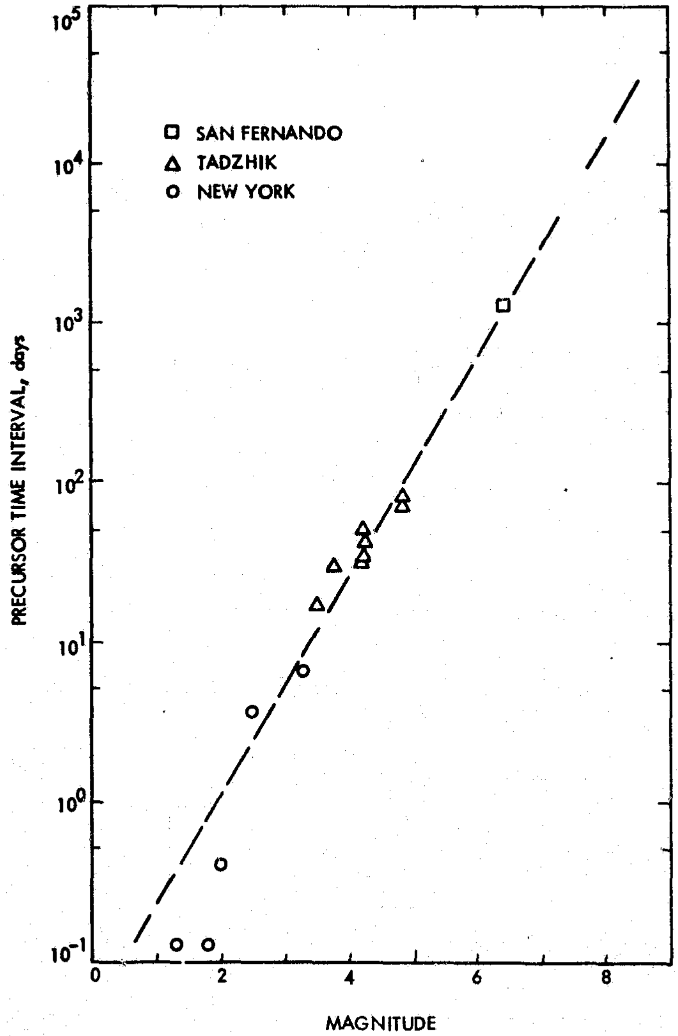

Fig. 4. Time interval of suspected dilatancy as a function of Richter magnitude. (From Ref. 7, by permission of Science and the authors. Copyright 1973 by the American Association of the Advancement of Science.)

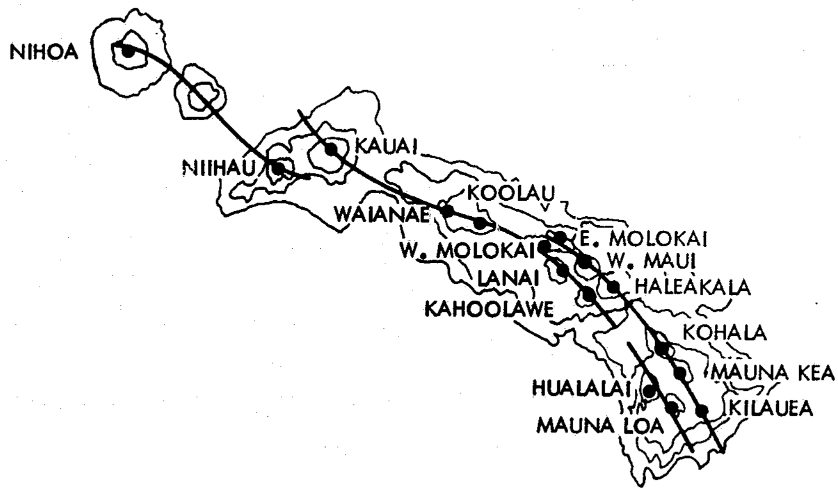

Fig. 5. Hawaiian shield volcanoes. Notice that these volcanoes lie on three roughly sinusoidal arcs. This pattern cannot be explained in terms of plate motion alone by any theory so far proposed. Caution should therefore be exercised in designing an experiment to deduce plate motion from measurements of local movement in the Hawaiian Islands. (After Ref. 10, by permission of the Geological Society of America.)

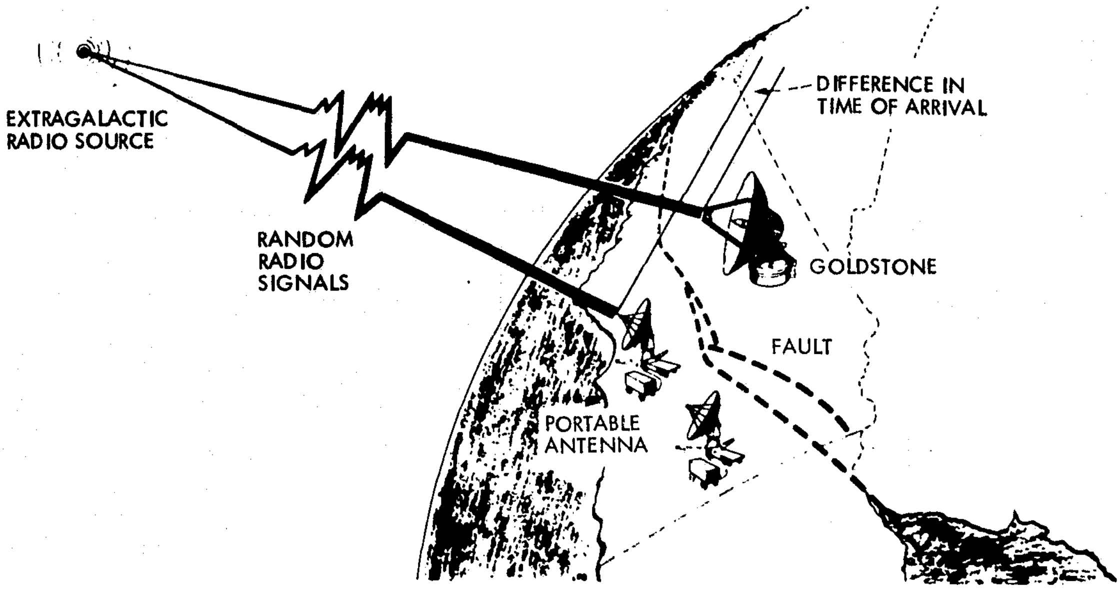

Fig. 6. Astronomical Radio Interferometric Earth Surveying (ARIES). The prime virtues of the ARIES technique are the speed with which results can be obtained by a portable antenna, the automatic reference to an extragalactic coordinate frame, and the ability to measure all three coordinates simultaneously on the solid Earth.

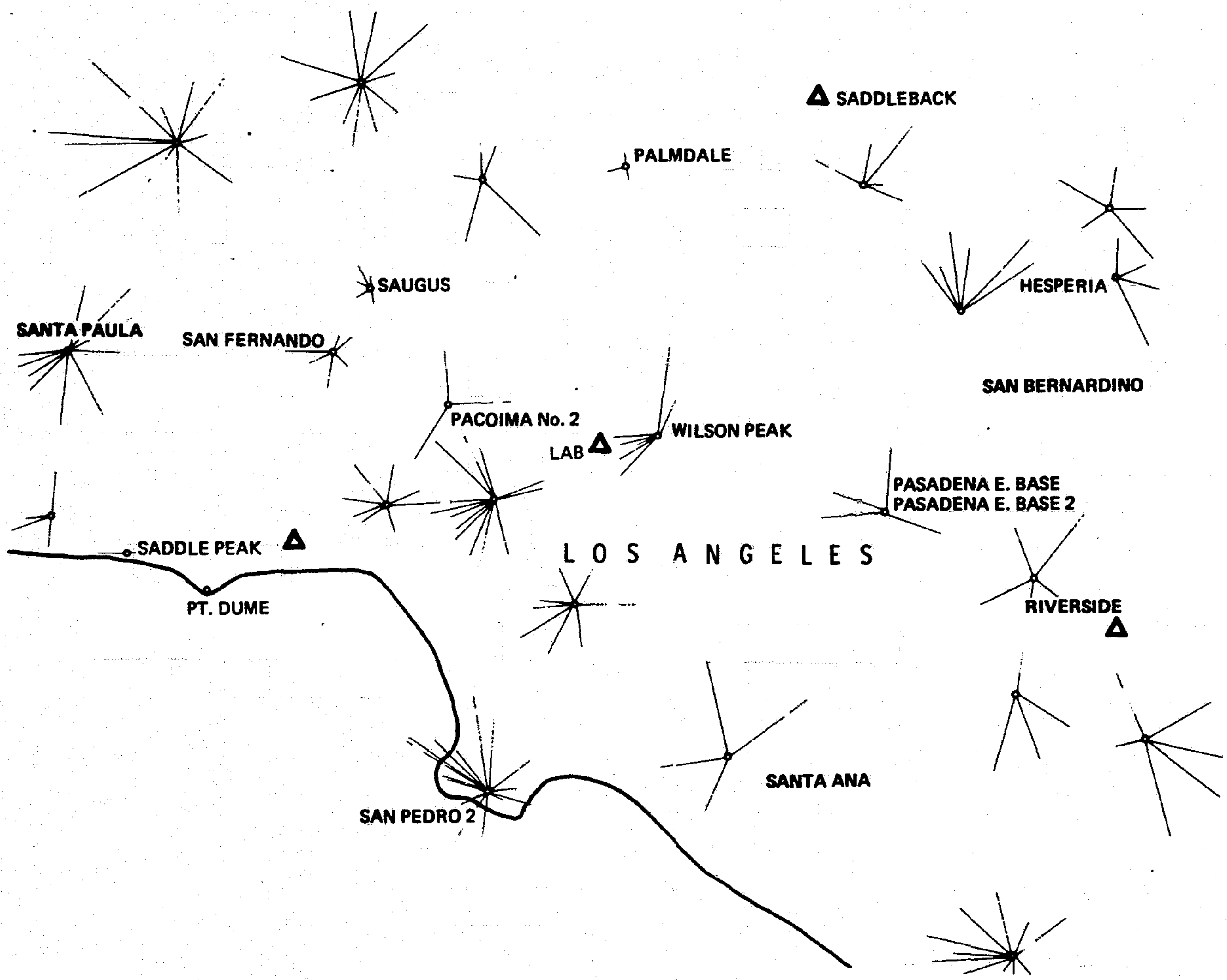

Fig. 7. Proposed ARIES/NGS interface. ARIES geodetic control points in the Los Angeles area (triangles), either already occupied or projected, shown against a few nearby control points of the National Geodetic Survey (NGS) grid. The goal of the ARIES Network Densification Task is to extend the accurate extragalactic measurements of ARIES to the dense network of the NGS, with frequency of measurement sufficient for geophysical purposes.

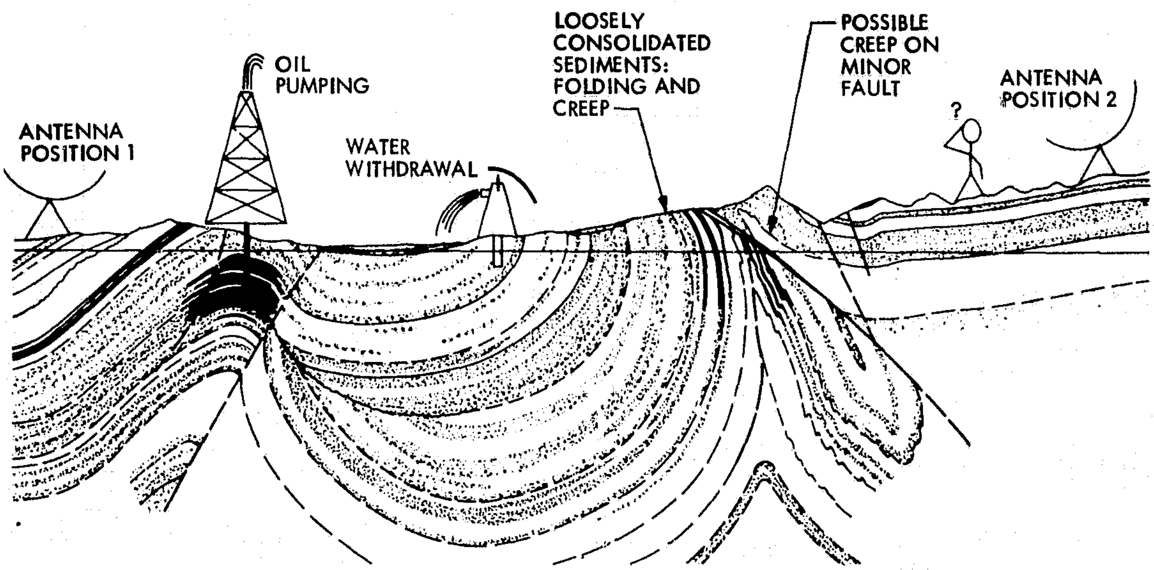

Fig. 8. Causes of vertical motion. Unless a network is sufficiently dense to monitor the several kinds of vertical motion in California, it may not be possible to recognize the uplift due to dilatancy, which may precede an earthquake. (Adapted from a structural section across part of the Ventura Basin, by Thomas L. Bailey, Ref. 1, p. 96.)

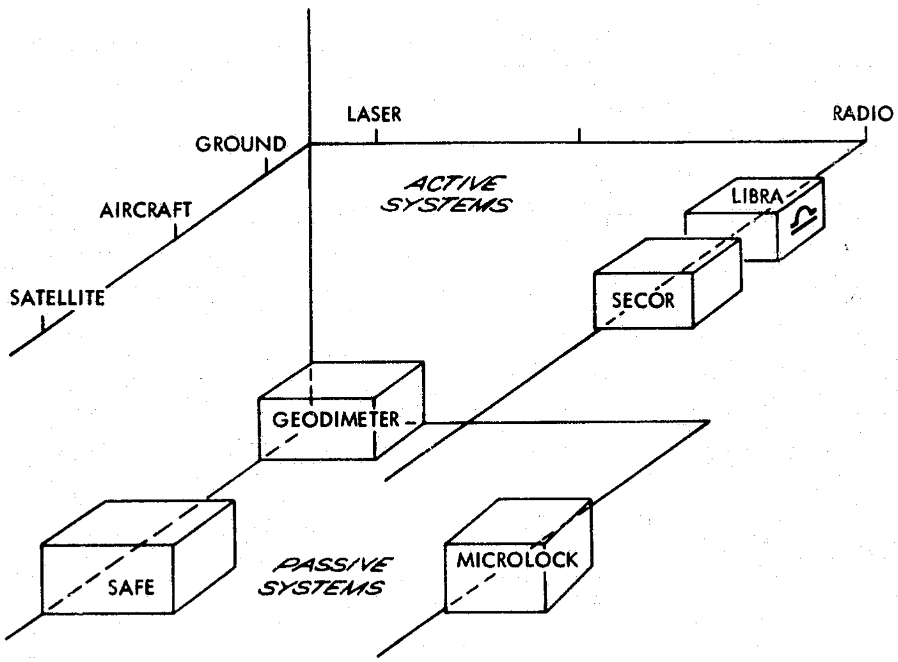

Fig. 9. Classification of positioning systems. Generally, all positioning systems that use range measurement can be classified in a three-dimensional taxonomy: (1) type of vehicle; (2) type of ranging device; (3) whether using active or passive target. A few representative systems are shown here.

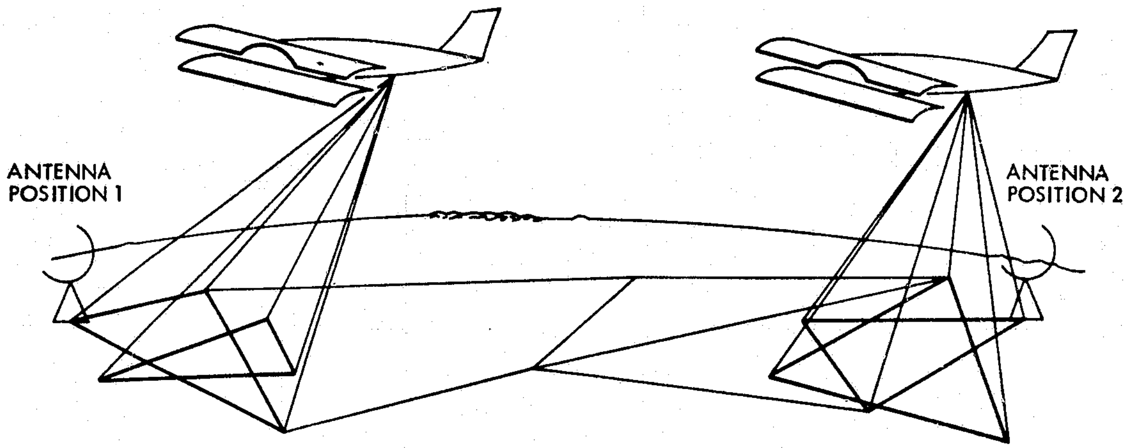

Fig. 10. Locations Interposed By Ranging Aircraft (LIBRA). In the LIBRA concept, an aircraft using radio or radar determines by the multilateration technique the relative locations of ground markers, a few of which are anchored to an absolute coordinate system by ARIES (cp Fig. 6). The aircraft permits closer network spacing than would a satellite; since all of the most complex apparatus is in the aircraft, the cost per ground marker is low.

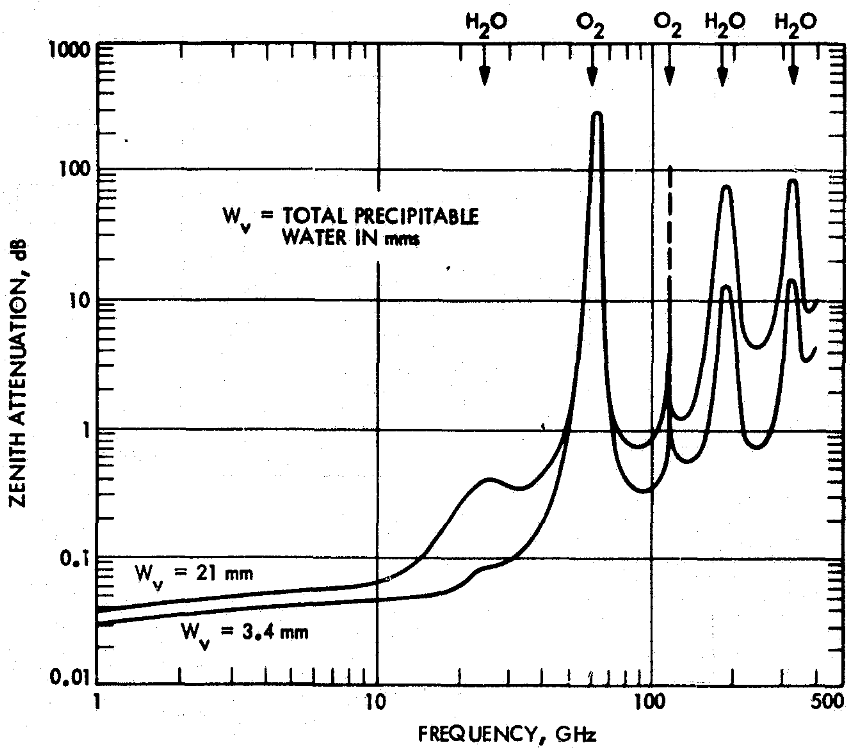

Fig. 11. Atmospheric absorption at millimeter wavelengths. At the high frequencies that would be necessary to recognize passive ground markers using airborne radar, atmospheric opacity becomes a serious problem. Notice the rapid increase of absorption with water vapor due to the H_2O band around 22 GHz. This points to the need for a lower frequency system, ranging to active markers. (From A. A. Penzias and C. A. Burrus, Vol. II, Annual Reviews of Astronomy and Astrophysics, 1973, by permission of Annual Reviews, Inc.)

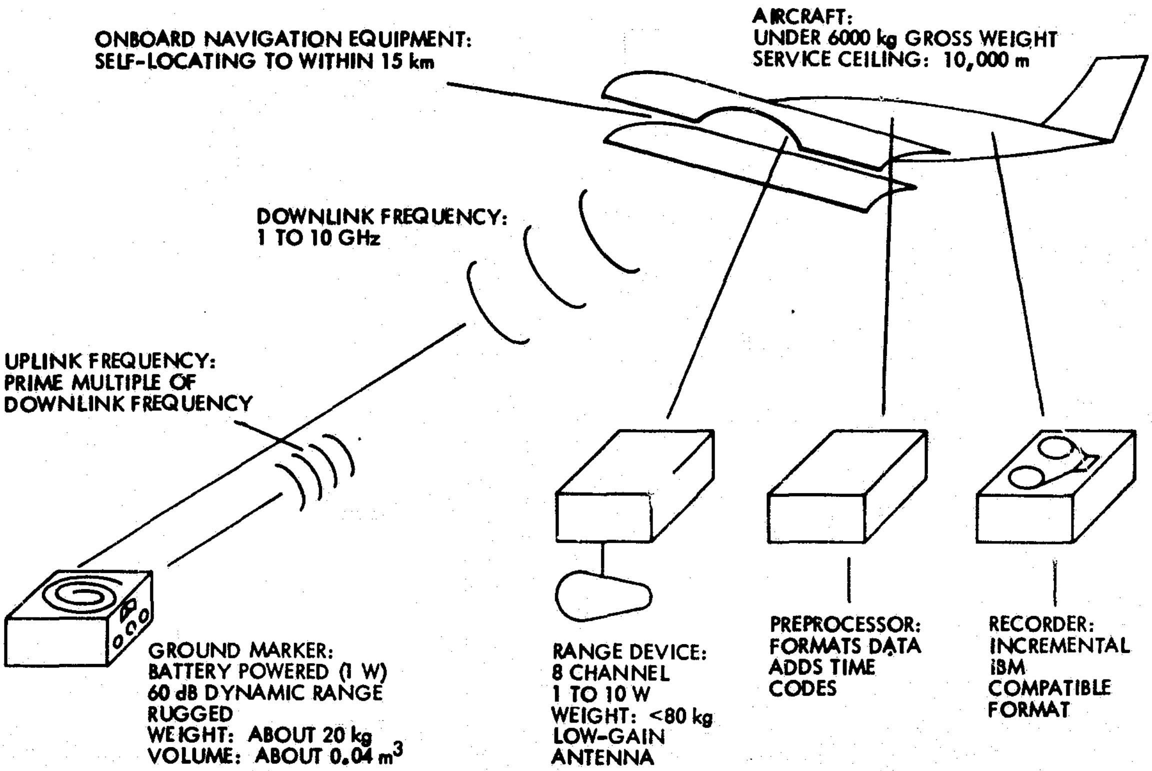

Fig. 12. LIBRA hardware specifications

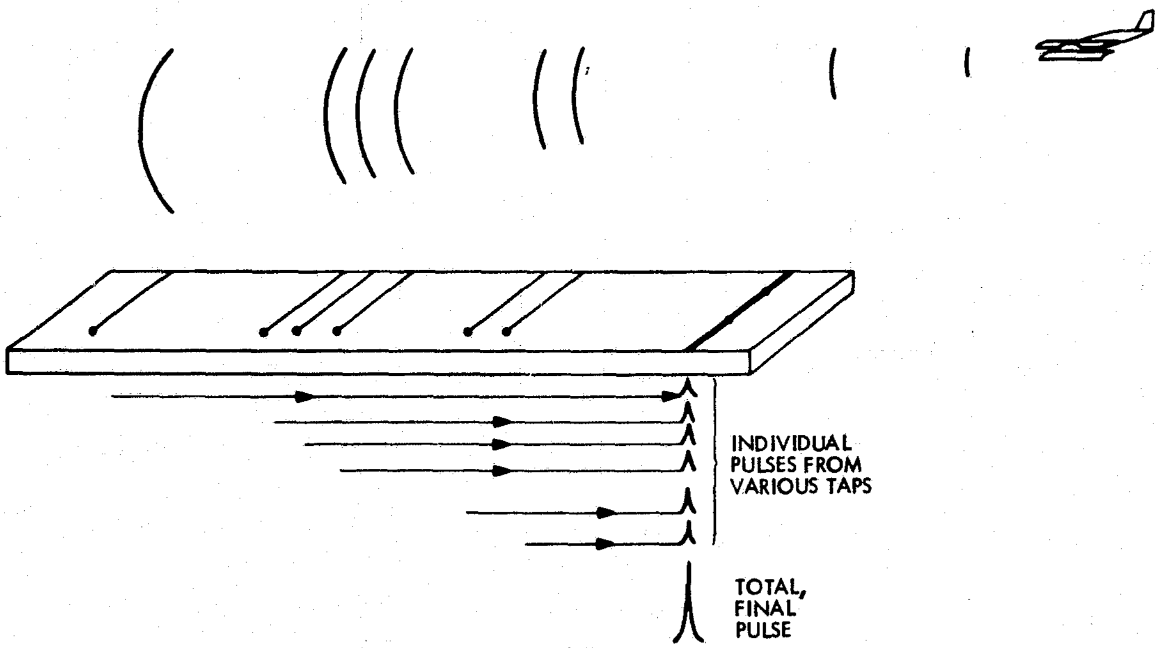

Fig. 13. Surface Acoustic Wave Device (SAWD) code recognition. The energy of the radio pulse is transformed at each tap into a surface wave (Rayleigh wave), which then moves across the device to an output pick-up at the right. When the time spacing of the radio pulses matches the physical spacing of the SAWD taps, the signals reinforce to form a sharp output pulse.

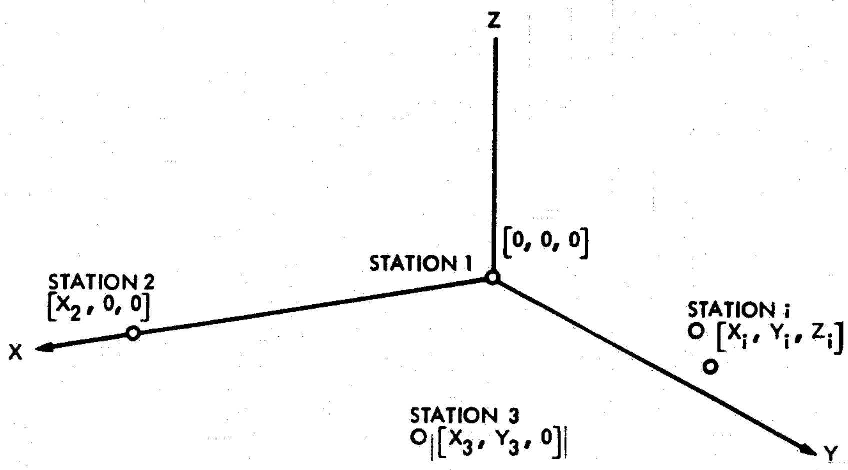

Fig. 14. Multilateration coordinates. The locations of four or more stations relative to one another are most easily expressed by means of the coordinate system pictured above. Station 1 defines the origin; station 2, the X axis; and station 3, the XY plane. Thus, the i-th station ($i \geq 4$) is located with respect to the first three.

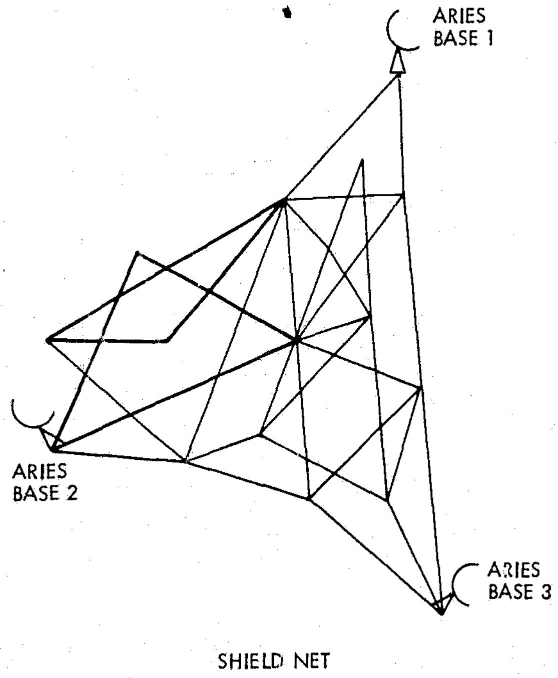

Fig. 15. Logic of network densification by multilateration. The only basic difference between classical triangulation and multilateration is that the basic geometrical unit of the latter is the pattern of six stations (heavy lines above) called the <u>shield</u>, instead of the triangle. Like triangulation, multilateration may be used to survey a broad area (by a shield net, left above), or a narrow track (by a shield chain, right above). Control by ARIES base stations prevents the errors in multilateration from propagating without upper limit.

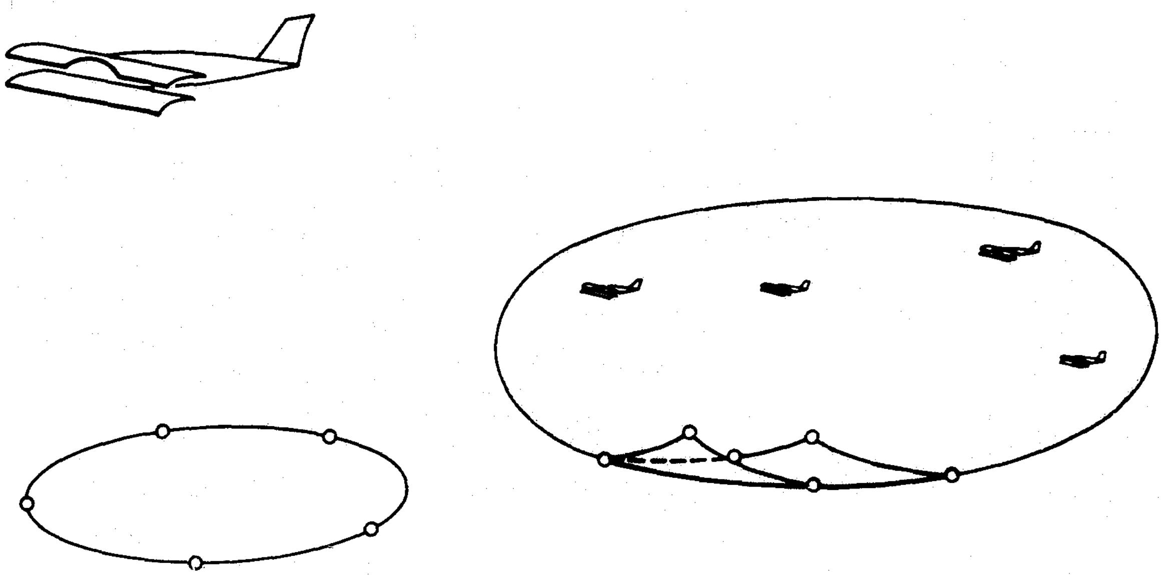

Fig. 16. Mathematical restrictions on the multilateration technique. A unique solution for ground marker coordinates cannot be obtained under two conditions: if all ground markers lie on a second-order curve (such as an ellipse, left above), or if all aircraft positions lie on a second-order surface (such as an ellipsoid, right above). Among other requirements, this fact demands that an aircraft range to at least six ground markers (since a second-order curve can be passed through any five points), and that the aircraft makes at least two passes at different altitudes. Fortunately, these requirements can readily be satisfied. (After Ref. 19.)

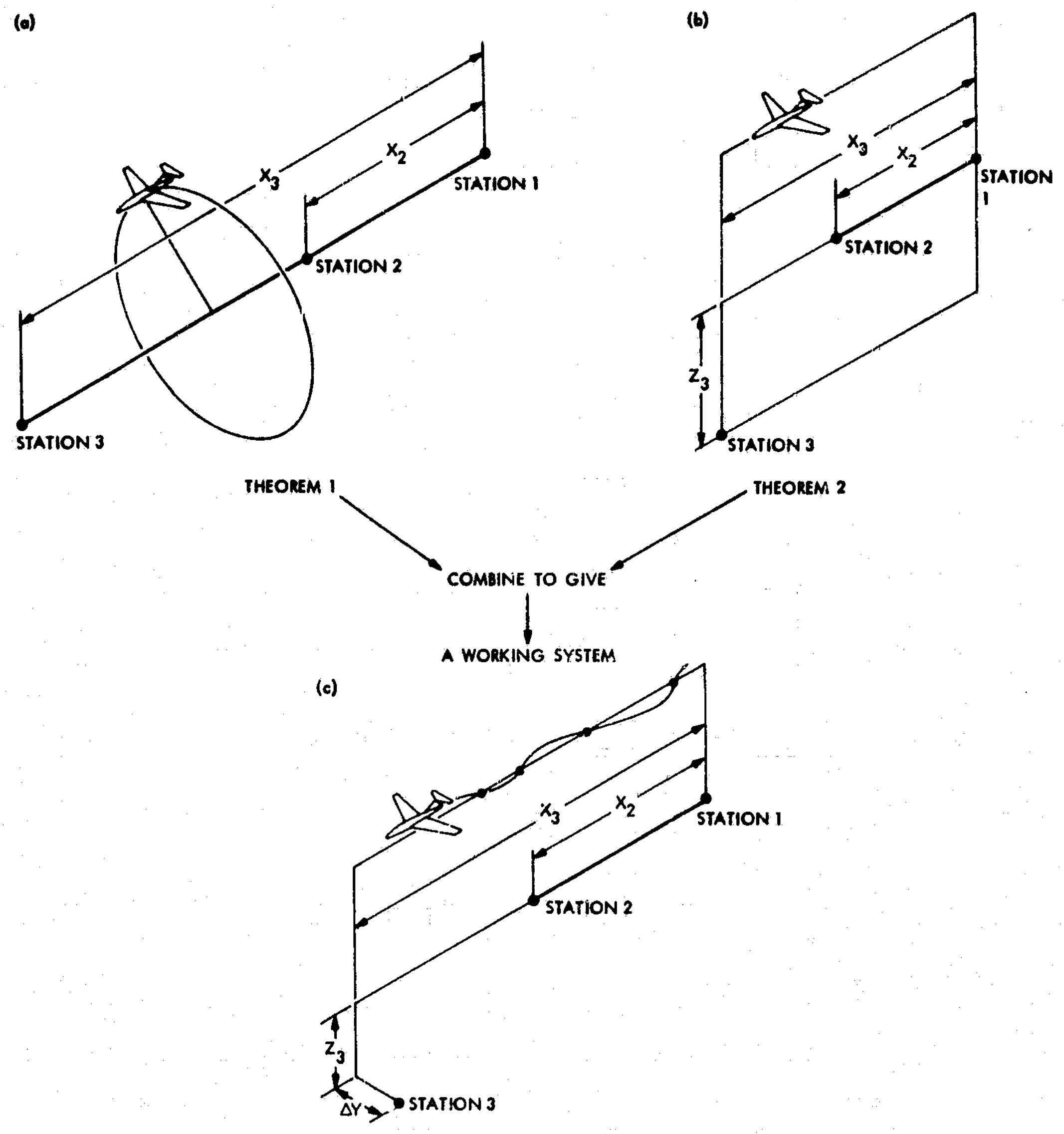

Fig. 17. An inexpensive, three-station multilateration method. These three figures illustrate a means of measuring relative distances and elevations using only three ground markers. The method depends on two theorems: (1) if the three stations lie on a straight line (as in part (a) of this figure), the relative distances X_2 and X_3 can be determined by ranging from three aircraft locations in three-dimensional space; (2) if the three stations and three aircraft locations all lie in a plane (as in part (b)), the relative coordinates X_2, X_3, and Z_3 can all be determined. A practical system combines both of these theorems: if (as in part (c)), the three stations lie approximately on a straight line (within a few tens of meters), and approximately in the plane of the ranging aircraft (ΔY not larger than a few tens of meters), then X_2, X_3, and Z_3 can be determined to a much higher approximation (~1 cm). In practice, the aircraft would fly a weaving pattern, and would range when crossing the common plane of the stations.

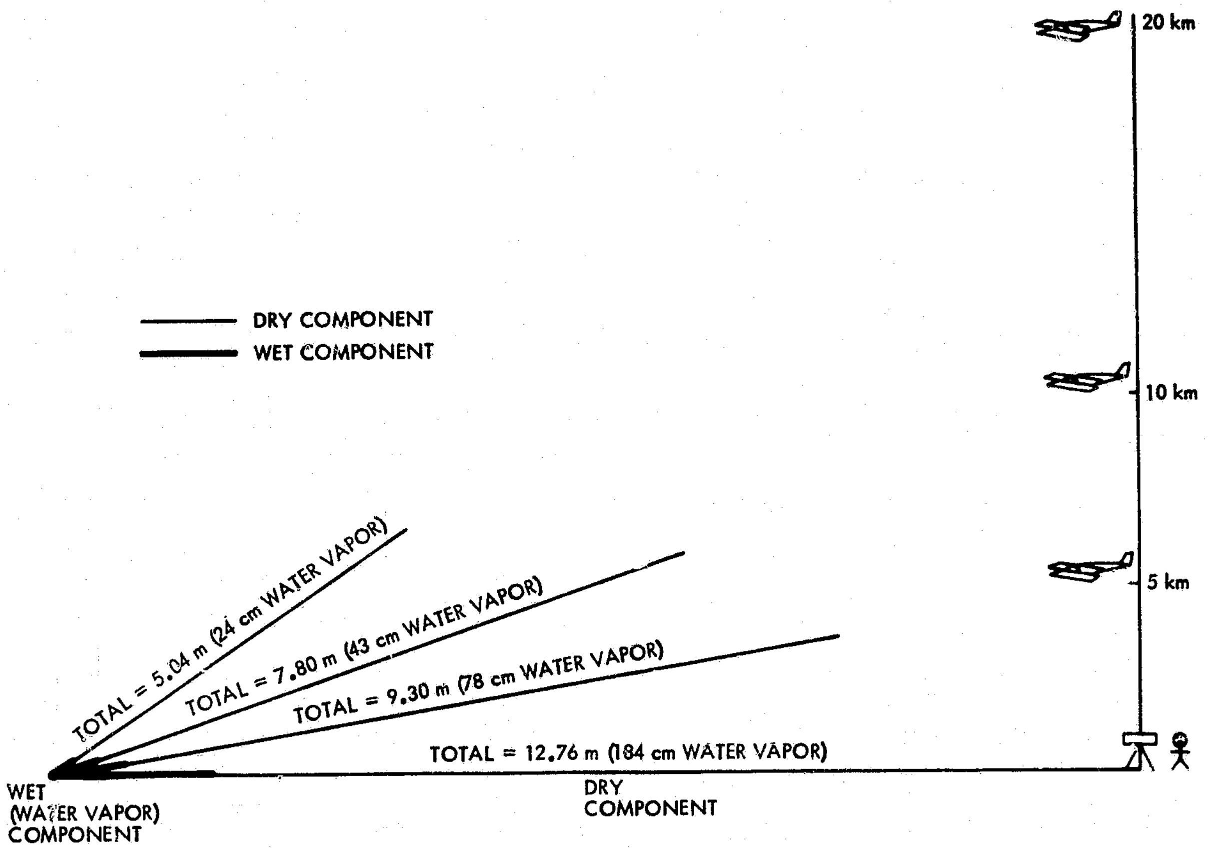

Fig. 18. Atmospheric range correction. A major advantage of making radio distance measurements from an aircraft rather than from the ground is that the line of sight slants away from the ground into thinner, dryer air, making the atmospheric correction smaller. Especially important is the rapid diminution of the troublesome wet (water vapor) component with aircraft altitude. Here, atmospheric corrections over a 40-km ground distance are compared for a ranging device at altitudes of 0, 5, 10, and 20 km (ICAO Standard Atmosphere, 60% humidity).

END

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