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HORIZONTAL SOUNDING BALLOON FEASIBILITY STUDY

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ABSTRACT

This Note discusses a study to determine the feasibility of using plastic balloons that float freely at constant-density altitude to provide a more comprehensive understanding of the atmospheric circulation in the Northern Hemisphere.

The study indicates that development of an effective and economical means of gathering weather data over the Northern Hemisphere using such balloons is feasible. One area that requires considerable research and development is the concept of two-dimensional and distributed electronics. There are other areas in the total program that also require development, such as, the balloon vehicle itself, a tracking network, and associated balloon distribution network. Nevertheless, it appears that all of these areas can be successfully developed prior to the development of two-dimensional balloon electronics.

The first step towards the future use of this technique will require considerable funding for development of minimal mass electronics, the balloon vehicle, balloon instrumentation, tracking, and statistical analysis of balloon flight trajectories.

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HORIZONTAL SOUNDING BALLOON FEASIBILITY STUDY

1. INTRODUCTION

The science of meteorology can fairly boast of many spectacular advances in the decade and a half since the end of World War II. The development of numerical prediction, radar meteorology, satellite meteorology and the advent of the automated weather system are all noteworthy achievements which have received their due share of public acclaim. Rightly or wrongly, the public has been led to believe that a revolutionary breakthrough is just around the corner. A critical and unbiased examination of the present state of the science reveals an altogether different picture. On the theoretical side we must conclude that the most significant scientific breakthrough occurred in the period just prior to World War II under the leadership of pioneers such as Rossby, J. Bjerknes and others. Since those days, theoretical meteorology, although excellent in quality, has been mainly concerned with filling in the gaps. The most important breakthrough on the observational side is of more recent origin. It consists of an upward extension of the upper air observational data. At the end of World War II the highest level for which daily charts could be plotted on a routine synoptic basis was 500 mb (20,000 ft). Today the limit is not far short of 10 mb (100,000 ft). This improvement has vastly increased our knowledge of atmospheric circulation, and has opened the door to further scientific advances. This remarkable result was brought about by a most unspectacular and modest development, namely, an improvement in the quality of the neoprene balloon. Thus it may be seen that scientific progress does not depend on gadgetry, however costly or elaborate, but rather on the quality of hard-core quantitative observations and the ability of the human mind to interpret these data.

The most serious deficiency which presently exists in the observational program is the horizontal coverage. When the vast blank areas over the earth's surface are considered, one must conclude that we are no better off today than we were a generation ago in this respect. It is this deficiency, for which there has never been an adequate solution, which has most impeded our scientific progress. The situation may be ameliorated somewhat by pictures from meteorological satellites; but these data, not being quantitative, are at best poor substitutes for rawinsonde observations.

The technique of horizontal sounding[1] is the only means that has ever been proposed which could conceivably provide quantitative data coverage over such inaccessible areas as oceans and polar land masses at a cost which, if not cheap, is at least not astronomical. It is within this context that the value of horizontal sounding must be judged at present; not as replacement for the radiosonde but as a source of sorely needed supplementary data.

Briefly, the technique makes use of a pressurized plastic balloon vehicle capable of floating at a constant density level for many days, a specialized set of instrumentation, and an associated tracking network. The balloons will

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(Authors' manuscript approved 22 May 1961)

be instrumented to transmit essential meteorological parameters to ground stations. The sequential positions of an individual balloon, tracked by the same ground stations, would yield an average wind at that location; and, the tracking of many such balloons would yield an integrated picture of the atmospheric circulation at altitudes to 100,000 ft. The entire balloon assembly is to be of minimal and distributed mass such that it cannot create a hazard to aircraft. It is estimated that 2000 of these balloons floating at their designated altitudes will provide adequate coverage for the northern hemisphere, with a replacement factor required in the order of 50 to 100 balloons a day.

The Commission for Aerology of the World Meteorological Organization of the United Nations, at its second session in Paris in June 1957, recommended that the feasibility of horizontal-sounding balloon techniques be investigated. It further requested the President of the Commission for Aerology to make arrangements for preparing a report for its third session in 1961 on developments in horizontal sounding techniques.

It was determined that the total feasibility could be evaluated through a careful analysis of the probable accuracy of the wind data in conjunction with an analysis of the balloon vehicle, the problems of balloon distribution, electronic miniaturization, and tracking. The factors enumerated above are the principal limitations to an operational capability. During the study period, the over-all feasibility of the technique was investigated through a series of contracts with civilian corporations, universities, and in-house studies.

This report consists of a discussion of the superpressure balloon, miniaturized balloon electronics, balloon tracking networks, the accuracy of wind data to be expected from conventional tracking methods, and several techniques for improving the accuracy of the observations. The present state-of-the-art as well as what improvements could be reasonably expected with further development are described.

2. DISCUSSION

2.1 Balloon Development

A study has been made to determine the actual design criteria of the superpressure balloon, and the techniques necessary for economical production of large quantities of reliable superpressure balloons.

This unique balloon, the superpressure balloon, has the inherent characteristics of constant-density level flight for long durations without the use of ballast. The balloon is a closed and almost nonextensible plastic envelope that contains its lifting gas at a greater pressure than that of the surrounding atmosphere. When such a balloon is subjected to the daily variation of radiant energy at its normal floating altitude, the internal pressure fluctuates accordingly; however, the balloon volume and weight is essentially unchanged. Consequently a constant-density flight level is maintained throughout successive nights without requiring ballast, the flight duration being limited only by the permeability of the balloon material.

The superpressure balloon study program has been oriented toward the development of small frangible balloons that can carry very light payloads to altitudes between 20,000 and 100,000 ft. These balloons are made of plastic film which, when under superpressure at the cold temperatures of altitude, will shatter harmlessly like a Christmas tree ornament if hit by an aircraft. The program has normally followed this pattern:

a. Materials Study - The engineering properties of several promising commercially available materials were investigated to determine the ones which possess the desirable properties of toughness, low cold brittleness temperature, low permeability, favorable spectral absorption characteristics, and high tensile strength and modulus. Laboratory tests were also made to determine the seal efficiency at cold temperatures in both peel and shear, and the sealability on a production basis.

b. Environmental Tests - Model balloons made of the most promising materials and incorporating the latest design and fabrication parameters were tested in an environmental chamber to measure their performance under the cold temperatures of flight altitudes. Necessary design and fabrication parameters were resolved prior to any flight testing.

c. Flight Tests - A flight-test program was conducted from the AFCRL Operating Location at Vernalis, California. This involved testing of new launch procedures, and testing the actual performance of the balloon on its selected flight profile until a feasible vehicle design was established.

Several small contracts with manufacturers of balloons and associated equipment were directed toward basic study of the physicochemical properties of balloon materials and fabrication quality control. (See References 2, 3, 4, 5, 6, 7, and 8.) After a thorough materials testing program, Mylar* was chosen as the best commercially available balloon material having the physicochemical characteristics necessary to satisfy the superpressure balloon requirements, together with a long-range outlook for reasonable production costs. The testing of some 150 model balloons in environmental chambers together with flight tests has resulted in an invaluable understanding of the total problem of reliably producing such balloons.

The flight tests conducted by the Research Instrumentation Laboratory from Vernalis, California have included a variety of superpressure balloon shapes including cylinders, tetroons, and spheres, each of which has unique properties of low production cost, relative ease of quality control, or high

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*Commercial name for a Dupont polyester film - Polyethylene Terephthalate payload-to-weight ratio. The sphere is the most efficient shape (less balloon material weight and lifting gas required for a given payload-altitude combination) and appears to be the most promising vehicle for future use. Therefore primary effort for the past year has been to improve its design and fabrication, and extend its flight duration. On a typical test flight, a 30-pound instrumentation payload was carried to an altitude of 67,500 feet for a duration of 6 1/4 days, at which time the flight was automatically terminated. See Fig. 1. The data received indicated that the balloon flew at a constant-density altitude throughout the flight (the instrument accuracy was ± 200 ft) and that the test could have continued for greater duration. This and similar flights demonstrate that there is no question that superpressure balloon flights of long duration are feasible, but it will require further investigation into design and fabrication techniques, quality control, and launch techniques before flight durations can consistently exceed 10 to 20 days.

The actual sizes of superpressure balloons to be used will depend upon the weight of the instrumentation package and the flight altitude. Figure 2 illustrates sizes and weights of balloons for different altitudes assuming instrument payloads of two and five pounds. Thicker plastic films are required at the lower altitudes to absorb the internal superpressure which, as a function of ambient pressure, decreases with altitude.

Recent environmental cold chamber tests indicate a breakthrough in the design of superpressure Mylar spheres. Model Mylar balloons incorporating a new sealing technique, the bitape, which requires tape seals on both sides of the balloon gores, have consistently reached stress levels 1 1/2 times higher than previous monotape sealed balloons.[9] If these chamber test results are also realized in actual test flights to be conducted in the spring of 1961, long duration flights at constant density altitudes will be a reality.

In conclusion, contracts with several balloon manufacturers, in combination with Air Force in-house efforts in design, have resulted in a demonstrated feasibility of producing superpressure balloons.

Another superpressure vehicle that has great promise is the blown or minimum seam balloon. One large corporation has sponsored an extensive in-house research and development program on the minimum seam balloon, and has successfully flown two superpressure balloons made with but one seam. This minimum seam balloon incorporates a new manufacturing process and material, and is a radical departure from the present fabricated, tailored gore, Mylar balloon. The feasibility of this type of vehicle cannot be determined until it has been thoroughly tested in cold chambers and on actual flights. Such tests as these will not be possible until many technical problems associated with the material and process have been solved. If this minimum seam concept can be perfected, the potential costs of the program would be greatly reduced.

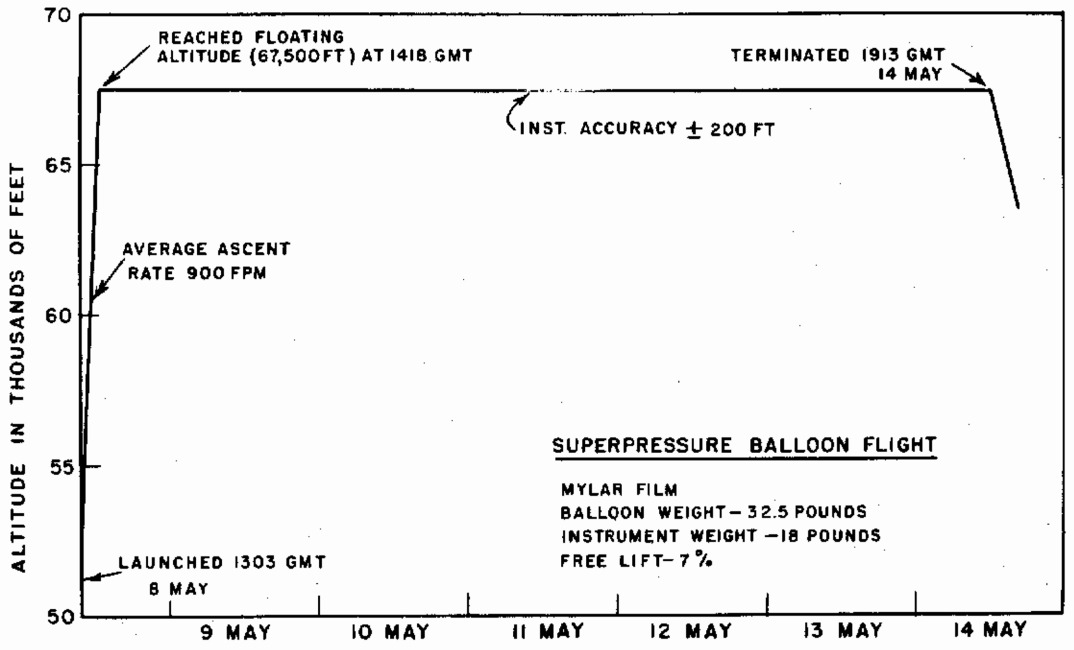

FIG. 1. Typical superpressure-balloon flight profile.

Altitude	20,000 (466 mb)		40,000 feet (188 mb)		70,000 feet (45 mb)		100,000 feet (11 mb)	
Payload	2 lb.	5 lb.	2 lb.	5 lb.	2 lb.	5 lb.	2 lb.	5 lb.
Balloon Diameter	6.5 feet	8.5 feet	8 feet	11 feet	12.8 feet	17 feet	22 feet	29 feet
Balloon Material Thickness 1/1000 of an inch	2 mil	3 mil	1.5mil	2 mil	1/2 mil	3/4mil	1/2mil	1/2 mil
Weight of Balloon	1.9 lb	4.9 lb	2.2 lb	5.5 lb	1.9 lb	5.0 lb	5.5 lb	9.5 lb

* Approximate Values based on commercially available sizes of Mylar, which has a density of 0.05 pounds/cu.inch

FIG. 2. Balloon size and weight as functions of altitude for superpressure flight with payloads of 2 and 5 pounds.

2.2 Minimal Mass Instrumentation

Before a large-scale horizontal sounding program at aircraft altitudes can be made acceptable to the Federal Aviation Authority and to aviation in general, balloon vehicles and their instrumentation must be developed of minimal and distributed mass that will create no hazards to aircraft in any possible collision.

The approach taken to this problem was to investigate the feasibility of reducing electronics to very small minimal-mass components that could be insulated in shock-absorbing foam plastics both to minimize the collision hazard and provide insulation from the cold temperature of flight altitudes.

It was considered possible that foam-insulated minimum-mass balloon components could be developed that would meet the requirements of the aircraft hazard criteria at relatively low costs, since millions of government dollars have already been spent on reducing the mass of electronics through microminiaturization, micromodularization, etc. The feasibility of applying existing technology for this program was determined through a limited development and testing program of such minimal-mass balloon components.

Because of their extensive background in micromodularization, a contract was negotiated with RCA[10] to study the technical and theoretical processes and capabilities associated with minimal-mass electronic components and instrumentation for use in plastic balloon flights at aircraft altitudes. This contract was to supply the latest information on minimal-mass circuitry and components, and a working model of an HF transmitter incorporating the latest concepts based upon RCA's experience in producing lightweight electronic equipment.

The final report on this study was received in August 1960 with the following general results and conclusions. A survey of a large variety of pressure and temperature transducers was made to determine the best approach to pressure and temperature sensing from the standpoint of accuracy and aircraft collision hazard. A study was furnished of presently available components which may be combined into a small, lightweight, balloon-borne unit. However, the scope of the contract did not permit detailed investigation of new or unique concepts pertaining to minimal-mass electronics other than the transmitter discussed below.

A lightweight radio transmitter was designed and constructed to produce 5 watts output at 5 megacycles, employing structural methods which were shown during the study phase to be desirable (Figs. 3 and 4). This transmitter indicates that solid-state printed-wiring technology, using a thin pliable substrate and smallest available high-quality components, considerably reduces the mass and mass concentration of the normal transmitter while increasing the frangibility. This lightweight transmitter, weighing only 54.8 grams (1.93 oz), was packaged in a Styrofoam container roughly 10 inches by 6 inches by 3 inches, the Styrofoam serving a dual purpose of both thermal insulation and shock absorber. Total package weight was 136.2 grams (4.8 oz).

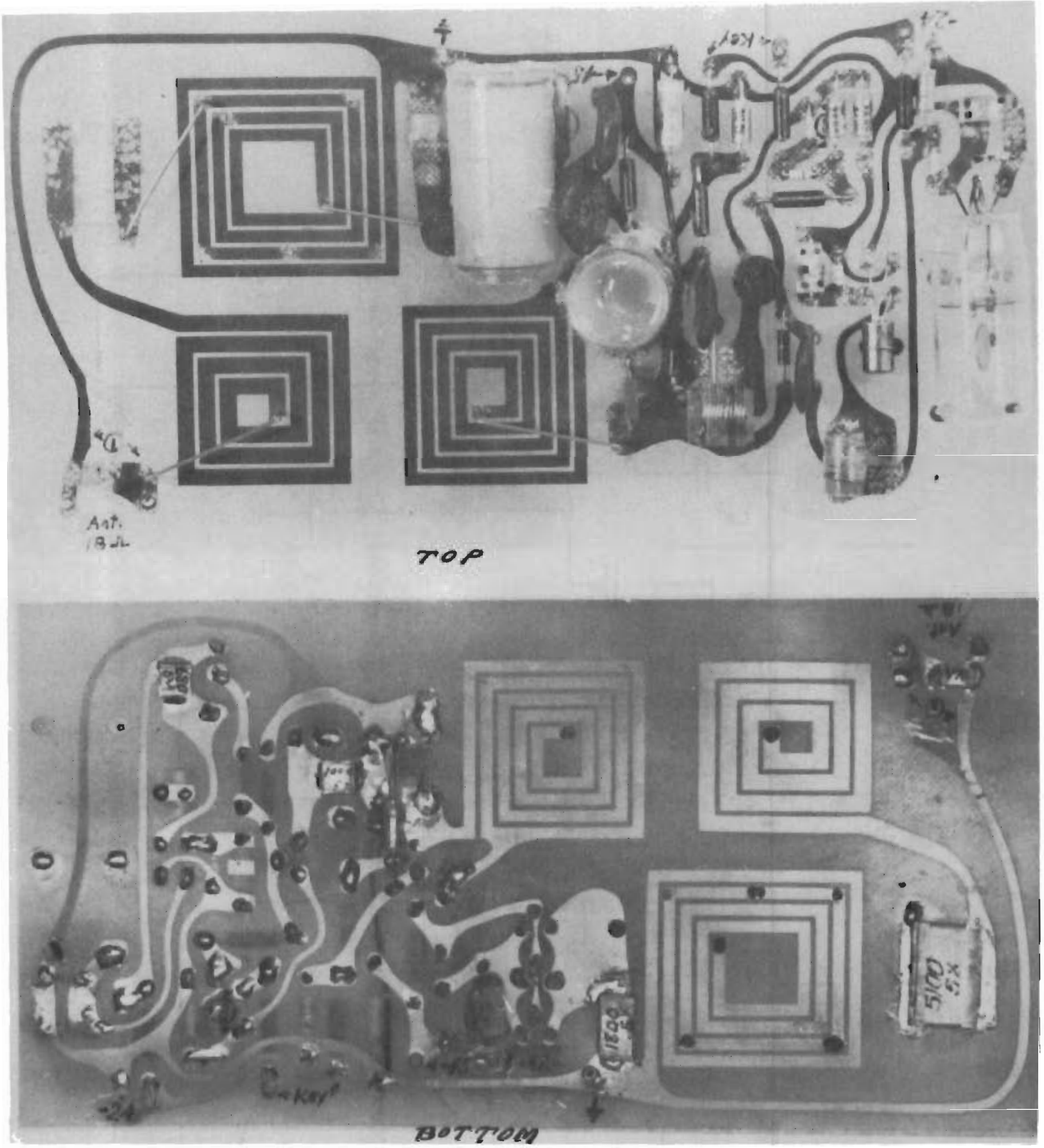

FIG. 3. Lightweight RCA-developed radio transmitter.

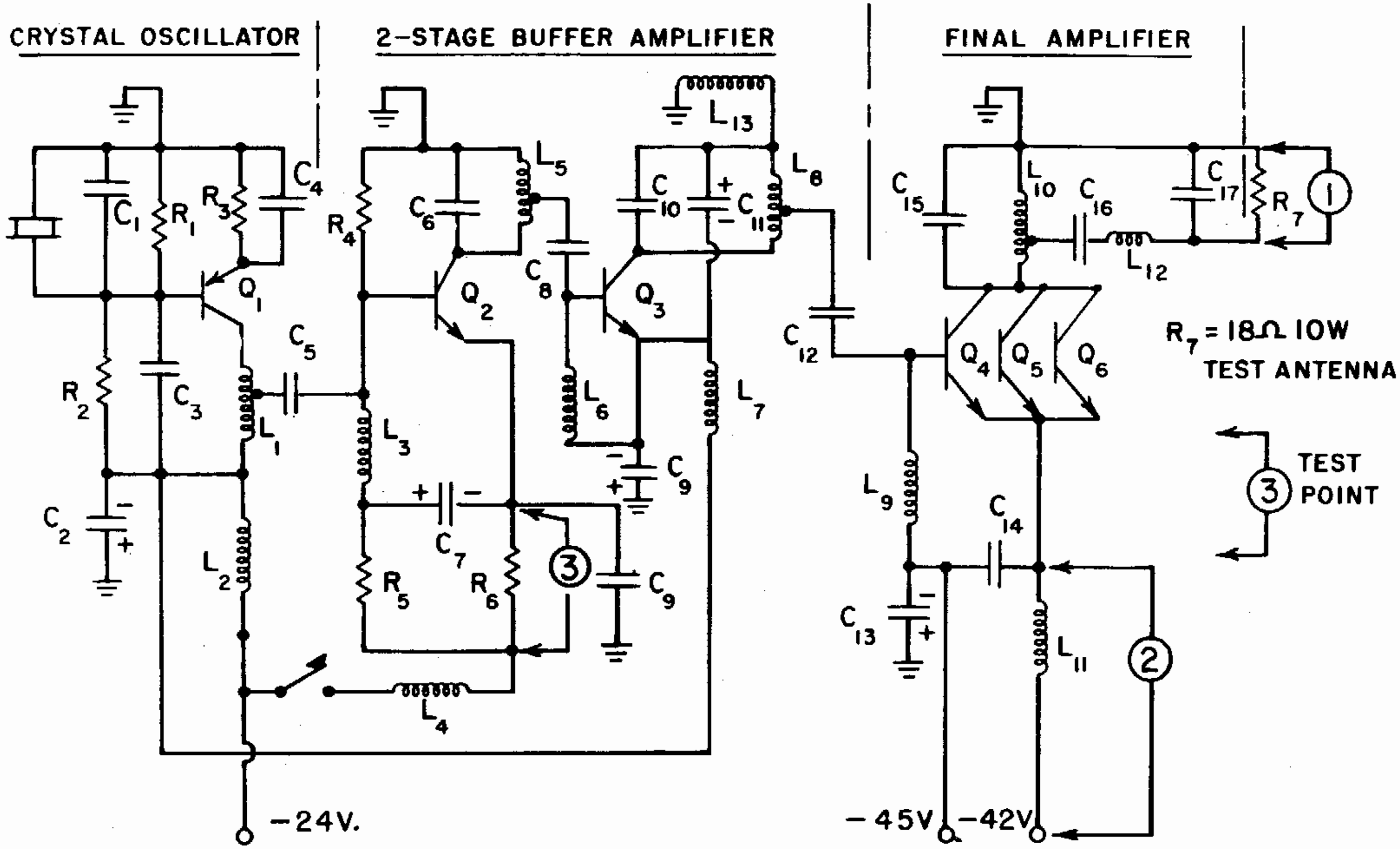

FIG. 4. Transmitter schematic diagram.

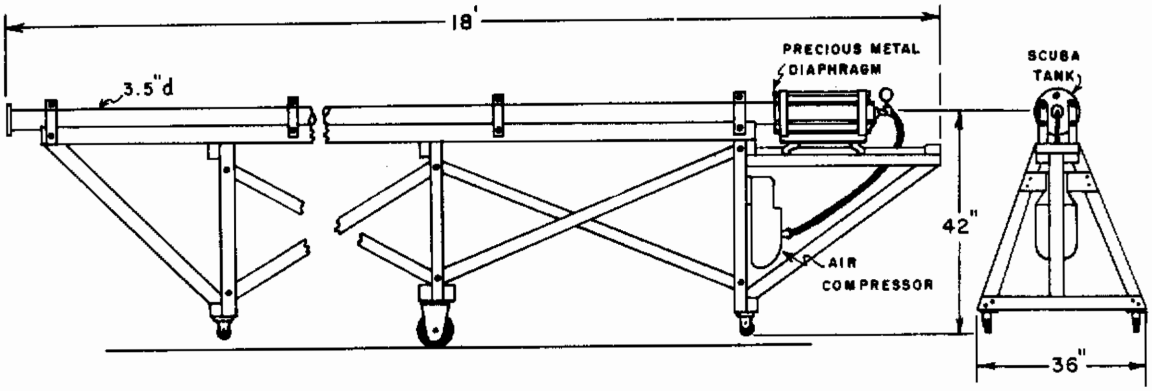

FIG. 5. Pneumatic shock-test machine.

It was assumed that the lightweight components of this transmitter plus their distribution inside the insulated foam would reduce the damage caused in any collision with an aircraft to an acceptable level. In April 1960, impact damage experiments were conducted on a scrapped RB-47E aircraft to determine how much damage a similar, insulated, lightweight package would cause in an aircraft collision. For this purpose, an air gun (Fig. 5) was designed to propel test plugs against the wing and windshield of the aircraft. The muzzle velocity of the air gun was tested with 250 lb/square-inch burst diaphragms and 5-oz plastic plugs. A spaced-wire timer indicated 470 mph was achieved. Because of an accident to the measuring equipment, the velocity achieved with 700 lb/square-inch burst diaphragms was not measured. Assuming all effects linear, extrapolation would indicate a velocity of 790 mph; the true figure is undoubtedly less, and is estimated as 600 mph.

The test plugs consisted of foamed plastic* (3.5 inches O. D. by 5 3/8 inches long) encapsulating a polystyrene foam cylinder (1 1/2 inches O. D. by 4 inches long by 1/4-inch wall) containing electronic components typical of this project. The package weights averaged around 5 oz, with the electronics accounting for about 1.9 oz, these weights being roughly the weights of the finished transmitter. Both the 250-lb and 700-lb burst diaphragms were used.

The first shot, 700 lb/square-inch bursting diaphragm, was directed against the windshield from a distance of 6 1/2 ft. The air gun was aligned parallel to the aircraft major axis and positioned for a square hit. The windshield is a laminated glass assembly consisting of two 1/8-inch, five 1/4-inch, and one 1/8-inch laminae as viewed from the outside. The laminae are plastic bonded in the manner of automobile safety glass. The buildup of 1 5/8 inches and its 45-degree fuselage inclination is intended to protect by allowing some object impact penetration. Thus the assembly protects against complete penetration, although the first few laminae can be shattered by moderate shock. The result of this test shot was to crack the first 1/8-inch glass lamina only.

Four subsequent shots were made against the leading edge of the right

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*B&B Chemical Company

wing of the B-47. The wing consists of three sections: leading edge, midsection, and trailing edge. The leading edge assembly consists of a formed hollow, soft aluminum sheet (1/16-inch thick) assembly with rib reinforcement every 5 1/4 inches, and reinforced on the leading edge with an additional 1/16-inch sheet to make a total thickness of 1/8-inch.

The first shot, a plug fired at 700 lbs/in^2 from a distance of 6 inches, penetrated to the first spar in the midsection. Similar results were obtained with a 250 lb/in^2 shot.

Two subsequent shots were made using completely homogeneous foam plastic plugs not containing any electronic components. Ejection pressures were 250 and 700 lbs/in^2, respectively. The leading edge areas chosen were reasonably similar to the previous one, with the object of having the results serve as an experimental control. Both dummy shots produced dimples about 2 inches deep in the skin. A slight skin cracking was observed at the base of each dimple. No penetration resulted however.

Collision damage to the leading edge of the wing and to the windshield indicates that three-dimensional, lightweight instrumentation, similar to that developed under the RCA contract, will cause damage, although not catastrophic, to the wing and windshield of an aircraft traveling close to 600 mph. Since shots of foamed cylinders containing no electronic components caused considerably less damage to the leading edge, it appears that it is the small dense electronic components that create most of the hazards to aircraft.

In this experiment, direct contact with the aircraft wing was made, which might not be the case in an actual flying situation for the layer of air built up in front of the moving aircraft would tend to cause more glancing contact.

Contacts with NASA installations at Langley, Ames and Lewis Research Centers and Boeing Aircraft Company, Seattle, Washington produced no quantitative data on minimum particle size, density, and state of motion for safe impact or ingestion into jet engines.

It can be assumed, since no reasonably quantitative or conclusive data exists on the subject, that damage to other areas of an aircraft by similar small electronic packages would produce comparable results.

This contract did not produce a minimum mass, distributed, instrument that could not possibly constitute a hazard to an aircraft. However the contract was highly successful in pinpointing the area to which all future efforts must be channeled, which is two-dimensional, distributed electronics. The RCA contract demonstrated that using standard components and advanced concepts, the weight of a normal transmitter could be reduced by a factor of 8 or more. If a reduction of this magnitude can be achieved in a minimum cost, 1-year study contract, it would seem reasonable that these same standard components could be further reduced and, through advanced technology, converted into two-dimensional and distributed circuitry. It is not the total mass of components that will cause damage to aircraft, but its form and distribution.

The technology for reducing electronic components to two-dimensional form is in existence today.[11] In the past few years several companies have sponsored extensive in-house studies on the techniques of reducing and depositing electronic components on thin plastic films, which indicate the feasibility of distributed two-dimensional electronics for balloon components. There are still formidable problems in thermal insulation of components and frangible power supplies. If the premise that daytime operation only of horizontal sounding balloons is acceptable to the meteorologist, and the balloons can remain silent at night, these problems of thermal insulation and power supplies would be minimized.

2.3 Balloon Positioning

The Federal Communications Commission was requested to draw on its experience to determine the HF-DF network that would be feasible for tracking weather balloons on a world-wide and large volume basis. This study was to cover a defined area, and include the number of balloons that could be kept under surveillance by the network on a continuous basis. As a basis for this study, these assumptions were made:

a. The area to be covered for tracking would lie between latitudes 10°N and 60°N, and between the coast of the North American continent on the East, and Guam, Japan, and the Asiatic mainland on the West.

b. Balloons would be released to float at 300-mile intervals throughout the area. A total of approximately 180 balloons would be required to cover the defined study area. For purposes of this study, these balloons could be considered as all floating at one altitude, or divided equally into two or more different altitudes.

c. Each balloon would be equipped with a 5-watt transmitter employing an optimum daytime frequency and an optimum nighttime frequency. A 1-minute transmission would be required for determination of the direction-finder bearing and the communication of the intelligence data.

d. A fix location for each individual balloon, accurate to within 60 nautical miles 75 percent of the time, would be provided.

e. A fix would be required for each balloon every two hours.

f. Only land locations which appear to provide suitable sites for long-range direction-finding equipment would be considered. The study would be limited to map reconnaissance and no consideration would be given to the economics of obtaining a suitable site.

g. Only operating and technical personnel requirements would be considered in the report.

The results of the FCC report indicate that it is feasible to use HF-DF equipment to track weather balloons, and that a minimum of 12 installations will be required in the North Pacific Test area to assure a fix location accurate to within 60 nautical miles 75 percent of the time.[12] The general area of these installations (within a radius of 100 miles) is indicated on Fig. 6.

The exact location selected in each of the 12 specific areas should meet the criteria for direction-finder test sites contained in the IRE Standards on Navigation Aids, Direction-Finder Measurements, 1951. These criteria in general require a site of relatively clear and level terrain having a radius of approximately 800 ft. The area should be devoid of trees, bodies of water, buildings, towers, antenna, or any other obstructions which might hinder direction-finder accuracy or operation.

A total of three constantly-manned direction-finder positions must be provided at each installation to handle 180 balloons floating within the test area. Therefore each station must be equipped with three active, plus one spare, direction-finding positions. Each position would be equipped with two receivers and a direction-finder control and indicator panel. Each direction-finder position will have equipment similar to that predominantly used by the FCC, that is, Adcock direction-finders with goniometric bearing display and bearing integrators. These direction-finders would have a resolution of 1° or better and an equipment error of 1° or less on signals with a minimum field strength of 4 microvolts per meter. Figure 7 illustrates a typical balloon fix of the required accuracy before application of any statistical smoothing as discussed in Section 2.4.

Based upon their own experience with DF operator fatigue and the similar fatique problem of FAA operators who are constantly observing radar oscilloscopes showing aircraft movements, the FCC recommends that each of the three direction-finder positions be staffed by two men at all times on each of three 8-hour shifts, so that the men may work short periods with frequent breaks. It is further assumed that a total of 10 DF operators will be required for each active position to cover vacant watches while personnel are ill, on annual leave, and on normal days off.

Summarizing, it appears feasible to track horizontal sounding balloons on a world-wide and large volume basis using high-frequency direction-finder equipment. A network of 12 sites in the North Pacific Test Area will be required to assure a fix accuracy to within 60 nautical miles 75 percent of the time.

The accuracy of these balloon fixes can be improved by increasing the number of HF-DF stations within the net, by using new and more accurate equipment than that in general use by the FCC, or by statistical smoothing methods as explained in the meteorological portion of this report, Section 2.4.

High frequency, phased, direction-finder equipment is presently available that couples a wide-aperture antenna system with Doppler-type instrumentation, and appears to have several advantages over Adcock HF-DF equipment for eventual use in horizontal sounding:

a. The length of time required to obtain an accurate and reliable estimate of the bearing is reduced. This would appreciably decrease the balloon-borne power requirements.

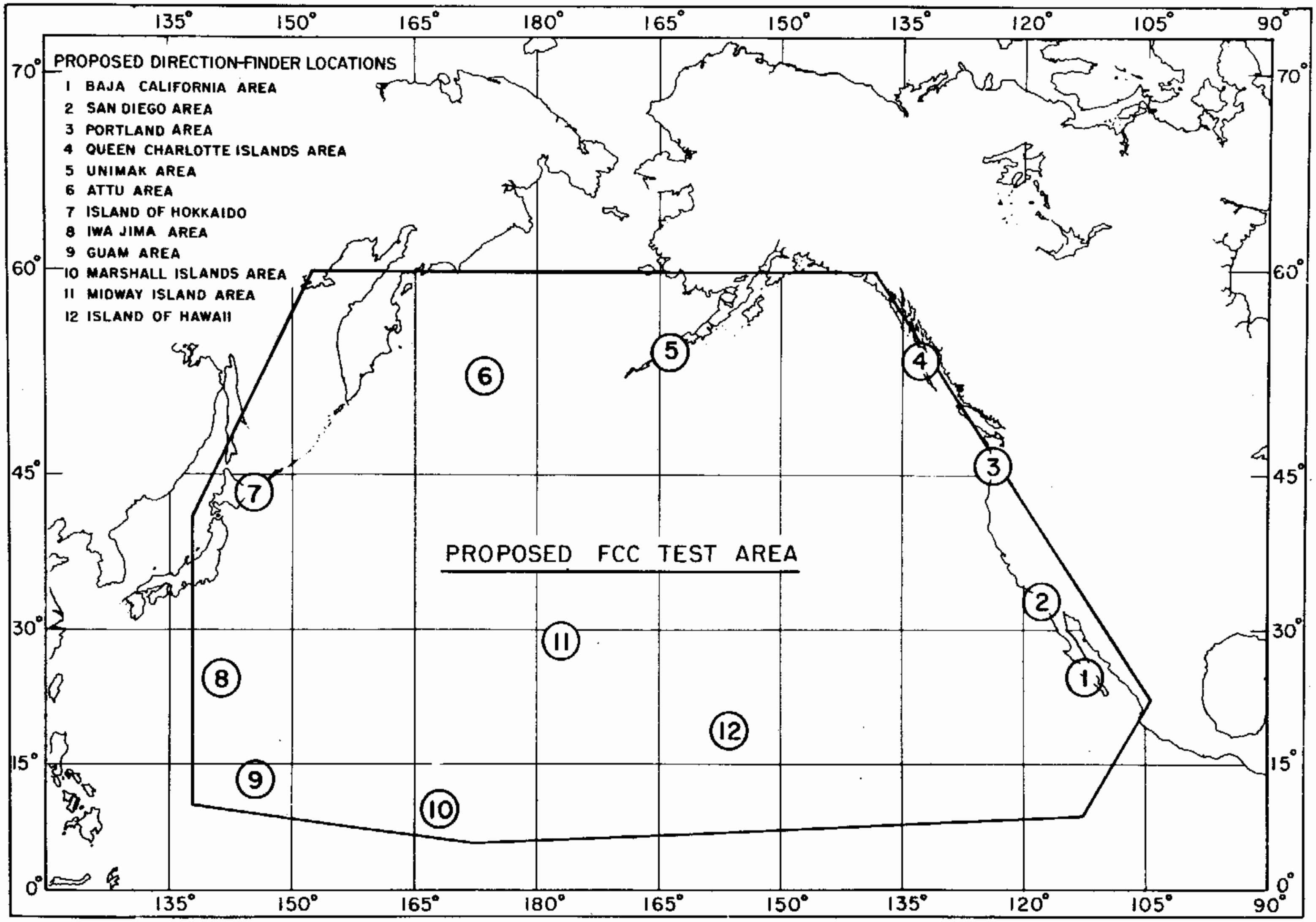
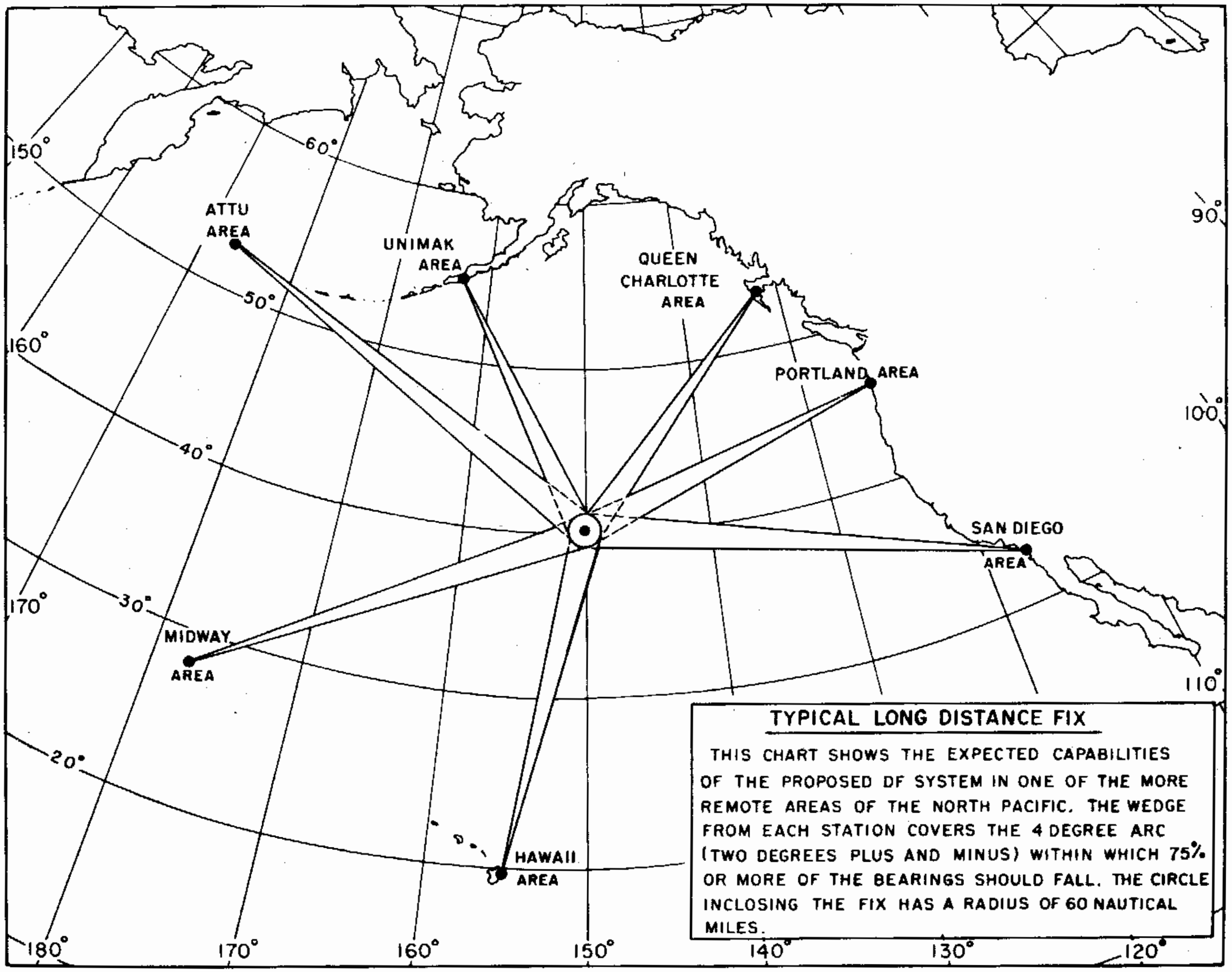


FIG. 6. Proposed FCC test area.



TYPICAL LONG DISTANCE FIX

THIS CHART SHOWS THE EXPECTED CAPABILITIES OF THE PROPOSED DF SYSTEM IN ONE OF THE MORE REMOTE AREAS OF THE NORTH PACIFIC. THE WEDGE FROM EACH STATION COVERS THE 4 DEGREE ARC (TWO DEGREES PLUS AND MINUS) WITHIN WHICH 75% OR MORE OF THE BEARINGS SHOULD FALL. THE CIRCLE INCLOSING THE FIX HAS A RADIUS OF 60 NAUTICAL MILES.

FIG. 7. Typical FCC HF-DF fix.

b. Capability of semiautomatic and automatic readout of balloon bearings. This capability eliminates operator bias and fatique, and would considerably reduce the operator-staffing problem and personnel costs of a direction-finder network for balloons.

c. Similar balloon-positioning accuracy to an Adcock HF-DF network can be obtained with fewer HF-DF stations.

Another method for tracking and positioning balloons has been proposed by Vincent E. Lally in his conjecture on future atmosphere-sounding systems, "Satellite Satellites."[13] Under this concept a polar-orbiting weather satellite with a communication link picks up the position and other meteorological measurements from each horizontal sounding balloon as the balloon passes under the electronic shadow of the weather satellite. The satellite then transmits this information to polar receivers, providing complete data, on a global basis, on the dynamics of the atmosphere. Since it was not possible to investigate any technical area of concept, no conclusions can be advanced at the present time as to its feasibility.

2.4 Meteorological Aspects of Horizontal Sounding Techniques

As mentioned in the introduction, a horizontal sounding array of 2000 balloons floating at designated altitudes will provide adequate observational coverage for the middle latitudes of the northern hemisphere, considering four levels, each containing 500 balloons and covering the area enclosed by the 30-degree and 60-degree parallels of latitude. The coverage obtained would be analogous to the density of rawinsonde stations in the United States.

Atmospheric parameters measured by this technique would be pressure, temperature, and wind. A high degree of accuracy is essential in fixing the position of the balloon, as the wind is determined from the difference of at least two position reports. Position data are not critical for the other parameters since these are measured directly. Horizontal sounding winds are computed from positions which are determined in space by radio-fixing devices. Of the atmospheric parameters mentioned, the most important is the wind. Representative data of the atmospheric wind structure is basic to analysis of the circulation patterns. These patterns delineate the centers of action which determine the weather. Therefore, in order to determine the feasibility of horizontal sounding balloons as a source of meteorological data, the accuracy of positioning must be determined.

The method of measuring wind by tracking of free balloons involves the ratio between the displacement in position, ΔS, at two successive time periods and the time interval, Δt. Assuming that two successive position errors are uncorrelated, the error in ΔS is larger than a single position error by a factor of the square root of two. On the other hand, the wind error is inversely proportional to Δt, the time interval over which the wind is averaged. Theoretically, at least, we could increase the accuracy of the wind at will by increasing Δt to any desired value. However the usefulness of such an increase in accuracy is severely limited by the uncertainty of the point in space and time at which the velocity applies. Thus the price paid for greater velocity resolution is a reduced time and space resolution, and vice versa. It has been determined that a practical limit for Δt is 6 hours.

As can be inferred from the foregoing discussion, the first step in an analysis of the problem is to evaluate the position error obtained from HF-DF tracking. Since there was a paucity of adequate data available, an experiment was set up to furnish a sufficiently large sample. In this experiment an airplane following a random flight path would circle over a known geographical point while broadcasting a simulated balloon transmission for a short period of time. FCC personnel were required to compute radio fixes from a number of bearings furnished by their network of tracking stations. To minimize personal bias, the FCC operating personnel were kept uninformed as to the true nature of the experiment. Since the FCC follows the practice of classifying fixes into three classes according to their quality, the experiment was designated to obtain approximately an equal number of A, B, and C class fixes. Altogether, a very excellent sample was derived from this unique experiment.

Figure 8 shows the distribution functions derived from this experiment. One important conclusion which may be drawn is that the three curves differ significantly in a statistical sense, and that therefore the FCC classification system is real and valid. It may be noted that the probable errors for A, B, and C class fixes are 19, 21, and 27 miles respectively, which yield standard vector errors in 6-hour wind speeds of 5, 6, and 8 knots respectively.

On account of the very great distance between tracking stations and target balloons, we must expect a certain amount of deterioration in results. For this reason we have decided to accept the C class fix as the standard which may be practically attainable, although past experience indicates that even over the ocean areas A and B fixes are frequently obtained.

With the aid of standard statistical techniques it is possible to compute, from the probability distribution function of curve C in Fig. 8, a wind error distribution function. This wind-speed error distribution function is presented in Fig. 9. The error in wind direction depends on the true wind speed. The probable wind direction error for various wind speeds is shown in Fig. 10. Both of these curves are computed for a time interval, Δt, of 6 hours.

It will be noted that wind-speed error is completely independent of the wind speed, depending solely on two successive position errors. Thus the percentage wind-speed error is inversely proportional to the true wind speed.

The errors described above may be thought of as raw or unsmoothed. Given a collection of observed values of a dependent variable, each of which contains a random error, it is theoretically possible to reduce the errors to a minimum by statistical smoothing. With the advent of electronic computers, powerful techniques have been developed in recent years which enable us to achieve excellent results. The amount of error reduction which can be obtained with these methods is limited solely by the size of the sample.

A simple synthetic statistical experiment was performed to illustrate the potential error reduction capacity of orthogonal least-square solutions. The steps in this experiment are as listed on page 19.

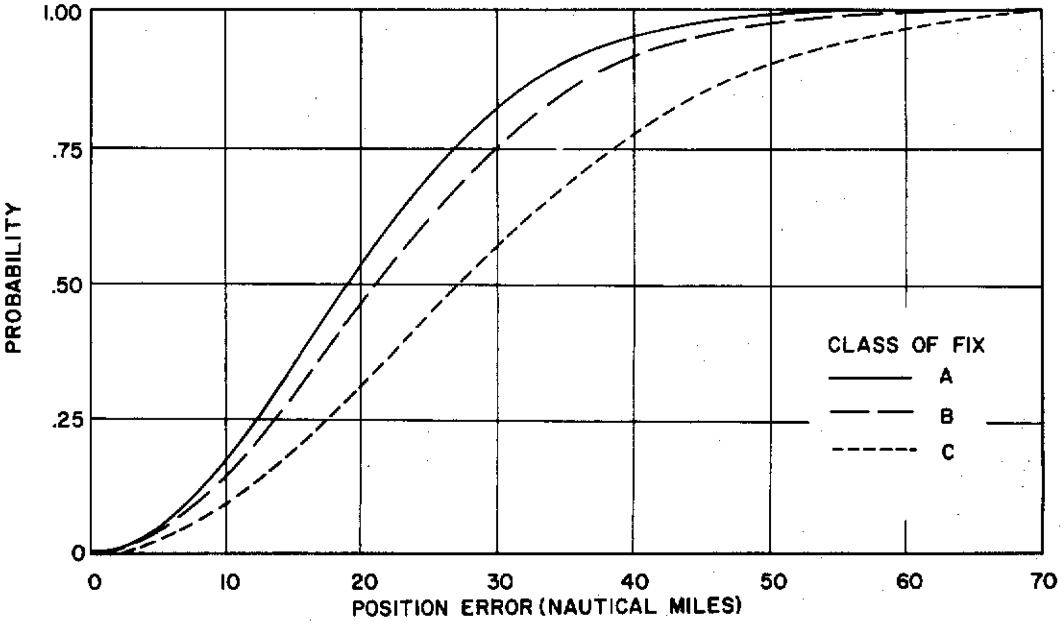


FIG. 8. Distribution of position errors by FCC tracking.

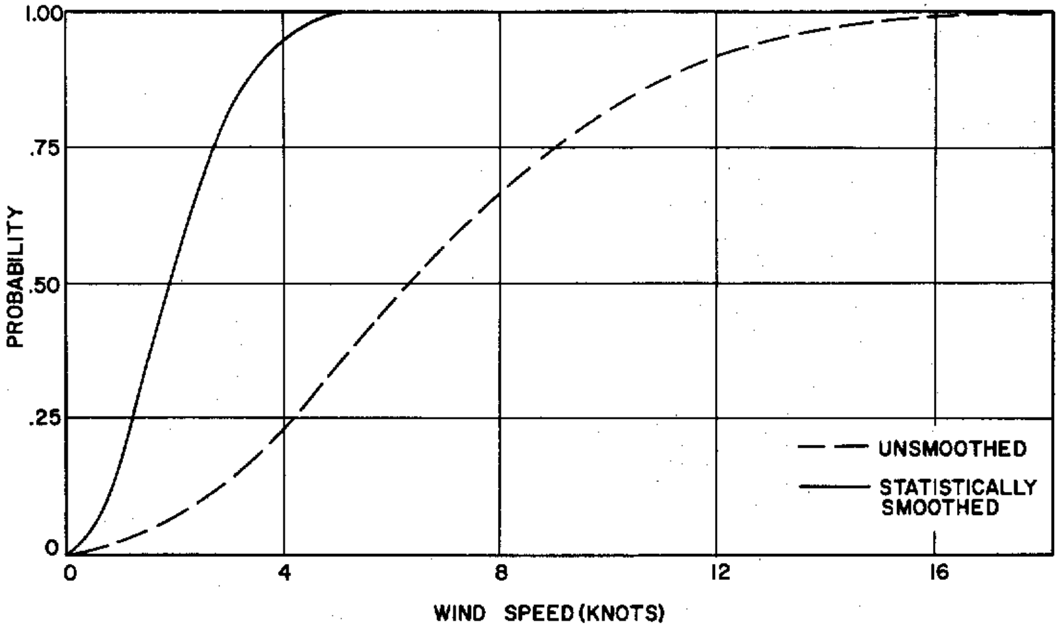


FIG. 9. Distribution of wind-speed errors for 6-hour time interval.

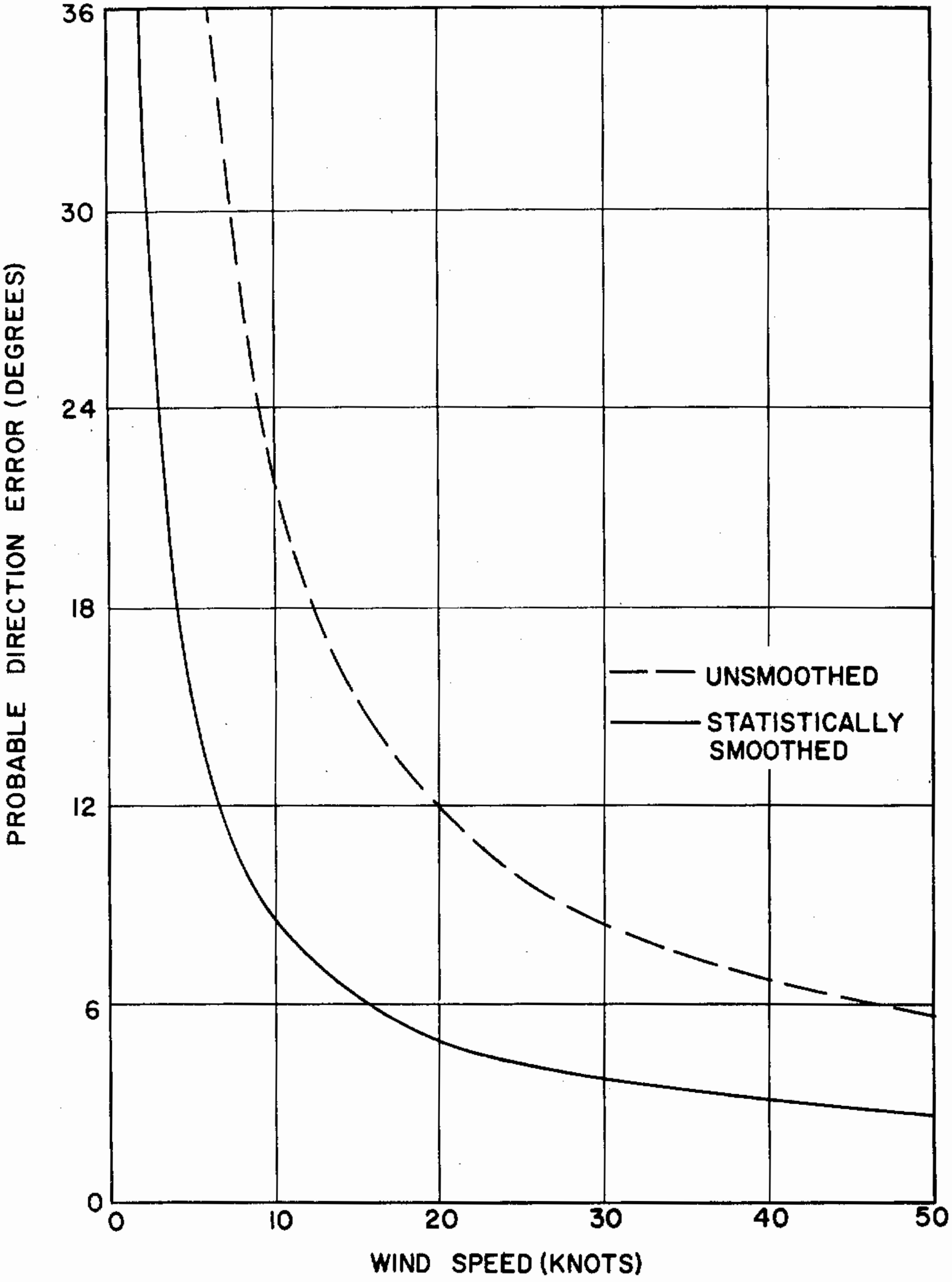


FIG. 10. Probable wind direction errors as a function of wind speed.

1. Assume that the field of atmospheric motion is exactly specified by an analytic function.

2. Inject into this atmosphere a network of balloons.

3. Compute the motion of each balloon over a specific time interval, Δt.

4. Add a random error to the initial and final positions of each balloon. The magnitude of the random errors are specified by the distribution function in Fig. 8 (curve C).

5. Compute the observed velocity of each balloon and the standard velocity error.

6. Smooth out the observed velocity data by least squares.

7. Compare the smoothed velocities with the true velocities and compute the new standard error.

8. Compare the new error obtained from the smoothed data with the original error.

In setting up the specifications for this experiment, we have endeavored to combine realism with simplicity and ease of computation. In doing so we have admittedly oversimplified the structure of the atmosphere. Nevertheless, regardless of the degree of complexity, the principle illustrated here remains the same, and similar results would be achieved with an atmosphere of greater complexity by more elaborate and refined computation techniques, provided the number of observations is increased proportionately.

Specifications

1. Assume a steady state

$$\frac{\partial u}{\partial t} = \frac{\partial v}{\partial t} = 0$$

2. The equation for a trajectory (or a streamline):

$$y = A \cos \frac{2\pi}{L} x$$

A = 450 nautical miles
L = 3600 nautical miles

3. $V = (u^2 + v^2)^{1/2} = 40$ knots (scalar wind speed)

4. The time interval, Δt, between initial and final position observations, is 6 hours.

5. Assume that 18 balloons are on a single streamline and initially located at x = 0,200,400, ...3400.

6. From the data in Fig. 8, curve C, compute 18 equally probable component errors (nine positive and nine negative) having a standard deviation of 23 nautical miles (± 2, 5, 8, 12, 16, 20, 24, 33, 46).

The complete experiment is presented in Tables 1A and 1B and the results shown in Fig. 11. For this particular case the data were smoothed by harmonic analysis, although any other least-squares technique would have been equally effective. It will be noted that one simple smoothing has produced a 70 percent reduction in error. By using this value as a basis of comparison we may now evaluate wind errors to be expected from an HF-DF sounding system, in which the raw data have been statistically smoothed. These are shown in Figs. 9 and 10.

The smoothing methods discussed above, although effective, are quite elementary. With the use of electronic computers it is possible to develop sophisticated and powerful techniques of error reduction. One such method which suggests itself and should be thoroughly investigated is based on the trigonometry of radio direction finding. The change in bearing from any station depends on the motion of the balloon, which in turn depends on the wind velocity. By a series of successive approximations we may adjust the bearings to fit the estimated winds, and then readjust the winds to fit the adjusted bearing, etc. This process is continued until the successive values converge.

The following nonstatistical methods could be used to reduce position errors:

1. Experience has shown that balloons launched simultaneously tend to remain near each other throughout long portions of their trajectories, providing they maintain the same altitude. If there are variations in altitude you can expect variations in wind velocity due to vertical shear. Since superpressure balloons float on a constant density surface, vertical shear is absent and little dispersion can be expected. If we may assume that the greatest part of the position error is random in nature, then position reports received at short intervals of time from each member of the multiple balloon system will have no correlation. Thus the error in the mean position will be smaller than the error in position of any one balloon by the factor $\frac{1}{\sqrt{n}}$, where n is the number of balloons. If we use this system the price we have to pay is a smaller number of observations.

2. Part of the position error which is due to propagation and reflection may be reduced by using different frequencies.

3. If the balloons were equipped with radio altimeters, geostrophic winds could be computed. Since the balloons float on a constant density surface, the wind is proportional to changes of height of the surface. Using this method, errors in position are not critical.

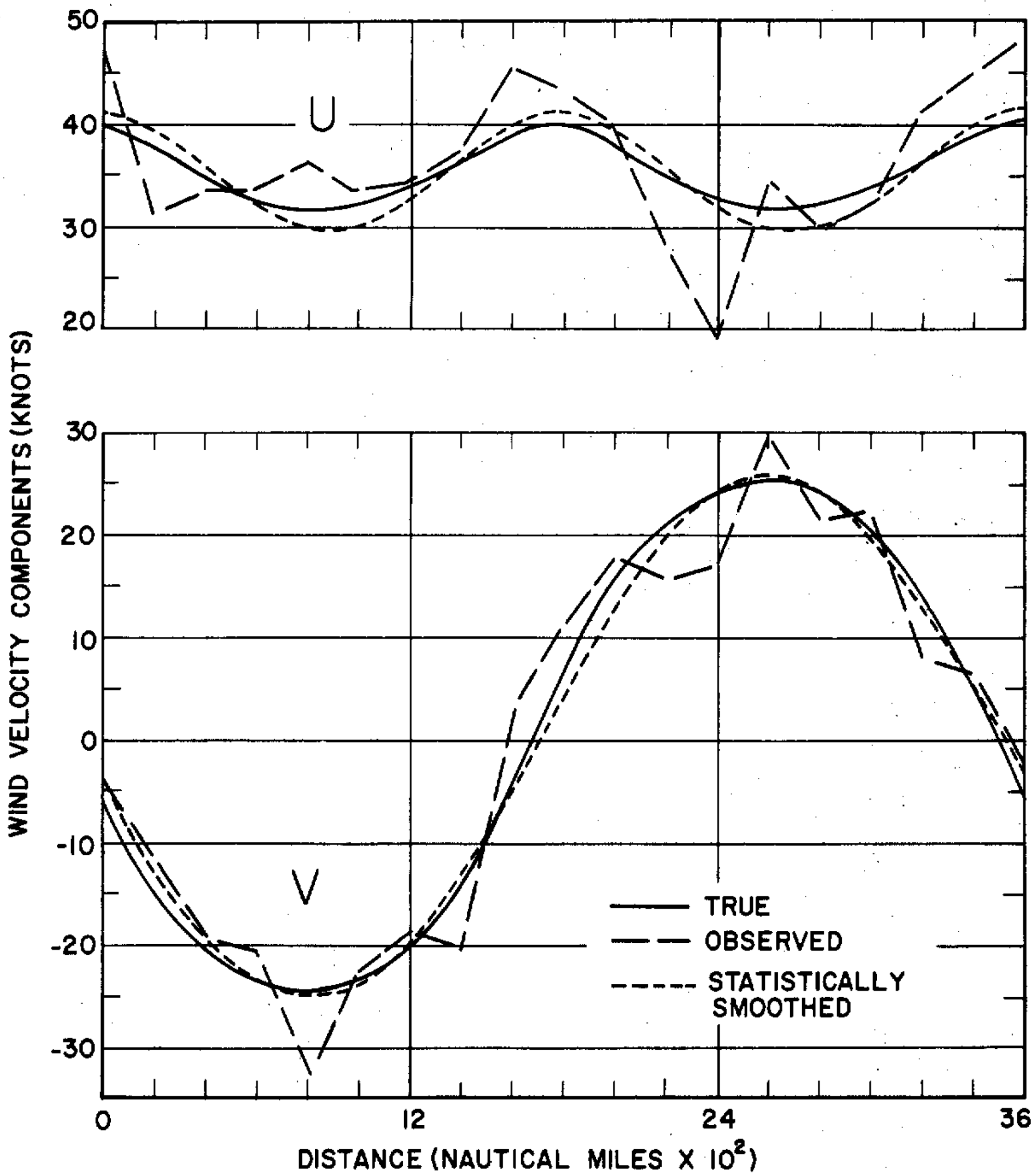


FIG. 11. Statistical experiment results.

TABLE 1A. Position data used in statistical experiment.

INITIAL POSITION (Nautical Miles)						FINAL POSITION (Nautical Miles)					
TRUE		OBSERVED		POSITION ERROR		TRUE		OBSERVED		POSITION ERROR	
X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
0	450	-25	462	-25	12	238	412	263	437	25	25
200	423	192	411	-8	-12	424	332	378	340	-46	8
400	345	416	312	16	-33	607	220	615	195	8	-25
600	225	588	200	-12	-25	794	83	789	78	-5	-5
800	78	798	80	-2	2	989	-70	1014	-116	25	-46
1000	-78	1025	-53	25	25	1191	-219	1224	-186	33	33
1200	-225	1208	-217	8	8	1400	-345	1412	-329	12	16
1400	-345	1395	-299	-5	46	1615	-427	1617	-422	2	5
1600	-423	1605	-418	5	5	1831	-450	1877	-404	46	46
1800	-450	1754	-455	-46	-5	2038	-412	2013	-387	-25	25
2000	-423	2002	-469	2	-46	2224	-332	2240	-365	16	-33
2200	-345	2233	-320	33	25	2407	-220	2399	-228	-8	-8
2400	-225	2446	-209	46	16	2594	-83	2561	-108	-33	-25
2600	-78	2567	-94	-33	-16	2789	70	2773	82	-16	12
2800	78	2812	76	12	-2	2991	219	2989	203	-2	-16
3000	225	2984	200	-16	-25	3200	345	3175	333	-25	-12
3200	345	3175	378	-25	33	3415	427	3420	425	5	-2
3400	423	3425	415	25	-8	3631	450	3619	452	-12	2
		STANDARD ERROR		23	23			STANDARD ERROR		23	23

TABLE 1B. Six-hour wind data (knots).

TRUE		OBSERVED		SMOOTHED	
U	V	U	V	U	V
39.7	-6.3	48.1	-4.1	41.0	-4.2
37.4	-15.2	31.1	-11.9	39.6	-12.5
34.6	-20.9	33.3	-19.6	36.0	-19.4
32.4	-23.7	33.6	-20.4	32.0	-23.9
31.6	-24.7	36.1	-32.7	29.4	-25.5
31.9	-23.5	33.2	-22.2	29.4	-24.1
33.4	-20.0	34.1	-18.7	32.0	-19.7
35.9	-13.7	37.1	-20.5	36.0	-13.0
38.6	-4.5	45.4	2.3	39.6	-4.7
39.7	6.3	43.2	11.3	41.0	4.2
37.4	15.2	39.7	17.4	39.6	12.5
34.6	20.9	27.8	15.4	36.0	19.4
32.4	23.7	19.2	16.9	32.0	23.9
31.6	24.7	34.4	29.4	29.4	25.5
31.9	23.5	29.6	21.2	29.4	24.1
33.4	20.0	31.9	22.2	32.0	19.7
35.9	13.7	40.9	7.9	36.0	13.0
38.6	4.5	44.8	6.2	39.6	4.7
STANDARD ERROR		5.3	4.5	1.5	1.3

The above discussion has dealt with the operational use of data derived from horizontal sounding balloon techniques. Let us now consider the value of this system as it applies to research into the many unsolved problems of the atmosphere. By its very nature, the atmosphere does not readily lend itself to scientific scrutiny and study. The essential problem in meteorology is to measure the forces and accelerations which each particle in the atmosphere undergoes. All weather phenomenon are produced by forces which operate on the individual air particles and cause both horizontal and vertical motions. Any system such as the rawinsonde which measures motion at fixed points requires that the equations of motion be expressed in complicated Eulerian form. In these equations of motion the forces and accelerations are small differences between large quantities. Therefore the solutions are hidden in the "noise level" of the equational components and unrealistic assumptions are necessary to arrive at any solution. The horizontal sounding system is the only method available which measures these accelerations directly. However, these measurements are not instantaneous values but averaged over an appreciable time interval. Thus we have a means of directly measuring the elements of motion such as translation, vorticity, deformation, and divergence. The foregoing discussion presupposes an extremely accurate method of determining position; otherwise the "noise level" produced by these errors will completely invalidate this proposition. Thus it may be stated that the horizontal sounding observational technique is potentially of the utmost value to meteorology, provided that sufficient accuracy can be developed.

3. CONCLUSIONS

a. It has been established that the use of the horizontal sounding balloon technique for the determination of atmospheric circulation is feasible.

b. Its effectiveness depends upon the balloon density, the number of DF stations, the accuracy to which the DF network can position an individual balloon, and the statistical use of the balloon position data in the determination of average winds over a period of time.

c. HF-DF tracking is satisfactory for tracking balloons on a large volume and global basis.

d. FCC HF-DF tracking will yield winds of marginal accuracy. These data can be considerably improved by statistical smoothing and/or the use of more advanced equipment.

e. The superpressure balloon has a demonstrated capability of constant density level flight without the use of ballast. Further development work is needed to increase reliability and to extend the flight durations to 20 or more days.

f. Aircraft collision-damage experiments using the equivalent of a 1.9-oz balloon transmitter indicate that the key to miniaturization is the development of two-dimensional, distributed, balloon-borne electronic instruments. The technology for reducing electronic instrumentation to two-dimensional form is in existence today, but actual development of compatible balloon-borne equipment will require an extensive research and development program.

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REFERENCES

1. Haig, T. O., Major USAF and Lally, V. E., "Meteorological Sounding Systems," Bulletin of the American Meteorological Society, (August 1958, Page 406-409).

2. Schjeldahl, G. T. Co., "Super Pressure Mylar Polyester Balloons," by R. J. Slater. Final Technical Summary, Contract AF19(604)-2286, (May 1, 1957 - March 1, 1958), AFCRC-TR-58-265, Confidential.

3. General Mills, Inc., Mechanical Division, "Balloon Barrier Materials," by A. A. Anderson and G. L. Marfitt. Final Report Contract AF19(604)-3876, (November 1959) AFCRC-TR-60-204.

4. General Mills, Inc., Mechanical Division, "Mylar Balloon Fabrication Study," by L. A. Bushay and L. R. Flink, Final Report Contract AF19(604)-5210, (November 30, 1959).

5. General Mills, Inc., Mechanical Division, "Super Pressure Balloon Study," by L. R. Flink. Final Report Contract AF19(604)-4985, (May 4, 1960) AFCRC-TR-60-273.

6. Andonian Associates, Inc., "Pressure Relief Valves for Super Pressure Balloons." Final Report Contract AF19(604)-5973, (May 31, 1960) GRD-TR-60-284.

7. Schjeldahl, G. T. Co., "Super Pressure Balloon Development and Fabrication," by S. J. Stenlund, Letter Report Contract AF19(604)-6190, (December 17, 1960).

8. Schjeldahl, G. T. Co., "Mylar Balloon Fabrication Study," Final Report Contract AF19(604)-7254, (February 28, 1961).

9. Tilton, Charles S., "Plastic Balloon Components and Techniques," ARDC Management Report, (December 20, 1960).

10. Radio Corporation of America, Missile Electronics and Controls Division, "Minimal Mass Communications Equipment Study." Final Report Contract AF19(604)-5999, (July 1, 1960) CR-59-588-27.

11. Bierman, H. and Haavind, R., "Guidelines to Microminiature Designs, "Electronics Design, (November 9, 1960).

12. Federal Communication Commission, Field Engineering and Monitoring Bureau, "World Wide Balloon Tracking Feasibility Study," Final Report CSO and A 59-537, (January 1960).

13. Lally, V. E., "Satellite Satellites-A Conjecture on Future Atmospheric Sounding Systems," Bulletin of the American Meteorological Society, (August 1960).