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STUDY OF HIGH RESOLUTION WIND MEASURING SYSTEMS -- PHASE I SURVEY

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FOREWORD

This document reports on Phase I of a three-phase study of high resolution wind measuring systems. The study was conducted by the Lockheed-California Company of Burbank, California, under contract NAS 8-11286 for the Aero-Astrophysics Office, Aero-Astrodynamics Laboratory, National Aeronautics and Space Administration, George C. Marshall Space Flight Center of Huntsville, Alabama. The contract monitor was James R. Scoggins and the principal investigator was Fox Conner. The Phase I study covered the period of July, August and September of 1964.

The design of large space vehicles is being pushed to a higher and higher degree of sophistication. This study fulfills a need for gathering together, under one cover, the manifold approaches to the problem of measuring the winds aloft to a higher degree of resolution. The Phase I study reported herein is a survey of all systems conceivable, proposed or in operation. Phase II and Phase III will analyze and exploit potential systems with special reference to their inherent engineering and scientific limitations.

ABSTRACT

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Reported herein is Phase I of a three-phase study of high resolution wind measuring systems. The primary area of interest is the collection of detailed design data for winds at altitudes up to 20 km. The various measuring systems and schemes are described and their errors discussed. The concepts worthy of serious consideration appear to employ either a probe, a tracer or sound. In addition to the system survey, the effect of wind variability on the representativeness of meteorological observations is explored.

author

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SECTION A: SURVEY OF SYSTEMS

INTRODUCTION

The design of large space vehicles is being pushed to a greater and greater degree of sophistication. An increasing need has arisen in recent years for defining the wind environment in greater detail than is possible by the tracking of the standard weather balloon. In answer to this need, the spherical balloon and FPS-16 radar system, the smoke trail and aerial camera system, and the ring wing shearsonde are being developed for the measurement of winds below 20 km. Data are also obtained from angle-of-attack instrumentation on some large rockets. Systems employing chaff clouds, falling balloons, sodium trails, etc. are being actively developed for extremely high altitudes. Many other schemes exist which have not passed the proposal or the study phase. The opportunity exists, therefore, for a study which will review and analyze the various possible schemes and which will recommend areas for future development. Other studies such as Fetter et al. (1962) which investigated indirect probing techniques, and Robinson (1962) which investigated new meteorological sensors have only touched portions of the field of interest.

Phase I of a three-phase study is reported herein. The systems tested to date and the schemes conceivable within the present state of knowledge are reviewed, categorized and their inherent errors discussed. It is believed the study is inclusive. In a separate section of this report, the space and time variations in the winds are examined for their effect on the representativeness of meteorological observations.

1.0 DESCRIPTION OF SYSTEMS

1.1 Systems Employing a Probe or a Tracer

1.11 Probes

All probes such as balloons, dropsondes, airplanes and rockets may be characterized by a response function which determines the motions of a probe in response to variations in the winds. For extremely slow variations, any probe will act as a perfect tracer while for extremely rapid variations, there will be no response. A wide range of response functions are possible depending on such variables as the configuration variables, the non-dimensional probe mass, the Mach number and the Reynolds number. It is evident that slow variations must be determined from trajectory data. Velocities can be measured directly by Doppler techniques or they can be derived by integrating accelerometer data or differentiating range instrumentation data. Only airborne instrumentation such as flow vanes will do for measuring the rapid variations.

For intermediate variations, the winds derived from trajectory data must be added to the winds measured with on board instrumentation. Figure 1 illustrates the basic measuring philosophy for a completely instrumented aircraft.

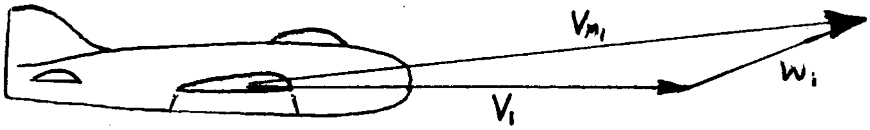
The concepts shown in Figure 1 concern direct measurements; "indirect" measurements of the winds are possible by employing the equations of motion. Measurements are made of convenient parameters like accelerations. A response function is derived from the equations of motion which relates the winds to the measured quantities. Reservations must be made for this concept, especially at high frequencies where the dynamic characteristics are difficult to determine or erratic motions may exist. The concept is basically valid, though, and leads to "desmoothing techniques" in data processing.

Examples of the above measuring concepts are given below:

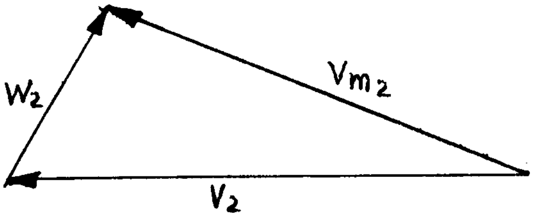
1. Range instrumentation only.
   - Weather balloons (Dvoskin and Sissenwine, 1958)
   - Spherical balloon (Engler and Wright, 1962a; Leviton, 1962; Scoggins, 1963a)

AIRCRAFT PROBE

Aircraft Motions
Relative to the Earth



Atmospheric Winds and
Turbulence Relative
to the Aircraft



$\vec{W}_1$ Aircraft motions due to the winds (disappears at high frequencies)

$\vec{W}_2$ Wind velocities measured by the aircraft (disappears at low frequencies)

$\vec{V}_1 = -\vec{V}_2$ Aircraft velocity in calm air

$\vec{V}_2 \cong \vec{V}_{m_2}$ if the higher frequencies are filtered out of V_{m_2}. (Airspeed is defined as the magnitude of the vector).

$\vec{V}_{m_1}$ Aircraft velocity from trajectory data.

$\vec{V}_{m_2}$ Atmospheric velocity measured by airborne velocity sensors.

$\vec{W}_1 + \vec{W}_2 = \vec{V}_{m_1} + \vec{V}_{m_2} = (\vec{V}_{m_1} - \vec{V}_1) + (\vec{V}_{m_2} - \vec{V}_2)$ Wind velocity relative to the earth.

Figure 1

- Parachute (Jenkins, 1959)

2. Probe with accelerometers
   - Ring wing shearsonde (Lees, 1958a; Hillman and Cheng, 1963)
3. Probe with velocity sensors
   - Rocket with flow vanes (Reisig, 1956; Hagood, 1962)
   - Rocket with pressure sensors (Ainsworth and La Gow, 1961)
4. Indirect measurements
   - Sphere with inertial platform and accelerometers (Otterman, et al, 1961)

Combinations of the above concepts are employed of course; for example, the ring wing shearsonde uses range instrumentation for determining altitudes.

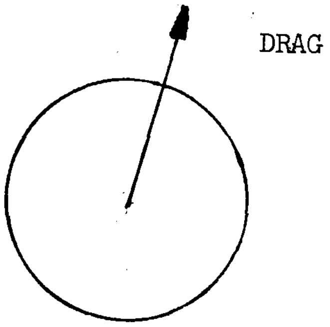
Possible probe shapes are now reviewed and their response to wind input discussed:

1. Spheres: Spherical balloons, one or two meters in diameter, figure in similar systems being developed at the NASA Marshall Space Flight Center (The Jimsphere balloon) and at the Air Force Cambridge Research Laboratory (The ROSE balloon). The balloons, fabricated of Mylar, are tracked by FPS-16 radar and represent an order of magnitude improvement over their predecessor, the weather balloon. Reed (1963) and others have thoroughly explored the equations of motion for a sphere and their use in "desmoothing" data. Lately, the importance of erratic sphere motions has been underscored by Murrow and Henry (1964), MacCready and Jex (1964) and others. The most important irregularities appeared to be related to an erratic line of flow separation. Not to be neglected is the side lift produced by balloon rotation and other possible effects. The erratic motions can be reduced by attaching a number of projections to the sphere (Scoggins, 1964) or by reducing the size of the sphere (Reid, 1964). The first technique is thought to stabilize the separation line by "insuring" the development of a turbulent boundary layer, while the second technique reduces the Reynolds number to sub-critical values over most of the altitudes of interest and thereby "insures" that laminar separation of the boundary layer occurs.

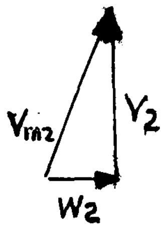
2. Parachutes: Jenkins (1959) describes a system for measuring winds at extreme altitudes using a parachute deployed from a rocket. A parachute has an advantage at extreme altitudes because of its very low weight-to-drag ratio. At lower altitudes, they suffer in comparison to other wind sensors due to swing motions and a tendency to glide sideways.

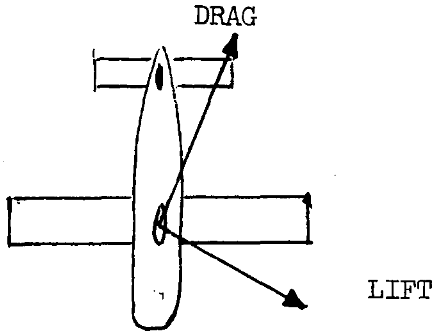
Advanced concepts, possible inverted cones, might prove more interesting if the practical aspects of deployment are solvable.

3. Winged Probes: Wings cause a probe to become more responsive to winds perpendicular to the flight path. In the diagram below a configuration with negligible lift is compared to a lifting type:



FALLING
BALLOON





CRUCIFORM
DROPSONDE

It may be seen that the drag only works through the sine of the angle to produce horizontal motions in response to wind variations. Since lift can be larger than drag and since it acts through the cosine of the angle, it is apparent a winged probe can respond more rapidly to horizontal winds; weight, vertical velocity, etc. being the same.

An example of a winged probe is the ring wing shearsonde being developed by the Army Signal Research and Development Laboratory. The primary purpose is to measure wind shears directly as shown by the equation,

$$\frac{dV}{dH} = \frac{dV/dt}{dH/dt} = \frac{\text{Acceleration data}}{\text{Airspeed data}}$$

The data are measured with on board instrumentation. The probe is "aerodynamically tuned" with the center of pressure close to the center of mass. This results in the probe maintaining a near vertical attitude as it descends through varying winds.

Private communications with Robert F. Stengel, now a graduate student at Princeton University, indicates he has conducted tests on small, uninstrumented probes with wings at NASA Wallops Station, Wallops Island, Va. Theory and test results are expected to be published shortly.

Airplanes instrumented with flow vanes are commonly employed for turbulence investigations. The long term variations can also be measured if accelerometers are installed or if range instrumentation is utilized.

4. Rockets: A rocket would be expected to respond very little to winds because of its large mass, high speeds and a low side lift to angle-of-attack variation. Whether the rocket response to winds could be ignored altogether would require careful consideration.

1.12 Tracers

Only passive tracers appear to merit serious attention. Typically these are smoke for optical wavelengths and chaff for radar. One interesting possibility is the use of tiny reflecting objects like glass beads in conjunction with an active optical device. Active tracers which rely on heat or a chemical reaction, say incandescent carbon particles, would rapidly lose their identity. Radioactive tracers present a severe fallout problem.

Smoke trails and chaff columns are capable of generating a much greater amount of data than a probe since a line in space can be tracked rather than a point. Data can be generated along a variety of space time tracks instead of just along the one trajectory that a probe happens to traverse.

Henry, et al (1961) describes a method using a smoke trail from which detailed measurements of the wind can be obtained. The trail is produced when a solution of sulfur trioxide in chlorosulfonic acid is expelled from an ascending rocket. Two fixed field, USAF type A-11 precision aerial mapping cameras take photographs every few seconds. The present system cannot detect vertical air motion but could, if the complexity of some sort of trail coding device could be tolerated.

Many rockets, particularly solid propellent types, leave a visible trail. Henry, et al (1961) comments that the specially produced condensation trail was considerably smaller in diameter and more regular in outline than that due to the rocket products of combustion. In addition, an "artificial" trail is necessary at altitudes above the thrusting portions of the trajectory.

Juisto (1962) describes a system proposed by the Cornell Aeronautical

Laboratory which measures the motions of a column of chaff with two large Doppler radars. The technique appears satisfactory and a few tests have been conducted to date. The chaff column has a number of advantages over the smoke trail. Wind measurements in clouds are possible and there is no need for modification for nighttime operation. The measurement of vertical wind velocity is readily accomplished by the addition of a third Doppler radar. Another advantage is that chaff is detectable for a longer period than smoke. Involved here is the fact that a rapidly rising rocket will disturb its environment. The wake will contain relatively small vortices which are of little importance. Of more importance, the wake may have a motion of its own which might take time to dissipate. Henry, et al (1961) observes, however, that the "initial momentum" of the smoke trail was lost in a few seconds. The subject bears further investigation.

1.13 Instrumentation

Instrumentation for motion measurements is readily classified according to the type of motion variable sensed and the reference axis as the following table summarizes. Angular rates and accelerations are of secondary importance and are not reviewed.

TYPE OF MEASUREMENT	AXIS SYSTEM		
	EARTH	PROBE	INERTIAL SPACE
Position	Radars Passive Optical Devices Lasers		
Velocity	Doppler radars Doppler lasers	Flow vanes Pressure sensors	
Acceleration			Accelerometers
Attitude	Magnetometers Cinetheodolites		Attitude Gyros

1.131 Radar and Optical Range Instrumentation

Generalities are discussed which will furnish the background for the review of ranging errors in a later section of this report. Only the optical and radar portions of the electromagnetic spectrum will be considered; other portions of the spectrum do not appear to be usable. Sound ranging is considered passé for establishing probe trajectories.

The components of ranging systems can be classified as being either active (A) or passive (P):

Ground			Air
Transmitter plus receiver	A	A	Transponder
Transmitter plus receiver	A	P	Scattered radiation
Receiver only	P	A	Beacon
Receiver only	P	P	Natural illumination

Passive-passive systems cannot be conceived for radar because the natural illumination is negligible, but for optical devices all four types are possible although an active-active system has yet to be built. Passive targets are desired since the cost and weight of a transponder or even a beacon may be intolerable. Optical systems are attractive for passive targets, because relatively simple theodolites and cameras may be employed during daylight hours.

The type of measurement can be related to the variables that characterized a wave; velocity of propagation, frequency, amplitude, phase direction and polarization. Of the five, the measurement of polarization is little used. The velocity of light is an accurately known constant that is used to compute the loop distance from the transmitter to the target back to a receiver from precision timing measurements. The transmission can be a pulse or a continuous wave. The Doppler shift in frequency between the transmitted and the received wave is proportional to the velocity of the target. Such a measurement is more accurate than that obtained by differentiating distances, a procedure that introduces large errors if the distance increments are small. Distance can be obtained by keeping count of the Doppler phases. Amplitude detection is utilized by tracking devices which compare the signal strength in the neighborhood of a target to determine its direction. The direction of a target can also be determined from an antenna array which measures the direction of arrival of an incoming phase. These arrays are sometimes referred to as interferometers.

Because of the sharp division between optical and radar devices, it is instructive to list the advantages and disadvantages of the optical devices. Active optical devices such as lasers and pulsed light theodolites are excluded. The rapidly developing laser technology is discussed in the next section.

Advantages of theodolites and cameras:

1. Small, simple, low cost
2. Reliable and proven
3. Greater side field capability: Capability of attitude measurements and event documentation
4. High degree of angle resolution

Disadvantages:

1. Cannot penetrate clouds and require good visibility conditions
2. No range data

1.132 Lasers

Maiman at the Hughes Research Laboratory was the first to demonstrate a generator for coherent light in 1960. Since that time, an exciting field of technology has sprung up with new devices and new uses being discovered rapidly. Lasers have potential as a precision ranging device. Of more interest, lasers might provide a method of indirect probing. A system can be conceived which measures the Doppler shift in the radiation back-scattered by natural aerosols in the atmosphere, the optical equivalent to Doppler radar wind measurements in precipitation.

Lasers have advantages over non-coherent light sources on a number of counts. The coherency of the beam permits extremely narrow beams of the order of a few seconds of arc. Spectral widths of 0.1Å are easily achieved and in gas lasers monochromacity of 10^{-7} Å has been reported (Goyer and Watson, 1963). Power pulses a few tens of nanoseconds in duration and peak powers of hundreds of megawatts are possible (Ligda, 1964). Presently, however, the power output of gas lasers are limited to watts. The Doppler shift in terms of wavelengths is:

$$\Delta\lambda = \frac{2V_r}{C} \lambda$$

where V_r is the radial velocity of a probe or tracer and C the velocity of light.
For $V_r = 1$ m/sec and say for $\lambda = 1$ micron, $\Delta\lambda = 0.67\text{x}10^{-4}$ Å which indicates a high degree of monochromacity is desired for Doppler measurements.

Ranging lasers are under development and their potential appears to mark the demise of the pulsed light theodolite (Jay, 1960). Plans have been announced for OPDAR for the Atlantic Missile Range which will use a continuous wave laser to measure the position, velocity and acceleration of a missile from 0 to 50,000 feet (de Biasi, 1964).

Goyer and Watson (1963) discuss the back scattering of lasers from aerosols in comparison with radar. They note laser scattering can be in the far Mie region or the region of geometric optics where the return energy can be intense with only a moderate concentration of energy. Experimental demonstrations of the importance of backscattering from aerosols are given by Callis and Ligda, (1964) and Elterman and Campbell, (1964). Elterman and Campbell's data from searchlight probing over the New Mexico desert indicates the total backscattering from both aerosols and air molecules is 1.2 to 1.6 times the theoretical backscattering from molecules to altitudes above 20 km.

Schotland, et al (1962) considers a laser device for measuring atmospheric temperature by examining the broadening of the Doppler return caused by molecules. Quoting "One can thus envision a system using a CW laser as a source directed upwards at 45°, a photomultiplier receiver of narrow angular field, at some lateral distance away, which could scan upward along the source beam and at the same time see a portion of the original source energy reflected to a beam splitter in front of the receiver. In this way, the photomultiplier mixes f_o (as a local oscillator signal) and the Doppler broadened return signal". The concept stated by Schotland is readily adaptable to a wind measurement where the Doppler shift, rather than the Doppler broadening, is detected. The expectation is that the returns from aerosols will appear as a "spike" in the Doppler frequency spectrum.

Many questions must be answered concerning the coherency of a beam after passage through the atmosphere, the broadening of the Doppler spectrum caused by Brownian motion, etc. The severe requirement for transmitted-to-received power ratio has been examined by Schotland. Perhaps Doppler laser should be first considered for a helicopter low airspeed measuring system or an indirect probing technique for the winds over the end of a runway. Developing the technology for these purposes would permit a better evaluation of the possibilities of Doppler lasers for high resolution wind measuring systems.

1.133 Velocity Sensors

The typical airborne system built around velocity sensors is complex. Attitude sensors are required and equipment must be carried for the storage or transmission of data. The requirement for trajectory data still remains although the demands for precision may be less.

Pressure pickups and flow vanes are the basis for most of the sensors which measure either the longitudinal or lateral components of velocity. One interesting possibility is a ruggedized version of the hot wire anemometer. Even EMAC, a concept discussed in a later section, and Doppler laser using the returns from natural aerosols are conceivable, but the equipment complexity is forbidding. In any event, the usual practice is to place velocity sensors ahead of the probe body at the end of a boom in order to reduce the position error and in order to reduce the difficulties with large and unsteady boundary layers.

Airspeed can be determined over the altitude range of interest with a high degree of accuracy by measuring the dynamic pressure. The derivation of the "true" airspeed from the dynamic pressure requires that static pressure and air temperature be measured by airborne instrumentation or determined by combining weather balloon data with trajectory data. Another technique which has been employed uses an air log device. The sensor is essentially a free wheeling propeller that rotates at a speed determined by the air velocity (Beling, et al, 1961).

Fixed sensors, such as fixed flow vanes (Crooks, 1964) or fixed pressure ports, will measure very rapid fluctuations in the angle of attack. At lower frequencies, servo types can be employed which, characteristically, have better resolution than non-servo types. Such concepts are especially applicable to pressure type sensors where a servo nulls a differential pressure input by rotating the head of the sensor. The output of the servo is measured rather than the input and hence only the detection of a difference is required, not the detection of a magnitude which results in improved resolution.

1.134 Accelerometers

The state-of-the-art in accelerometer design has advanced rapidly since the advent of inertial platforms and accelerometers in the determination of missile trajectories. The primary use of accelerometers for wind measuring systems would be the determination of the fine scale trajectory variations to supplement ranging data. Accelerometers are available in a variety of types such as servo, magnetic reluctance and strain gage types; all, of course, are based on the detection of the linear motions of an inertial mass. System cost and complexity appear to be a limit rather than accuracy.

1.135 Attitude Indicators

Airborne attitude indicators are often position gyros where the angles between the probe and an inertial rotating mass is measured. Similar to accelerometers, the state-of-the-art has advanced to a point where accuracy does not appear to be a limitation.

Other methods such as magnetometers, optical aspect systems, etc. exist which will indicate the attitude angles with respect to earth axis. The type to be used would be dictated by a tradeoff of cost versus accuracy considerations. Attitude can also be determined without on board instrumentation if the limitations of a cinetheodolite can be tolerated.

1.14 Data Processing

The normal differentiating, integrating, trigometric transforms, calibrations, etc. required of the raw data will not be discussed. Rather, two concepts will be examined for "improving" the data; namely, the "desmoothing" of data and the smoothing and filtering of data.

"Desmoothing" is the system engineer's concept of compensation which utilizes the response function of the probe to calculate the "true" wind input from the indicated wind data. Reed (1963) and Engler (1962) both indicate the desirability of employing the equations of motion of a sphere for processing spherical balloon data. The sphere is relatively simple to analyze and nonlinear equations can be developed. Reed's account is particularly enlightening since he includes virtual mass, an effect from unsteady aerodynamics that is particularly important when the buoyancy lift is large.

The compensation concept is also applicable to instrumentation systems but the usual philosophy is to improve the instruments rather than to compensate. Finding the response function is typically a complex and uncertain task. At high frequencies, the response function drops off rapidly and dynamic effects combine to degenerate the data into noise.

A review of the data reduction techniques employed for smoothing the data obtained from spheres by Engler (1962) and others indicates that the least square polynomial fit technique is often employed. Because of the aerodynamic characteristic of a sphere, it is known that certain undesirable cyclic phenomena are introduced into the basic measurements. The polynomial fit smoothing technique is widely used for eliminating undesirable random characteristics in data; however, this technique does not filter out a known range of cyclic characteristics.

In the last few years numerical filtering techniques have been developed which can perform filtering with sharp roll-off characteristics and with errors in the gain function as low as 0.1% (may be higher or lower depending on the requirements). These techniques can provide low-pass and high-pass filtering of digital data.

These numerical filtering techniques are fully outlined by Ormsby (1961) and Graham (1963). Lockheed has developed an IBM 7094 computer program which computes smoothing (filtering) weights and evaluates these smoothing weights in terms of a gain function versus frequency. The program is described in detail below.

Basically smoothing weights H(n) are computed using the following equation:

$$H(n) = \frac{\pi}{2t} \frac{[\sin W_t t + \sin W_c t]}{[\pi^2 - (W_t - W_c)^2 t^2]}$$

$$H(n) = H(-n)$$

where:

t = $n \Delta t$, time on either side of point being smoothed, sec.

n = 1, 2, . . . N

Δt = time interval between successive data points, sec.

N = number of data points being used on either side of data point being smoothed. (2N + 1 equals number of smoothing weights used.)

$H(n)$ = smoothing weights

W_c = $2\pi f_c$, radians/sec.

f_c = cut-off frequency, hz

W_t = $2\pi f_t$, radians/sec.

f_t = termination frequency, hz

The central value, H(0), is defined as

$$H(0) = f_c + f_t$$

The smoothing weights are then normalized such that

$$H(0) + 2 \sum_{n=1}^{N} H(n) = 1$$

The weights are applied to the (2N + 1) data points as the scalar or dot product is found in vector analysis, to obtain a filtered or smoothed data point, which corresponds to the central point of the set of data points to which the weights are applied. Denoting a set of (2N + 1) data points by X_1, X_2 - - - X_{N+1}, - - - X_{2N+1}, the filtered data point $X_{S_{N+1}}$ is given by

$$X_{S_{N+1}} = \sum_{n=-N}^{N} H(n) \quad X_{(N+n)+1}$$

Special consideration must be given to end points when actually applying these weights to data.

The weights when applied to data will have (ideally) the following low-pass filter characteristics:

$$G(f) = G(-f)$$

$$G(f) = 0; \quad |f| \geq f_t$$

$$G(f) = 1; \quad |f| \leq f_c$$

$$G(f) = \frac{1}{2} \left\{ \cos \left[\frac{(f - f_c)\pi}{f_t - f_c} \right] + 1 \right\} ; \quad f_c \leq f \leq f_t$$

where:

$$G(f) = \text{gain function} = \frac{\text{output amplitude}}{\text{input amplitude}}$$

A high-pass filter is the complement of the low-pass filter and is obtained by subtracting the weights for the low-pass filter from the weights of an all-pass filter. An all-pass filter has weights of all zero, except the central weight is unity, that is, 0, 0, . . . 1, . . . 0, 0.

A band pass filter is the difference between two low-pass filters. The weights of a band pass filter are obtained by taking the difference between the weights of two low-pass filters that define the band width.

An evaluation of the smoothing weights, H(a), can be made in terms of gain functions, G(f), versus frequency, f, using the following expression:

$$G(f) = H(0) + 2 \sum_{1}^{N} H(n) \cos (n \Delta t \; 2 \pi f)$$

The computer program calculates low-pass, high-pass, and band-pass smoothing weights for a given cut-off frequency (FREQC), termination frequency (FREQT), time interval between data points (DTIME), and number of smoothing weights (NWGTS) and evaluates the gain function of these smoothing weights over a particular frequency range.

These numerical filtering techniques have been successfully employed by Lockheed in gust analysis work where it was desired to filter out cyclic influences

PREPARED BY A.V.
DATE 4-17-64
CHECKED BY

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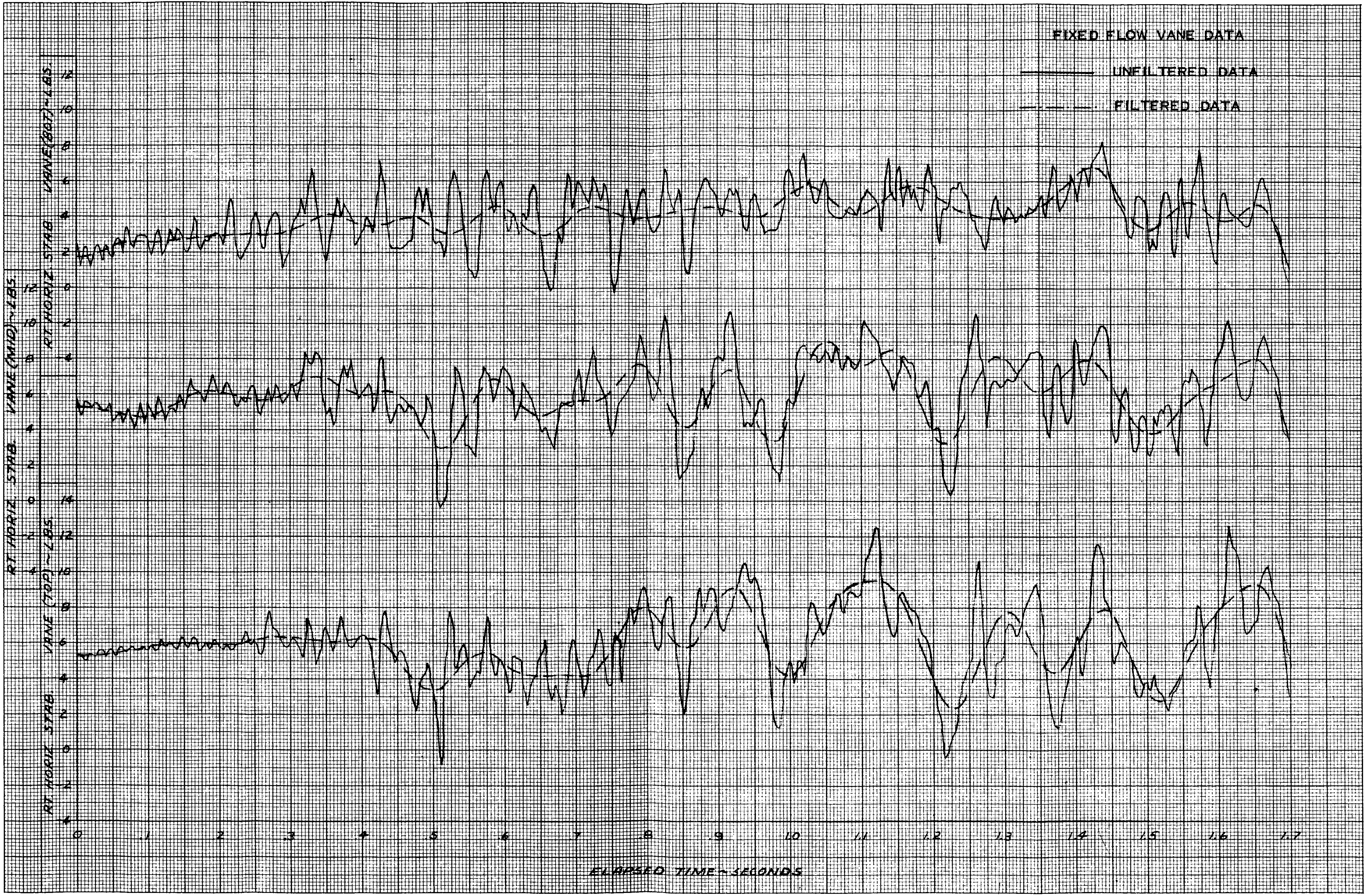

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FIGURE 2

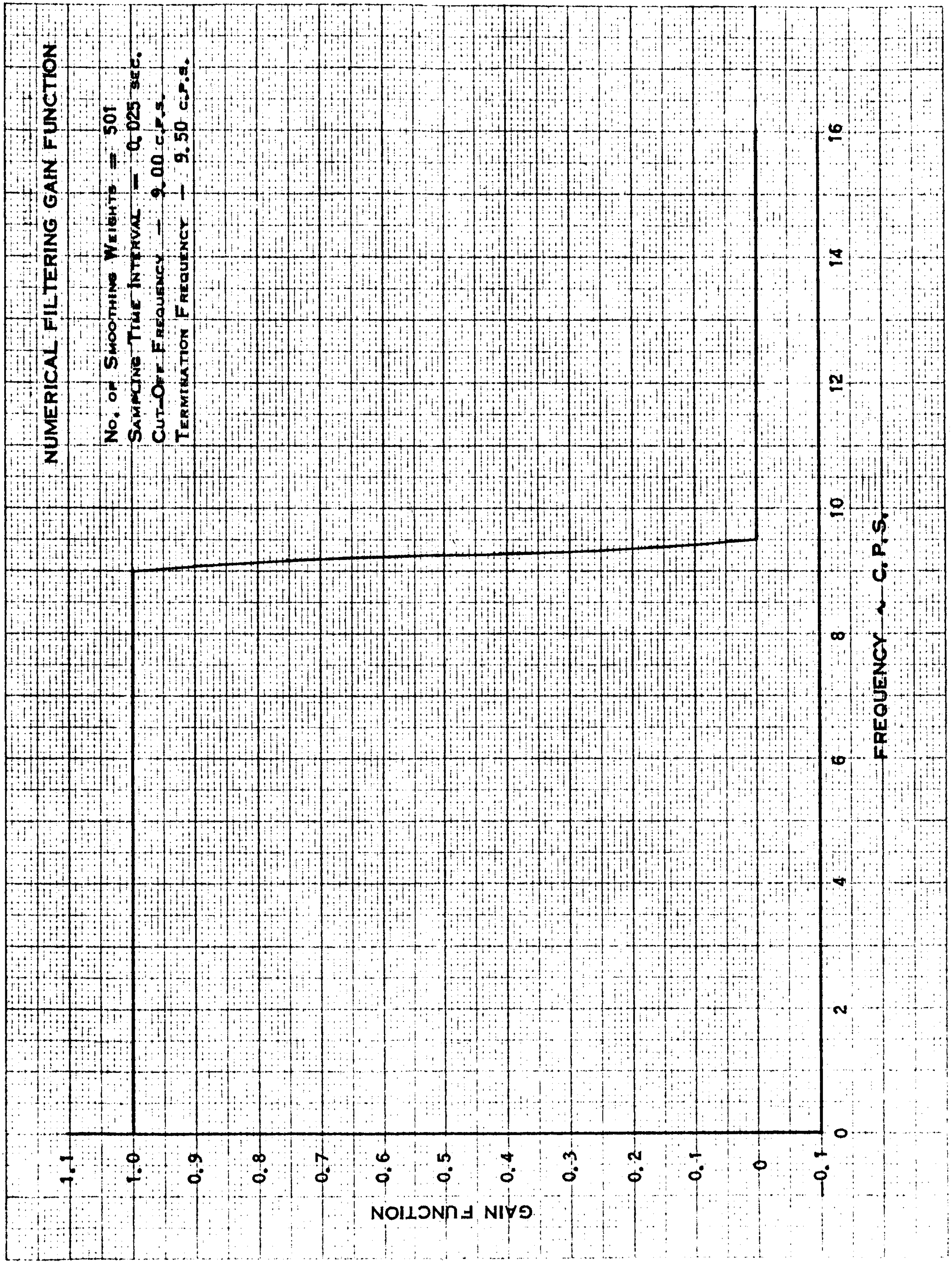
NUMERICAL FILTERING GAIN FUNCTION
No. of Smoothing Weights = 501
Sampling Time Interval = 0.025 sec.
Cut-Off Frequency — 9.00 c.p.s.
Termination Frequency — 9.50 c.p.s.
GAIN FUNCTION
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
FREQUENCY ~ C.P.S.
0
2
4
6
8
10
12
14
16

FIGURE 3

above 9.5 cycles/sec. A typical time history of unfiltered and filtered data is shown on Figure 2. A low-pass numerical filter was employed using data with a time interval of 0.025 sec., a cut-off frequency of 9.0 cps and a termination frequency of 9.5 cps. The gain function characteristics of this particular numerical filter is shown on Figure 3.

1.2 Systems Employing Sound

Refraction and scattering effects form the basis for wind measuring systems based on sound. The possible systems can be classified depending on whether the sound source is on the ground or is carried aloft. The sound can be detected by microphones or the EMAC concept can be employed (Smith and Fetter, 1961) where the sound velocity is measured in terms of the Doppler shift in a radar wave scattered from an acoustical disturbance.

Completely ground based systems have been studied and tested in the past and are represented by the Signal Corps "sodar" concept and by the Cook "acoustisonde" or "echosonde" (Fetter, et al, 1962). Such schemes have been pursued since they can be used for indirect "probing" where the returns scattered from the atmosphere are detected by microphones. To date, practical systems have not been realized even at short ranges. At ranges of 20 kilometers and over, these systems appear to be hopeless. Electromagnetic ranging of an acoustical disturbance offers promise for an indirect "probing" technique but again range appears to be limited. Research is presently being sponsored by the Bureau of Ships, Department of the Navy, to extend the range of EMAC to hundreds of meters.

Aerial sound sources are used for measuring winds aloft at extreme altitudes and they could be used at lower altitudes. A rocket-grenade system has been developed by the Army Research and Development Laboratory which measures winds at altitudes up to and slightly above 90 km. (Stroud, et al, 1960.) The grenade blasts are detected by an array of microphones on the ground. These measurements are used to reconstruct the path of the sound ray and the velocity of the blast wave relative to the earth. The mathematical analysis is based on the velocity relative to the earth being equal to the speed of sound plus the velocity of wind (Grove, 1956; Weismer, 1956).

A low altitude scheme similar to the rocket grenade system can be conceived where a sine wave is produced by a whistler in a descending vehicle. As with the rocket grenade experiment, each emitted phase must be located in time and space by telemetering and range instrumentation. In order to identify the emitted phases with the received phases, there is a requirement for modulating the sound source; for example, by turning the source on and off in a unique digital code of some sort.

The noise of a rocket engine does not appear to be a practical sound source. A serious question exists as to whether a telemetering record of a microphone carried aloft could be matched with the record from a ground microphone.

An electromagnetic ranging device might track the sound wave emitted by an aerial blast or whistler. If the very weak signal expected could be detected, such a method might offer competition to sound ranging with microphones.

1.3 Miscellaneous Systems

Systems which do not use a probe, a tracer or sound do not appear to offer competition but they are included for the record.

1. Electromagnetic Scattering from Natural Atmospheric Turbulence: This concept is marginal. Fetter, et al, (1962) examined the idea in some detail and points out that there is doubt that the "turbulence blobs" are carried along with the wind. Severe problems also arise because of Doppler broadening and in obtaining adequate reflection levels from turbulence. Present day radars do not give consistent returns from clear air turbulence in spite of the many reports of "angels". Furthermore, the atmosphere is often stable and without "turbulence blobs" to scatter the transmitted radiation. Fetter investigated the maximum range predicted from the dielectric sphere model, the Booker-Gordon theory and the Villars-Weisskopf theory and states "It may reasonably be concluded, then, that on the basis of present knowledge the maximum range at which atmospheric turbulence could be detected by radar consistently enough for the proposed wind-measuring system to be usable is of the order of 1 km."

2. Electromagnetic Scattering from Artificial Atmospheric Turbulence: A dependable source of turbulence could be generated by the passage of a rocket through the atmosphere or by other means. However, most of the

questions raised by Fetter still remain.

3. Infrared Tracking of an Artificially Heated Bubble: Fetter analyzed an unusual scheme. Quoting, "This method would use remote means, such as intersecting acoustic infrared or microwave beams which could be focused on, and absorbed by a remote volume of air, to raise its temperature above ambient. The heated volume of air, referred to as a bubble, would rise in the atmosphere at a rate dependent on its temperature difference and the local lapse rate. As it rises, its path would be influenced by the local wind field in the same manner as a balloon. Theoretically, the bubble could be tracked by a multiple theodolite system to obtain its position as a function of time, from which the wind profile could be determined".

Fetter concludes that "an analysis of bubble generation indicates that the original proposal for heating a volume of air with intersecting beams of energy does not appear feasible at distances which are large in terms of transducer size and spacing - - the simple model shows that the assumed bubble could retain its identity as a detectable sensor to a height of 1,500 meters. Additional parameters such as radiation loss, diffusion, turbulent mixing, and shear and drag forces could be included in a much more complete analysis. It is believed that these parameters will, in general, degrade the bubble configuration, causing it to lose its identity in the first few meters of its travel".

2.0 ERRORS IN MEASUREMENT

Central to a study of high resolution wind measuring systems is an error analysis. In the following sections, the errors due to probe motions, to range instrumentation and to velocity sensors are reviewed. Note that the system engineer thinks in terms of wavelength while the meteorologist thinks in terms of wind shear over an altitude interval. Only two points are needed to determine a linear wind shear but three points are needed for a sine wave. A resolution specified as a sinusoidal variation over a 50 meter interval is, in a manner of speaking, equivalent to wind shear being resolved for a 25 meter interval.

2.1 Probe Motions

The equations of motion cannot explain the response of a probe in every detail. Unstable effects, unfortunately, can introduce large erratic motions which cannot be described readily. Murrow and Henry (1964) give rms values from 2 to 3.5 m/sec. for smooth, two meter, spherical Mylar balloons. These balloons were released inside the Lakehurst Hangar No. 1 and rose to a height slightly above 50 meters before they were restrained. Scoggins (1964) demonstrates these erratic motions can be approximately halved by attaching large roughness elements to the smooth surface. A research program is presently under way at NASA Marshall Space Flight Center to detail the nature of the erratic motions and the best method for reducing their severity. (Personal contacts with Scoggins indicate balloon motions have been reduced so they are not detectable by FPS-16 radar by a careful selection of roughness elements and by the addition of a small mass which stabilizes the balloon and prevents rotation.)

Configurations such as the ring wind shearsonde and other streamline shapes would be expected to be less sensitive to erratic flow separation. For these bodies, separation is less and tends to be stabilized at the rear of cylindrical shapes and at the trailing edge of wings.

2.2 Ranging Errors

The measurement of winds to a high degree of resolution with an uninstrumented probe requires a high degree of precision in the range instrumentation. Typically the FPS-16 radar is employed as these high precision radars are usually available at the missile ranges. A detailed analysis of the errors in the FPS-16 radar is discussed by Barton and Sherman (1960). They give a comparison between a boresight camera, the primary standard, tracking a balloon and a FPS-16 radar tracking a 6-inch sphere inside the balloon. The errors were examined based on samples analyzed over a 30-second period. A comparison between the errors from the test and theory indicated the major errors were due to glint errors, propagation errors and receiver thermal noise. The azimuth rms error was less than 20 sec. of arc out to a range of 30 km and increased rapidly thereafter. Barton and Sherman state that if the derivation of propagation noise is correct, "...it is believed that this is the first time the effect of atmospheric propagation anomalies has been observed with a single radar".

The errors of a number of pulse type radars (the only type considered) which are readily available and applicable to the tracking of spherical balloons are summarized by Hetrich (1963). Only the FPQ-6 is shown to be better than the FPS-16 radar, having the same 5 yard rms error in range but half the error in azimuth and elevation. Single station, dish tracking types such as the FPQ-6 radar represent a high degree of sophistication. Scoggins (1963b) calculated the maximum rms errors in wind speeds over 25 meter intervals from FPS-16 tracking data to be between 0.6 and 3.0 m/sec out to a range of 100 km using a spherical balloon target. This analysis considers the improvement obtained by averaging (smoothing). If accuracies in wind speeds an order of magnitude greater are required, the study of other types of radars suggests itself. The demands on the tracking equipment are even greater if the target is a small, highly responsive dropsonde falling rapidly.

Range triangulation should be considered if extremely accurate position measurements are desired. Two effects discourage the use of triangulation based on angle measuring equipment. First, atmospheric refraction causes a first order effect in ray direction but only a third order effect in the distance along a ray. Secondly, the errors in lateral distances become rapidly greater with range if based on angle measurements. However, accuracies in the angles an order of magnitude greater than with the FPS-16 radar are possible using interferometer techniques such as employed by the AZUSA radar. Such installations are very expensive and require a transponder in the probe (Inter-Range Instrumentation Group 1961). A more interesting system would be the SECOR which employs three distance measuring equipments (DME). A range error from 1 to 5 feet is quoted by the Inter-Range Instrumentation Group (1961). The uncertain knowledge of the speed of light, 2 parts per million, is a limitation in accuracy. The system uses a target with a transponder (Cubic Corp., 1963).

The problem of precision position measurements can be avoided if the velocities are determined directly with Doppler radar. Such radars are limited in type. The Inter-Range Instrumentation Group (1961) lists a velocimeter manufactured by the Resdel Corp. (no model number given) for passive targets with an accuracy of 1/3 m/sec. Typical capability is given as a 12.7 cm rocket to a range of 6.5 km. Other radars could be modified for Doppler detection. Juisto (1962) describes the errors for a large Doppler radar proposed for a chaff column ranging system.

Optical devices are capable of a high degree of angular resolution. The Askania cinetheodolite, the work horse of most test ranges, has an accuracy between 20 and 30 sec. of arc. The Inter-Range Instrumentation Group (1961) also lists a proposed tracking instrument mount that was representative of the state-of-the-art in precision mount design at that time. The predicted system accuracy is 5 to 10 sec. of arc.

The effect of rapid variation in atmosphere refraction can be averaged out while the steady state effect of a stable atmosphere represents a systematic bias for which corrections can be derived. The ability of data processing to account for rapid variations becomes questionable for resolutions of the order of 10 sec. of arc. Barton and Sherman (1960) assign this value to tropospheric propagation rms error in their analysis of both theodolite and radar equipment as a result of their review of the numerous studies on this effect. A value of only 4 sec. of arc is assigned to a plate camera with a star background.

2.3 Velocity Sensor Errors

Errors exist which are common to most types of velocity sensors. For pressure sensors and flow vanes they can be classified as static and dynamic instrument errors; body, boom and sensor position errors (effect of the probe configuration on the free stream flow field); and errors due to the static and dynamic bending of the body and boom. The Lockheed-California Company experience in flight test indicates it is possible to establish the "true" airspeed to within 0.5 m/sec rms and the angle of attack to within 0.1 degree rms for pressure pickups and flow vanes, respectively. For transonic speeds and for non-static conditions the errors will increase in spite of a careful program of instrumentation design, wind tunnel tests, calibrations, etc.

2.4 System Errors

One common method employed for error analysis is a comparison of systems, an approach popular for tracking equipment where two different devices are trained on the same probe. A comparison by Barton and Sherman (1960) between an optical boresight camera and the FPS-16 radar was discussed previously. A comparison between the GMD-1A and GMD-2 rawin sets by Salmelan and Sissenwine (1959) and a comparison between data from the GMD-1B radiosonde and the FPS-16 radar by Sandlin (1963) are additional examples.

Comparisons are also frequent between winds measured with independent measuring systems. Such efforts are degraded, more or less, by the effect of wind variability operating on the different types of space-time tracks. Juisto (1962) compares smoke trails, chaff columns and radiosondes; Smith (1960) compares data from a chaff cloud, from flow vanes on a rocket and from a radiosonde, etc.

The errors in a system employing a chaff column were analyzed by Juisto (1962). Two large Doppler radars, were proposed to observe the motions of chaff dipoles expelled continuously from 15 km to the ground during free fall of a chaff dispenser carried aloft by a rocket. The study concluded that the wind velocity could be measured with a probable rms error of 0.9 m/sec and that 90% of the time the wind shear could be measured with an accuracy of 0.0017 $\sec^{-1}$ for a 30 m height interval. The analysis indicated most of the error could be attributed to the mismatch in the altitudes sampled by the two radars.

Henry, et al (1961) investigated the accuracy of wind determination from photographs of smoke trails made with USAF type T-11 precision cameras. The reading error, the random local film shrinkage or stretching and the lack of flatness were considered to be the errors of importance, except for the error of assuming that the vertical wind was identically zero which could not be assessed quantitatively. Treating the errors as a combined film coordinate rms error, a value of 0.01 mm was estimated to be the accuracy obtained with actual trails under typical operating conditions. This reading error gave an rms error of 0.38 m/sec in winds over a 30 sec. interval, the error being inversely proportional to the length of the time interval. The altitude was 15 km and typical camera-to-camera-to-smoke-trail spacings were assumed.

Of considerable interest are the error analyses performed for the rocket-grenade experiment. Groves (1956) concludes random experimental errors may be as low as 1 m/sec in his consideration of the potential errors in the rocket-grenade experiment. Stroud, et al (1960) states the errors in wind speed and direction as being generally less than 5 m/sec and 15 deg., respectively, below an altitude of 75 km. A major source of error is in the measurement of the arrival time of the grenade blast at the microphone array.

CONCLUSIONS AND RECOMMENDATIONS

1. Certain relatively unexplored concepts are worthy of further study. They are:
    a. Electromagnetic and/or sound ranging of an aerial blast or a whistler.
    b. Doppler detection by laser of the motions of natural atmospheric tracers.
    c. Searchlite or laser ranging of smoke or tiny reflecting particles.
    d. Optimum configuration for balloons or small uninstrumented dropsondes.
2. The adaptation of range instrumentation based on distance triangulation or the use of Doppler radar should be investigated.
3. The spherical balloon and FPS-16 radar system, the smoke trail and precision aerial camera system, and flow vane instrumentation on launch vehicles are the best methods available today for high resolution wind measurements.
4. Systems worthy of serious consideration employ a probe, a tracer, or sound.

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SECTION B: REPRESENTATIVENESS OF METEOROLOGICAL OBSERVATIONS

INTRODUCTION

Real knowledge of the physical world is determined ultimately from observations of samples of this world. The representativeness of the observational data of the physical conditions of the real world is determined not only by the precision of the instruments and data processing techniques but also by the size of the samples and the frequency of sampling of the real world. This sampling technique in turn is determined usually by practical considerations such as money and time involved and modification of the environment by the sensor versus the sensitiveness of the test or problem to lack of knowledge of the real conditions of the environment.

The objective of this section is to consider the representativeness of atmospheric observations. In particular, this section considers the manner in which the real atmosphere deviates in space and time from an observed sample. To do this, the state-of-the-art of atmospheric motion is summarized and areas are indicated in which knowledge should be extended. Eventually, this knowledge will be used to determine optimum accuracy and useful precision for observing systems as a function of the spatial and temporal intervals between observations and the applications.

It would appear that this sampling variability may be a particular problem in preparing pre-launch and launch evaluation wind information for space vehicle or missile launches. Balloon or other sensing systems must necessarily observe the wind at a different time and place than the space vehicle. Part of the difference in wind velocity that this causes can conceivably be forecast, but much of the difference must be accepted as a physical limit to the accuracy of observing or forecasting what the vehicle will experience. Thus, if it should be found that the standard deviation of the errors resulting from spatial and temporal variations cannot be reduced below 5 knots, then it would be needlessly expensive to build a sensing system with an accuracy of 0.1 kt for operational monitoring purposes. Of couse, the very accurate system is needed for research purposes and design data calculations.

This is the inverse of a similar problem which has long harassed meteorologists. For synoptic forecasting, the optimum spacing of observations in time and space is a function of the available accuracy of the observing system as compared to the real perturbations. Thus, if errors are random and of the same magnitude as the true variation between observing points, fictitious perturbations are recorded. A similar problem exists in oceanography. There, it has been found that temperature variations of 1°C often occur in less than one hour (Baer and Hamm, 1964). Many oceanographers, however, are asking for sensors having accuracies on the order of 0.01°C.

A similar problem also exists in forecast verification. A forecast does not strictly apply at one precise location and time. Instead, it is only meaningful in terms of some area and time span which is probably a function of the spacing of the observational network and the time interval between observations (or iteration interval in a dynamical forecast). In order to estimate this wind variability, a great mass of these data were summarized by Ellsaesser (1960). Though most of the previous work refers to synoptic scale and near surface variability; there is some reference to the smaller scales in the free atmosphere which are of interest here.

PHYSICAL CONSIDERATIONS

Real fluids can sustain a wide variety of motions that are characterized by certain kinematical and dynamical relationships among the fluid variables. Not only must the motion, pressure, and temperature fields be considered but also other effects such as the earth's rotation and the underlying surface conditions. The many forcing functions cause a wide spectrum of motions in the atmosphere ranging from fractions of a second to years.

Because of this continually changing character of the atmospheric motion patterns due to the infinite possible patterns of the initial conditions and the three-dimensional forcing functions, there is never enough data to determine and describe the complete characteristics of all of the atmospheric motions. Thus, it is both necessary and expedient to formulate dynamical and statistical models that represent the essential features of the atmosphere and to utilize these models as tools to interpolate and extrapolate both in space and time as well as to estimate the characteristics of the atmospheric motions.

The specific procedures for investigating this spectrum of motions varies with the problem at hand. A common method is to divide the motion into two categories, mean flow and turbulence, which is generally equivalent to calling them deterministic and probabilistic flows. The mean or deterministic flow is that flow that can be described by ordinary vector and scalar functions as opposed to the turbulent flow which must be described by probabilistic parameters or functions. The division between the two flow regimes is discussed in the following section.

Another approach is to consider the perturbations in the free atmosphere to be made up of two components; (1) wave motion or undulance, and (2) irregular motion or turbulence (Hildreth, et al, 1963). Turbulent properties appear to be better known than those for small scale undulance. Turbulence elements are advected with the wind while undulant elements, on the other hand, have specific phase and group velocities that are functions of the type of wave, the wavelength, and other factors such as Coriolis parameter as well as the temperature and wind field structure.

Although the wind variability in the ground layer appears to be dominated by the turbulence components, undulance may be significant or dominant under many conditions in the free atmosphere. The structure and theory of turbulence is fairly well known and for some small scales appears to follow Kolmolgorov's similarity hypothesis. It has been described empirically for other scales. Thus, it is possible to estimate the wind variance fairly closely as a function of distance and time under strict but relatively simple turbulence conditions. Similar estimates could be made for undulance and have been for ocean waves, both surface and internal. However, it is not obvious how this can be done for a mixture of turbulence and undulance.

For a compressible but inviscid fluid on a rotating earth, three general classes of waves which affect our problem may occur in the atmosphere; high frequency acoustic waves ($> 10^{-1}$ hz), gravity waves (10^{-2} to $^{-4}$hz), and inertia and synoptic scale waves ($< 10^{-4}$ hz). Acoustic waves will not be considered here because of their extremely high frequencies and usually small amplitudes. Which wave types are activated appears to depend on the characteristics of the perturbating function as well as the wind and temperature structure of the mean flow.

According to the classical theory there are only two general areas of instability, long synoptic waves and the short gravity waves; however, according to a recent analysis (Hildreth, 1964), another region of instability which may be either an energy source or sink exists in the mesoscale between inertia and gravity waves at approximately 100 kilometers wavelength with frequencies of 10^{-2} to 10^{-4}hz. Once the perturbations have been initiated, the net effect apparently changes continually due to the dispersive characteristics and non-linear interactions. Non-linear processes transfer energy from one perturbation wavelength or direction to another.

Other regular perturbations can occur as transient cellular motions such as cumulus clouds and sea breezes. These perturbations are of special significance because either the observing sensor or the vehicle might pass through one without the other being similarly affected. Similarly, of a series of observations taken sequentially, these transients may be present in some of the results but not in others.

Another cause of variability is due to actual inhomogeneities or eddies in the atmosphere. This is what is classically referred to as turbulence. The vortex motion which is needed to preserve the individuality of these inhomogeneities adds variations to the mean flow. Also, because the field may have strong density gradients (though over small regions) corresponding velocities must occur because of the dynamic relationships. These would increase the observed fluctuations both in the wind profile and with time and space as they are advected with the mean wind.

There is thus ample reason to expect real fluctuations in wind velocity to occur. These fluctuations manifest themselves as a spectrum with peaks in specific regions. The larger scale variations can, theoretically at least, be forecast from multiple observations. The smaller can at the least be lumped into one pot and described statistically if enough observations are available.

STATISTICS

The fluctuation of a variable such as wind can be represented by correlation functions, by spectral distribution functions or by lag-variability either in the space or time domains. In general, the functions in the space and time domains are not proportional to one another, although in the case of pure random turbulence, it has been found that Taylor's hypothesis in which distance is considered equal to the product of time and the mean wind speed holds quite well. In general, though, the time and space scales are not proportional because the energy of waves propagates at a group velocity which is usually a function of the wavelengths of the perturbations and other factors as described previously.

In the case of many observational systems, one does not obtain data which can be used to evaluate strictly the time or space domain. For example, when airplanes, rockets or free balloons are used as platforms, a representation in the joint time and space domain is obtained which may obscure the time or space variability. Each of these measuring systems can be expected to present a different picture because different scales affect them. By separating the space and time variability and recombining them properly, any situation can be simulated in theory.

The response of the atmosphere to the many forcing functions is vividly displayed by spectral energy distribution which usually shows several peaks. It is usual to assume that the complete turbulent spectrum of motion (or other parameter) has a region of low energy which has been called a gap between the spectral peaks. By judicious choice of scales, then, the larger scales of wavelength greater than the gap are treated as deterministic mean flow and smaller by statistical means. The several different physical phenomena have different scales so that there is some choice. The physical reality of the peaks was discussed in the previous section. Since the interest here is of the smaller scales, it is important to note that Panofsky and Van der Hoven (1955) found an important peak below a period of 1 minute using data from near the surface. Perhaps this is caused by mechanical mixing. Few data are available on this scale at higher altitudes. There seems to be some disagreement on the next scale of possible importance, that of convection which has been found to vary from 1 minute to 30 minutes. A major gap in spectrum on the order of 1 hour has been postulated by Van der Hoven (1957), although the very crude analysis by Bushnell and Huss (1958) did not indicate the gap. Using 3-minute averages of rawinsonde soundings, Lenhard, Court and Salmela (1962) and others have shown constantly increasing mean square successive differences up to 48 hours and at altitudes of 3 to 12 km which tends to substantiate the lack of a gap in the free atmosphere. However, recent tranosonde measurements reported by Mantis (1963) indicate the gap in the mesoscale. Kao and Woods (1964), utilizing project jet stream data, have found that the spectra in the mesoscale increases with decreasing wave number. Obviously many more dependable observations are needed.

The most direct measure of the representativeness of wind observations is the vector mean square successive difference often called the lag variance. Adding the assumption of circular normality, Ellsaesser (1960) attempted to assimilate many different types of data. He presented the root mean square successive difference in wind velocity (lag-standard vector deviation) which will be equaled 63% of the time as a function of space or time for many altitudes. In this empirical study he assumed that space and time were equivalent so that the same scale could be used for both. Of special import is that over time differences of 1/2 hour (space interval of 8 km), the 63% variation ranged from about 4 to 8 kts. The variability seems to increase with both wind speed and with the time or space interval.

UNSOLVED PROBLEMS AND FUTURE RESEARCH

The foregoing establishes that significant small scale variability exists. It becomes obvious that the ultimate practical wind sensing system must be determined by more than the accuracy and precision of the sensor. This most basic problem is how well this sample from a different time and place will represent the actual conditions to be experienced along the trajectory by a missile or other vehicle.

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