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STUDY OF HIGH RESOLUTION WIND MEASURING SYSTEMS – PHASE II ANALYSIS

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FOREWORD

This document reports on Phase II of a study of high resolution wind measuring systems. The study was conducted by the Lockheed-California Company in Burbank, California, under contract NAS8-11286 for the Aerospace Environment Office, Aero-Astrodynamics Laboratory, National Aeronautics and Space Administration, George C. Marshall Space Flight Center in Huntsville, Alabama. The contract monitor was James R. Scoggins and the principal investigator was Fox Conner. The Phase II study was conducted during October, November, and December of 1964, and during January and February of 1965.

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 wind environment with a higher degree of resolution. Phase I, already reported, was a survey of all systems conceivable, proposed or in operation. In this report, three analyses are presented on different types of measuring systems; analyses which, in addition to other analyses already reported in the literature, furnished the background for a comparison of all possible systems in the last section of this report.

ABSTRACT

Reported herein is Phase II of a study of high resolution wind measuring systems. Improved wind measuring systems will aid the design of space boosters by obtaining data of higher resolution on the random and regular features of the wind environment. For this purpose, a resolution of 25 m is desired in the wind profile at altitudes up to 20 km. A comparative analysis was conducted which showed five types of systems appearing to be worthy of further research and development:

1. An uninstrumented wind probe with precision tracking radar.
2. An instrumented probe.
3. A chaff column system with multistation Doppler radar.
4. A smoke trail system with precision cameras.
5. A sonic system.

The comparative analysis was preceeded by analyses of optical, wind-sensor and sonic wind measuring systems. The completion of these analyses aided in comparing the potential of these three systems with other types.

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INTRODUCTION

The design of large space vehicles is being pushed to a higher and higher 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 existed, therefore, for a study which will review and analyze the various possible schemes and which will recommend areas for future development.

The first three sections of this report are analyses not available in the literature. These analyses are for optical, wind-sensor and sonic systems, and their completion allowed a more intelligent comparison to be made of all the potential candidates for high resolution wind measurements. A number of optical schemes were investigated with the greatest interest being centered on a system which measures the Doppler shift in the laser radiation scattered by natural aerosols. This scheme is the optical equivalent to Doppler radar measurements in precipitation. The second analysis concerns itself primarily with the errors involved in tracking wind sensors of various shapes while the third analysis investigated the potential of sonic systems. The sonic systems investigated can be considered variations of the rocket-grenade experiments where the sonic sources are not grenades but instead generators of sine waves or sonic pulses at a rapid rate.

1.0 ANALYSIS OF OPTICAL SYSTEMS

Ultraviolet, visible, and infrared electromagnetic radiations interact with the gaseous and particulate constituents of atmospheres to produce a number of distinct phenomena. Much of our present knowledge and understanding of the solar and planetary atmospheres is directly associated with the study of these phenomena. For example, almost all of the knowledge of the composition and temperature of the solar photosphere, chromosphere, and corona is directly associated with the spectral analysis of the radiation from these sources. Details of the motion from moderate depths into the photosphere to the outer corona have been determined by spectral analysis and by photographs of the light in narrow spectral band widths. Motion of portions of the atmospheres of Jupiter and Mars have been determined exclusively by optical techniques. Motion of the terrestrial atmosphere has been detected by observations of the particulate constituents such as clouds, smoke, dust, etc. and in some cases of the gaseous constituents that are present in trace amounts only. Optical techniques such as Schlieren and streak cameras have played an important role in the measurement of motion and density gradients in wind tunnels. Can the use of optical techniques be extended to yield detailed information on the motion in the atmosphere at vertical heights up to 20 km? This report will consist of a discussion of answers to this question although it will, of course, be desirable to rephrase the question so that specific optical phenomena and techniques may be related to particular properties of the atmosphere.

The constituents of the atmosphere emit electromagnetic radiation and they react upon the radiation. The emission by the gaseous components is confined to lines and bands of the spectrum with each gas having a unique set of lines and bands. The particulate matter radiates throughout broad spectral zones and these broad zones are not so readily identified with a specific type of particle. As the electromagnetic radiation travels through the atmosphere there are interactions that may result in scattering, absorption, refraction, or diffraction of the radiation. The absorption has characteristics similar to those of emission. If the scattering is related to particles (molecules or aggregates of molecules) that are small compared to the wavelength of the radiation, then the properties of the scattered light are expressed by Rayleigh's law. If the scattering particles are not small compared to the wavelength of the incident radiation then the term "Mie scattering" is used. (Actually, Rayleigh is a special case of Mie scattering.) Under special conditions Raman, Brillouin, or resonance scattering may be observed although these types of scattering are probably not important for our present purposes. Refraction and diffraction affects the direction of propagation of the radiation through the atmosphere.

The magnitude of the measurable effect associated with these interactions of the atmosphere with electromagnetic radiation is a function of the composition, density and density gradients of the atmosphere. In some cases the presence of gaseous components in trace amounts plays a dominant role and in others the irregular distribution of particulate material is important. The relative importance of any given optical phenomenon or atmospheric constituent is largely a function of the wave length of the radiation being considered. Those gaseous constituents of the atmosphere (nitrogen, oxygen, argon...) for which there are no large sources of addition or subtraction are uniformly mixed by turbulence to altitudes in excess of those to be considered in this report. Other gases such as ozone, water vapor, industrial contaminants and all particulate material have relatively large sources of addition and removal and hence are not uniformly mixed. Often these constituents are found in relatively well defined layers and clouds, and the boundaries of these layers and clouds are zones of sharp gradients in the optical properties of the atmosphere.

If an optical technique is to be used to detect motion of the atmosphere, the technique and the phenomenon upon which it is based must be specifically related to the motion of a particular volume element over a given increment of time and at a given coordinate position. In general, the motion of the atmosphere may be represented by a vector field; that is, each volume element of specified size has a single valued velocity that may be represented by a vector. The vector field representing the motion of the atmosphere is not unique because the velocity at each point in space is a function of the size of the volume element and the increment of time over which the velocity is averaged. Once the size of the volume element and increment of time is decided upon, the velocity will have both spatial and temporal variations and both of these variations may be separated into periodic variations of many frequencies, aperiodic and secular components.

1.1 Discussion of Specific Techniques

1.11 Laser Radar*

Occasionally there is a new development in physics that excites the imagination of those interested in technological applications and of the science writers of the press associations. Such a development occurred early in 1960 when T. H. Maiman succeeded in constructing the first laser (light amplification by stimulated emission of radiation). Since that time, newspapers and the trade journals have published many articles enumerating the possible applications of lasers. These discussions of the applications of lasers often include the use of lasers for meteorological measurements. Perhaps it is worthwhile to attempt to place these discussions and predictions of applications of lasers in a proper perspective by giving a brief review of the history of the development of lasers and comparing this development with other leading activities in physics.

Three ideas were essential to the development of lasers. The first of these is the Fabry-Perot interferometer. This was first proposed and constructed in 1898. The second idea is that of stimulated emission. This was discussed first in 1917 by Albert Einstein. The third idea essential for the development of the laser is the concept of amplification. A. L. Schawlaw and C. H. Townes in 1958 were the first to combine these three ideas and suggest the possibility of constructing what is now known as a laser. The idea of amplification was an outgrowth of the work on amplification of microwaves. C. H. Townes, Nikolas G. Basov and Alexandre M. Prokhorov were awarded the Nobel prize in physics on 29 October 1964 for their fundamental work in the field of quantum electronics which has led to the construction of masers and lasers.

Since the announcement of Maiman's success in constructing a laser in mid 1960, over 1400 papers on lasers have been published in the technical journals. During this same period the total number of papers in the field of physics (as indicated by Physics Abstracts) has increased from 14,000 per year to 31,000 per year. From

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* The first laser ranging device was developed by Buddenhagen, et al in 1961. Shortly thereafter Stitch, et al developed a coherent light detecting system which they named COLIDAR. Ligda and Collis at Stanford Research Institute have developed more advanced versions which they have named LIDAR.

these figures it is seen that the publications on lasers constitute a significant fraction of the new work in physics but there are other fields where the concentration is as great or greater.

Most of the work on lasers that has been done to date has been concerned with adding to our knowledge of the basic operating principles and with constructing new types of lasers. Dr. J. R. Pierce, Executive Director of Research, Bell Telephone Laboratories, has pointed out that in the past the struggle to produce a practical application of a new development in physics has always been a long and difficult one. This has been true of the transistor, the wave guide, the nuclear reactor, etc. In each case, preliminary estimates of the ease of developing a practical application have been overly optimistic. The laser is still so new that, in spite of the present pace of work, it perhaps is unwise to expect too much too soon. This statement is not to be construed as one supporting a slackening of the present efforts. Rather, it is to be taken as a support for further efforts. All of our past experience indicates that new, difficult, and unforeseen problems will arise before any practical laser radar will be developed. Semi-facetious comments have been made indicating that the only clearly defined practical application of lasers that has been developed thus far is that of burning holes in razor blades and bursting balloons.

The most obvious application of lasers to the problem of detecting atmospheric motion is the use of a laser in a detection and ranging device. The return signal would be associated with scattering by either the gaseous or particulate components of the atmosphere. The utility of the laser ranging system for detecting motion in the atmosphere is thus a function of the characteristics of the laser radar and the scattering and absorption properties of the atmosphere. The laser radar may either give just the range of a given source of return signal or it may give the velocity along the line of sight by detecting the Doppler shift. Each of these will be discussed in the following paragraphs.

A laser used as a ranging device may be used to detect horizontal motion of the atmosphere if there is a natural or artificially induced gradient in the scattering properties of the atmosphere and if this zone of relatively strong gradient is readily identifiable over an appropriate time interval and if the boundary of the zone has a horizontal motion sufficiently similar to that of the surrounding atmosphere. With rare exceptions, clouds and haze do not satisfy these conditions. Scarf clouds, lenticular altocumulus, and often strato cumulus do not move with the horizontal wind velocity. Cumulus clouds usually do not present a readily identifiable persistent boundary segment that moves with the wind. Irregularities in stratoform clouds are seldom of such a character that they could be followed readily by a laser ranging device. Haze usually has boundaries that are less readily identified than the boundaries of clouds. The gaseous constituents of the atmosphere never present sharp gradients in the scattering properties. Artificially injected particulate material may, however, offer opportunity to obtain laser return signals that may be used to measure atmospheric motion. The particles should be small enough to have a negligible rate of fall and large enough to have a relatively slow rate of diffusion. The cloud of injected particles should not subtend an angle of view as seen from the laser transmitter that is very large compared to the cone angle of the laser beam. It should not be as small as the cone angle of the laser beam because this would introduce major difficulties in the search procedure. (This presumes that the laser beam width is less than three minutes of arc.)

The general requirements of a coherent pulse-Doppler laser have been discussed in detail by Biernson and Lucy. The purpose of their discussion was to concentrate on the requirements of such a system and not the means of designing a laser to satisfy these requirements. For this reason, the advances in laser technology that have occurred in the eighteen months since their paper was written do not alter their conclusions. The system analyzed by Biernson and Lucy may be represented by the following block diagram.

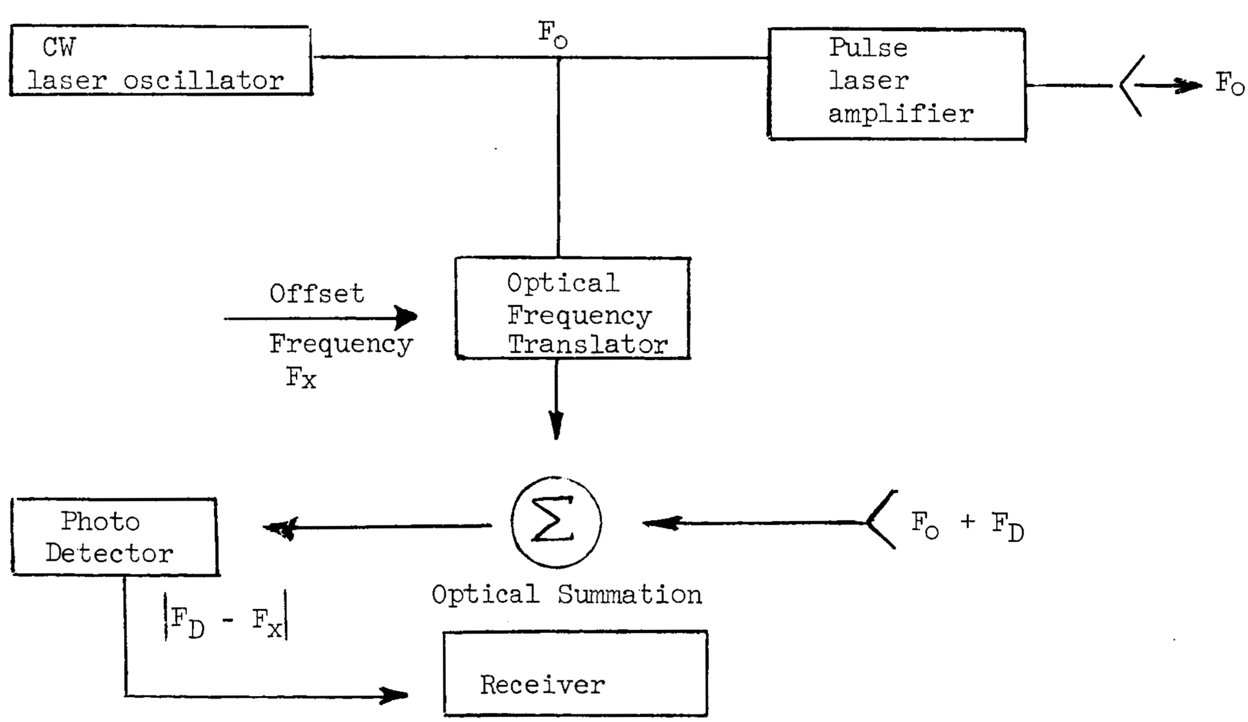

FIGURE 1-1 - BLOCK DIAGRAM OF A COHERENT OPTICAL RADAR

For laser light wavelengths in the red or very near infrared, the Doppler shift is approximately $3 \frac{Mc}{m/s}$. When the system illustrated in Figure 1 is used for the specific purpose of detecting atmospheric motion, several problems arise that are not discussed by Biernson and Lucy. These problems are associated with the characteristics of the surface producing the return signal. If clouds, haze, smoke, or artificially injected particulate material are used as the source of the return signal, then the random motion of the individual particles and the extent to which the motion of the boundaries of the clouds or layers represent the ordered motion of the gaseous constituents of the atmosphere must be considered. The random motion may be of the same order of magnitude as the ordered motion. In addition, the return signal will originate in a finite volume which will be sufficiently large that the ordered motion throughout the volume may vary significantly. Yet another problem associated with the recording of the range and velocity is that the laser beam may penetrate two or more layers or clouds of particulate material, in which case two or more velocities must be detected for each pulse, and the velocities corresponding to the appropriate range must be clearly identified.

If a velocity resolution of 1 m/s was required, the bandwidth (Δf) of the receiver should be 3 Mc. This means that approximately 30 receiver channels would be required to cover the range of probable atmospheric velocities. To achieve optimum detection the pulse width, τ, should be equal to $1/\Delta f$ or $0.3 \mu s$. Such a laser ranging system would achieve a range resolution of 50 m. A linewidth of less than 10 Mc is desirable and within reasonable limits of what can be achieved. These limits of resolution for the velocity and range are near the optimum that may be expected.

The sources of noise that were discussed by Biernson and Lucy plus the noise introduced by the tenuous boundary, the random motion of the cloud particles, the gradient of velocity in the cloud, and the multiple layers of particles or clouds would decrease the signal to noise ratio.

The coherent pulse-Doppler laser radar measures velocities of the source of the return signal parallel to the axis of the receiver beam. This means that the horizontal component of the ordered motion of a cloud, haze, or smoke layer can only be measured if the receiver beam is at an angle to the zenith. Also, if clouds, haze, smoke or artificial particulate material are the sources of return laser radar signals, then the atmospheric motion can only be determined at one, or at most a few altitudes at any given time. These altitudes would be determined by the altitude of the boundaries giving the return signal.

The characteristics of the present lasers that appear to be relevant for their application to the problem of detecting atmospheric motion are:

Wavelength: There are many types of crystaline, glass, liquid, and gas lasers. In general, each of these may emit coherent light beams at more than one discrete spectral line and the wavelength of the spectral lines may be shifted slightly by a change in temperature of the laser. Further, the Raman effect, or the Brillioun effect may be used to shift the wavelength to almost any given value. Potassium or ammonium dihydrogen phosphate crystals may be used to produce frequency doubling. Sum frequencies may also be obtained through the use of gallium arsenide diodes. From this it is evident that coherent light beams may be produced in any given wavelength. Thus, the choice of wavelength, for optimum absorption or scattering in the atmosphere, is not limited by restrictions on the availability of coherent light beams.

Power output: Ruby and glass lasers have been devised that have a very high power output. This pulse consists of a number of irregularly spaced spikes. The duration of the spike is approximately 1 μs. With the use of a Kerr cell, Faraday cell, or rapidly rotating mirror for Q switching, the spiked pulse may be converted into a giant pulse whose duration is a few nanoseconds. This high power, short duration pulse is useful for ranging but not for Doppler measurements. The Q-spoiled laser has not been developed yet to where a reference signal will beat with the return signal, and the pulse duration is so short that the beat frequency associated with low velocities cannot be determined. The CW lasers have adequate stability but up to now are all of relatively low power output. One of the major fields of effort in laser research is the development of higher power CW (continuous wave) lasers. It appears probable that significant progress will be achieved in this effort within the next few years.

Other aspects: The spectral linewidth, spatial and temporal coherence, stability of output, efficienty, useful lifetime, and cost are other areas of special interest for the application of lasers to the problem of measuring atmospheric motion. Considerable progress is being achieved in all of these aspects.

A CW coherent laser beam may be utilized to measure motion at right angles to the axis of the beam. Two types of phenomena may be used. In one case, the laser beam is used to illuminate an interferometer. One mirror of the interferometer is fixed and the object giving the return signal is the other mirror. As the second mirror moves, the fringes in the interferometer system move. The rate at which the fringes move is related to the motion of the second mirror. In the systems studied thus far a corner mirror has been used to give the return signal. The possibility of using a diffuse surface such as a cloud or haze layer as part of the interferometer system has not been discussed in the available literature. The second type of phenomenon seems less likely to lead to a feasible system. This phenomenon is the structure of the coherent light reflected from a diffuse surface. When a beam of coherent light is used to illuminate a diffusely reflecting surface, the reflected light gives the surface a mottled appearance with small spots of increased brightness. As the surface is moved the spots appear to move. This phenomenon has been used to detect relatively slow motion at a distance of the order of a meter.

Summarizing, a Q-spoiled laser appears to offer an excellent opportunity for ranging, or when used with a distant receiver and a frequency shifting device to detect the concentration of the gaseous constituents of the atmosphere. The detection of motion in the atmosphere by using the variation of range of the origin of the return signal would be difficult because of the large size and rate of change of shape of the target. The achievement of an adequate pulse repetition rate also presents a major difficulty. Pulse Doppler laser radar may be a feasible system but power of CW or reference frequency, stability of reference frequency, inherent limitations in accuracy introduced by contradictory pulse length requirements for ranging and Doppler shift, and number of sources of noise all present technological difficulties. The detection of atmospheric motion by using a cloud or haze layer as one mirror in an interferometer system appears to be worthy of further study but probability of ultimate usefulness appears to be low. The use of motion of reflection patterns of coherent light to detect cloud motions is almost certainly not feasible.

1.12 Searchlights and Flash Lamps

Searchlights and flash lamps have been used to detect haze, smoke, and thin cloud layers and for measuring atmospheric density. When used with a distant receiver the ranging and detection sensitivity is probably adequate for altitudes of 20 km. These techniques do not appear practical ones, except for very special cases, for measuring atmospheric motion.

1.13 Passive Techniques

Stellar scintillation, day sky scintillation, twilight, airglow, absorption and emission by non-uniformly distributed trace gaseous constituents, Rayleigh scattering by the gaseous constituents of the atmosphere, photographs of clouds, smoke, haze and other aerosols, resonance scattering, and photographs of atmosphere through light of an absorption or emission band have all been considered in some detail as possible sources of detecting atmospheric motion. Most, if not all of these phenomena may be used under special cases but, at present, it appears that none are general enough to offer a practical system. Perhaps, however, a combination could be utilized to produce useful information. Further study would be required to produce a more definite answer to this problem.

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2.0 ANALYSIS OF WIND SENSOR SYSTEMS

In this section, the errors in a system employing a wind sensor, either a dropsonde or a balloon, are investigated in detail. Three independent sources of error are assumed; an error in the magnitude of the transfer function, an error in the tracking data, and an error due to self-induced motions (which tend to be erratic in nature and which exist even in calm air). The analysis proceeds to the derivation of an error equation relating the overall system error to the variance and spectrum of the component errors. Detailed calculations are limited because of the lack of data on self-induced motions and because a detailed study of tracking errors has not been conducted to date. Tests are underway or planned by other organizations which will aid in defining the nature and magnitude of the self-induced motions. The data available to date are reviewed in a subsection of this analysis.

2.1 Symbols

A	Reference area
B	Force due to buoyancy
$C_1 = \dfrac{B z_b \cos\theta}{\frac{1}{2}\rho V^2 A \ell}$	Coefficient of buoyancy moment
$C_M = \dfrac{M}{\frac{1}{2}\rho V^2 A \ell}$, $C_X = \dfrac{F_X}{\frac{1}{2}\rho V^2 A}$	Typical force and moment coefficients
$C_{D_{d\alpha}} = \dfrac{\partial C_D}{\partial(d\alpha/d\tau)}$	Typical, non-dimensional stability coefficient
D	Drag force
f	Frequency
F	Aerodynamic force measured along body axes
g	Acceleration of gravity
$h = \dfrac{I}{\rho S \ell^3}$, $h_Y = h - \frac{1}{2} C_{M_{d^2\theta}}$	Non-dimensional pitching inertias
H	Transfer function

I	Body inertia in pitching
K	Added mass constant
ℓ	Reference length
L	Lift force
$L_p = \frac{2(m + m_a)}{\rho A C_D}$, $L_x = \frac{2 m_x}{\rho A C_D}$, $L_z = \frac{2 m_z}{\rho A C_D}$	Probe response lengths
L_w	Scale length of turbulence
m	Structural mass plus mass of gas inside wind sensor
m_a	Added mass
$m_x = m(\mu_x/\mu)$, $m_z = m(\mu_z/\mu)$	"Total" masses
M	Pitching moment
$s = i\omega$	Complex frequency
$S = f\ell/V$	Strouhal number
t	Time
V	Body velocity relative to inertial axis
V_a	Body velocity relative to wind axis
w	Inertia body velocity perturbation relative to body Z-axis
W	Wind velocity relative to inertial axis
$W = mg$	Weight of probe
x, y, z	Direction or component along X, Y or Z axes
z_b	Distance from center of gravity to center of buoyancy

$\delta \alpha_x = \frac{-\delta V_{ax}}{V}$	Variation in the angle of attack
$\delta \alpha_z = \frac{\delta V_{az}}{V}$	Non-dimensional variation in V_{az}
$\delta \beta_x = \frac{\delta W_x}{V}$, $\delta \beta_z = \frac{\delta W_z}{V}$	Non-dimensional variations in the winds
$\delta \gamma_x = \frac{\delta V_x}{V}$	Variation in the flight path angle
$\delta \gamma_z = \frac{\delta V_z}{V}$	Non-dimensional variation in V_Z
θ	Pitch angle
$\kappa = \frac{2\pi}{\lambda}$	Wave number
κ_c	Cutoff wave number
λ	Wavelength of wind variation
$\mu = m/\rho S \ell$, $\mu_x = \mu - \frac{1}{2} C_{L_{d\gamma}}$, $\mu_z = \mu + \frac{1}{2} C_{D_{dV}}$	Reduced masses
ν	Kinematic viscosity
ρ	Air density
$\rho_s = m/\nabla$	Wind sensor density
σ	Root-mean-square wind error
σ_I	Wind error due to self-induced motions
σ_V	Tracking errors in velocity
σ_W	Root-mean-square wind velocities
σ_X	Tracking errors in position
τ	Reduced time
Φ, Φ_I, etc.	Error spectrums with root-mean-square values σ, σ_I, etc.
$\omega = 2\pi f \ell / V$	Reduced frequency
∇	Probe volume

2.2 Dynamic Response Functions

The analysis begins by linearizing the equations of motion and deriving the transfer functions which relate the observed motions of a wind sensor to the wind inputs. The greatest errors will usually occur over the minimum altitude interval to be resolved, something less than a hundred meters in wavelength. At these wavelengths the winds tend to have the character of turbulence with "gust" velocities that are small compared to the terminal velocity of the sensor.

The wind sensor will be assumed to be rigid and axially symmetric. Axial symmetry is closely approximated if three or more wings are equally spaced around a body of revolution (Purser and Campbell, 1945). Since the equations of motion will be linearized, only the longitudinal, lateral and pitch degrees of freedom need be considered. Because of symmetry there is no cross coupling between the three degrees of freedom considered and the remaining three degrees of freedom for rigid body motions if it is assumed the sensor is not rolling.

Right-handed body axes are established with the Z-axis pointing downward. The positive directions for velocities, angles, forces and moments are illustrated in Figures 2-1 and 2-2 for a dropsonde. The equations of motion are generated by equating the aerodynamic force to the forces of gravity, buoyancy and inertia. If the body axes are momentarily aligned with the flight path, the equations of motion can be stated as

$$\frac{1}{2}\rho V_a^2 S C_Z + (W-B)\cos\theta - m\frac{dV}{dt} = 0 \qquad (2.1)$$

$$\frac{1}{2}\rho V_a^2 S C_X - (W-B)\sin\theta - mV\frac{d\gamma_x}{dt} = 0 \qquad (2.2)$$

$$\frac{1}{2}\rho V_a^2 S \ell C_{M} + B z_b \sin\theta - I\frac{d^2\theta}{dt^2} = 0 \qquad (2.3)$$

for surging, heaving and pitching about the Z, X and Y axes, respectively, where

1) $\vec{V} = \vec{V_a} + \vec{W}$

2) $\vec{W} \equiv \vec{W}(\vec{x}, t)$

3) $C_Z \equiv C_Z\left[\rho(\vec{x},t),\ \nu(\vec{x},t), \cdots, \theta, V, \frac{d\theta}{dt}, \frac{dV}{dt}, \frac{d^2\theta}{dt^2}, \cdots\right]$

and likewise for C_X and C_M.

The symbols are defined in the list of symbols. $\vec{W}$ is regarded as a forcing function. The solution has the form $\theta(\vec{x}, t), \vec{V}(\vec{x}, t)$

The linear equations of motions are derived by considering small perturbations in the wind inputs which result in small perturbation (δ's) of the other variables. The following approximations can then be made:

$$\delta \frac{d(\ )}{dt} = \frac{d\delta(\ )}{dt}$$

$$\sin(\theta + \delta\theta) = \sin\theta + \delta\theta \cos\theta$$

$$\cos(\theta + \delta\theta) = \cos\theta - \delta\theta \sin\theta$$

In deriving the linearized equations of motion, ρ is treated as a constant. At the shorter wavelengths, which are of primary interest, the variations due to air density are small. For example, ρ varies less than 2% over a 100 m interval in altitude.

The assumption of axial symmetry leads to still another simplification; namely, the steady state lift and pitching moment are zero (no sideways gliding in calm air). The perturbation in the aerodynamic forces along the body axes can then be related to those along the "Wind" axes by the equations

$$\delta C_Z = -\delta C_D$$

$$\delta C_X = -\delta C_L - C_D \delta\alpha_X$$

Finally, by substituting the unperturbed equations for stable motion into the perturbed equations and by making use of the approximations and assumptions discussed above, a set of linear equations can be derived.

$$\frac{1}{2}\rho V_a^2 A \delta C_D + \rho V A C_D \delta V_a + m \frac{d\delta V}{dt} = 0 \qquad (2.4)$$

$$\frac{1}{2}\rho V_a^2 A \delta C_L + \frac{1}{2}\rho V^2 A C_D \delta\alpha_X - \frac{1}{2}\rho V^2 A C_D \delta\varepsilon - mV\frac{d\delta\gamma_X}{dt} = 0 \qquad (2.5)$$

$$\frac{1}{2}\rho V_a^2 A \ell \delta C_M + \frac{1}{2}\rho V_a^2 A \ell C_B \delta\theta - I \frac{d^2\delta\theta}{dt^2} = 0 \qquad (2.6)$$

The equations above were derived for a dropsonde, but they are applicable to a balloon without change. The original set of equations, numbers 2.1 through 2.3, would have required a reversal of sign in the weight and buoyant terms.

The aerodynamic forces are assumed to vary as

$$\delta C_D = C_{D_{dV}} \frac{d\delta\gamma_z}{d\tau} + C_{D_{d\beta}} \frac{d\delta\beta_z}{d\tau} \tag{2.7}$$

$$\delta C_L = C_{L_\alpha}\delta\alpha + C_{L_{d\theta}}\frac{d\delta\theta}{d\tau} + C_{L_{d\gamma}}\frac{d\delta\gamma_x}{d\tau} + C_{L_{d\beta}}\frac{d\delta\beta_x}{d\tau} + C_{L_{d^2\theta}}\frac{d^2\theta}{d\tau^2} \tag{2.8}$$

$$\delta C_M = C_{M_\alpha}\delta\alpha + C_{M_{d\theta}}\frac{d\delta\theta}{d\tau} + C_{M_{d\gamma}}\frac{d\delta\gamma_x}{d\tau} + C_{M_{d\beta}}\frac{d\delta\beta_x}{d\tau} + C_{M_{d^2\theta}}\frac{d^2\theta}{d\tau^2} \tag{2.9}$$

Non-dimensional notation was employed. C_{L_α} and C_{M_α} are the static derivatives, $C_{D_{dV}}, C_{L_{d\theta}}, C_{L_{d\gamma}}, C_{L_{d^2\theta}}, C_{M_{d\theta}}, C_{M_{d\gamma}}$ and $C_{M_{d^2\theta}}$ include the added mass derivatives as discussed by Imlay (1961), and $C_{D_{d\beta}}, C_{L_{d\theta}}, C_{L_{d\beta}}, C_{M_{d\theta}}$ and $C_{M_{d\beta}}$ include the dynamic derivatives. A number of the derivatives can be eliminated by the consideration of symmetry.

The stability derivatives are treated as constants, an assumption whose accuracy depends on the value of the reduced frequency ω. Since $\omega = \frac{2\pi f \ell}{V}$ and $V = f\lambda$, the reduced frequency can be restated as $\omega = \frac{2\pi\ell}{\lambda} = K\ell$. If ℓ is say one meter and the minimum wavelength of interest is say 25 m, ω is a maximum of 0.25. Wings are entering the flutter regime at this value and the derivatives may begin to become frequency dependent. This conclusion is independent of the terminal velocity.

Reynolds and Mach number variations are usually small and will not affect the assumption that the stability derivatives are constant over the small altitude intervals of interest (although they may vary significantly over large intervals of altitude). Reynolds number variations are difficult to formulate and are related to the self-induced motions to be discussed in a later section.

The relatively low frequencies allow the simplification

$$C_{L_{d\theta}} = -C_{L_{d\beta}} \quad \text{and} \quad C_{M_{d\theta}} = -C_{M_{d\beta}} \tag{2.10}$$

as pointed out by Lee (1958). The aerodynamic effect of a pitch rate is a linear variation in the lateral velocities over the length of the body which is the same magnitude but reversed in direction from that due to a constant wind shear.

Again the ratio l/λ must not be too large or the wind shear can not be assumed to be constant over the length of the body.

To proceed further, the kinematic conditions must be linearized. In non-dimensional notation the equations become

$$\delta \gamma_x = \delta \beta_x - \delta \alpha_x + \delta \theta \quad (2.11)$$

$$\delta \gamma_z = \delta \beta_z + \delta \alpha_z \quad (2.12)$$

for a right-handed axis system as illustrated in Figure 2-1. The desired form for the equations of motion are derived by non-dimensionalizing equations 2.4 through 2.6, substituting in equations 2.7 through 2.12 and substituting a solution of the form $\delta \beta_x = \beta_x e^{s\tau}$ etc. They are

$$[2C_D + (C_{D_{dV}} + 2\mu)s]\gamma_z = [2C_D - C_{D_{d\beta}} s]\beta_z \quad (2.13)$$

$$[C_{L_\alpha} + C_{L_{d\theta}} s + C_{L_{d^2\theta}} s^2]\theta + [-(C_{L_\alpha} + C_D) + (C_{L_{d\gamma}} - 2\mu)s]\gamma_x = [-(C_{L_\alpha} + C_D) + C_{L_{d\theta}} s]\beta_x \quad (2.14)$$

$$[(C_{M_\alpha} + C_B) + C_{M_{d\theta}} s + (C_{M_{d^2\theta}} - 2h)s^2]\theta + [-C_{M_\alpha} + C_{M_{d\gamma}} s]\gamma_x = [-C_{M_\alpha} + C_{M_{d\theta}} s]\beta_x \quad (2.15)$$

The above equations are in the frequency domain instead of the time domain. A constant wind shear, for example, corresponds to a spectrum of sinusoidal components with amplitudes that vary as the inverse of the frequency squared.

The linear equations of motion can be compared with those obtained by Lee (1958), Jex and Tennant (1964), and Stengel (1965). It is found that certain terms are retained in one analysis and dropped in another, but each set of equations served the purposes of their respective authors satisfactorily. It should be realized that the stability derivatives can be defined differently. As an example, the static derivatives of C_L can be established by expanding δC_L as

$$\delta C_L = C_{L_\alpha} \delta \alpha_x$$

or

$$\delta C_L = C_{L_W} \delta W + C_{L_\beta} \delta \beta_x$$

By employing the kinematic relation $\delta W = \delta \alpha_x - \delta \beta_x$ and equating coefficients, the relations $C_{L\alpha} = C_{LW} = C_{L\beta}$ are obtained which are typical of relations which can be developed.

At this point in the development, it is appropriate to mention other schemes for measuring winds and wind shears which have been suggested. A number of the suggestions can be classified as the multiple sensor types. Some sort of ranging instrumentation is conceived which measures the wind shear "directly" by measuring the horizontal and vertical motion between several wind sensors. It is difficult to understand how two probes will respond better than one and such schemes add to the complexity of a wind measuring system.

Other schemes come under the classification of weathervaning. Again it is suggested the wind shear could be measured directly by some sort of measurement of the weathervaning angle θ. One version would employ a long sausage-shaped balloon that weathervanes in response to the average wind shear. The transfer function of interest is $\frac{\theta}{\beta_x S}$. This transfer function might not "drop off" until higher frequencies are reached compared to the transfer function $\frac{\gamma_x}{\beta_x}$ which relates wind shear with the trajectory data. Unfortunately, the measurement of the pitch angle is difficult for a passive target. The angle could be measured with "on board" instruments, but then the approach is similar to the wind shear probe concept (Aviation Week, 1965) for which accelerometers rather than pitch rate gyros appear to be more appropriate.

The transfer functions of interest can now be examined. Without further simplification, the following functions can be derived from equations 2.13 through 2.15.

$$\frac{\gamma_z}{\beta_x} = 0 \qquad (2.16)$$

$$\frac{\gamma_x}{\beta_z} = 0 \qquad (2.17)$$

$$\frac{\gamma_z}{\beta_z} = \frac{1 - C_{D_{d\beta}} S / 2 C_D}{1 + \mu_z S / C_D} \qquad (2.18)$$

where

$$\mu_z = \mu + \frac{1}{2} C_{D_{dV}}$$

The γ 's are obtained from the trajectory data and the β 's are the unknown wind inputs. The "cross talk" derivatives γ_z/β_x and γ_x/β_z are zero because of axial symmetry which decouples the drag equation from the lift and moment equations.

A simple form also exists for the horizontal wind transfer function if the "tuning condition" is met (Stengel, 1965 and Lees, 1958). The condition is equivalent to stating that there is no variation in the angle of pitch. Equations 2.14 and 2.15 indicate

$$\begin{aligned}(2\mu_x + C_{L_{d\theta}})\, C_{M_\alpha} &= (C_{L_\alpha} + C_D)(C_{M_{d\theta}} - C_{M_{d\gamma}}) \\ 2\mu_x C_{M_{d\theta}} &= -\, C_{L_{d\theta}} C_{M_{d\gamma}}\end{aligned} \qquad (2.19)$$

when the condition is met, where

$$\mu_x = \mu + \frac{1}{2} C_{L_{d\gamma}}$$

The horizontal transfer function then becomes

$$\frac{\gamma_x}{\beta_x} = \frac{1 - \dfrac{C_{L_{d\theta}}\, s/C_D}{C_{L_\alpha}/C_D + 1}}{1 + \dfrac{2\mu_x\, s/C_D}{C_{L_\alpha}/C_D + 1}} \qquad (2.20)$$

The condition of equation 2.19 can only be met at one altitude and hence equation 2.20 is of limited interest. Equation 2.1 will yield the ratio

$$\frac{\mu}{C_D} = \frac{V^2}{g\ell}$$

found in equation 2.20 for stable motion if buoyancy and added mass ($C_{L_{d\gamma}} = 0$) are neglected. The equation is plotted in Figure 2-3 for $C_{L_\alpha}/C_D = 4$, a modest value as might be obtained with low aspect ratio wing, for $V^2/g\ell = 10$, and for $C_{L_{d\theta}} = 0$. Even allowing for the simplifying assumptions, the figure readily demonstrates the beneficial effect of wings. A much more detailed evaluation of lifting sensors has been completed recently by Stengel (1965) which indicates a much greater degree of response can be obtained (to horizontal winds only) especially at lower altitudes. Some difficulty is experienced at extreme altitudes in a dropsonde configuration because the terminal velocities are high. (The variations in the terminal velocities would be much less for a balloon.)

For a non-lifting sensor, equation 2.20 can be simplfied, dimensionalized and transformed to the time domain to yield

$$\delta W_x = \left(1 + L_x \frac{d}{dZ}\right) \delta V_x \tag{2.21}$$

where the relation

$$\frac{d\delta V_x}{dZ} = V \frac{d\delta V_x}{dt}$$

was employed. The response length is defined as

$$L_x = \frac{2 m_x}{\rho S C_D} \tag{2.22}$$

which is the same as Reed's (1963) definition if the configuration is a sphere. Note that equation 2.18 for the response to vertical winds has a response length half of that given above for horizontal winds ($I_f \, C_{D_{d\beta}} \cong 0$). As a result, one can say a sphere is twice as responsive to vertical winds as it is to horizontal winds, provided the wind velocities relative to the balloon are small compared to the rising or falling velocity.

2.3 The Error Equations

The errors in a wind sensor system can be described now that the response functions have been examined. The general form for a linear response function is

$$V = HW \tag{2.23}$$

where $W \equiv W(\mathcal{K})$, $H \equiv H(\mathcal{K})$, and $V \equiv V(\mathcal{K})$ are the wind speed, the transfer function and the wind sensor velocity, respectively, and $\mathcal{K}$ is the wave number. An error equation can be derived from equation 2.23 as

$$\Delta W = -W\frac{\Delta H}{H} + \frac{\Delta V}{H} + \frac{\Delta V_I}{H} \tag{2.24}$$

for small errors where the term $\Delta V_I/H$ was added. This term accounts for the self-induced motions which cannot be described with a transfer function.

Every system has a high frequency limit, either intentional or unintentional, above which there are no variations in the data output. This frequency is termed the cutoff frequency. Squaring equation 2.24, going over to the continuous case and integrating from zero to the wave number determined by the cutoff frequency, yields

$$\sigma^2 = \int_0^{K_c} \Phi_W \left(\frac{\Delta H}{H}\right)^2 dK + \int_0^{K_c} \frac{\Phi_V}{H^2}\, dK + \int_0^{K_c} \frac{\Phi_I}{H^2}\, dK \qquad (2.25)$$

in spectrum notation for the mean-square error. Note the stating of a cutoff frequency is equivalent to stating a vertical resolution in height since $2\pi f_c = 2\pi V/\lambda_c = K_c V$ where λ_c would be the vertical resolution interval.

The integrals which contained the products of errors were dropped as the errors ΔV, ΔH and ΔV_I are assumed to be independent.

The calculations to follow are for a non-lifting sensor. It will be apparent, however, that the general conclusions from this study are applicable to lifting sensors. A non-lifting sensor can be described in terms of its response length, equation 2.22, which can be rewritten as

$$L_F = \frac{2\nabla}{A C_D}\left(\frac{\rho_s}{\rho} + K\right) \qquad (2.26)$$

The added mass is taken as a constant k times the mass of the fluid, $\rho\nabla$, displaced by the sensor as suggested by the application of potential flow theory to ellipsoids (Lamb, 1932, pp 152-155). Since separation occurs over most of the aft surface of bluff bodies, the theoretical values without separation must be treated with reservation for spheres, etc. It is suspected the theoretical values for k are too large when no attempt is made to account for separation.

The drag equation, equation 2.1, for stable motion can be used to reformulate L. The drag equation can be rewritten as

$$\frac{V^2}{g} = \frac{2\nabla}{A C_D}\left|\frac{\rho_s}{\rho} - 1\right| \qquad (2.27)$$

Substituting equation 2.27 into equation 2.26 yields

$$L_P = \frac{V^2}{g} \frac{(\rho_s/\rho + K)}{|\rho_s/\rho - 1|} \qquad (2.28)$$

Note the heavy dependence on velocity. The minimum response length is obtained when the wind sensor is filled with hydrogen, rather than helium, a heavier gas. Equation 2.26 give values for L of about 4 m at sea level and 10 m at the floating altitude for a two meter spherical balloon filled with hydrogen and with k = 1/2 and C_D = 0.4.

Assume the response error is a constant of the form $\Delta L_p/L_p$. This error may be related to the error in the transfer function by employing equation 2.21 which leads to the complex transfer function

$$1/H = 1 + i K L_p$$

having the magnitude

$$\sqrt{1 + (K L_p)^2} = 1/H \qquad (2.29)$$

where the magnitude symbol for H was dropped. For small errors,

$$\frac{\Delta H}{H} = \frac{\Delta L_p}{L_p} \frac{(K L_p)^2}{1 + (K L_p)^2} \qquad (2.30)$$

ΔH has the desirable characteristic of vanishing at very low ($K \rightarrow 0$) and very high wave numbers ($H \rightarrow 0$).

A knowledge of the small scale wind variations is desirable. The vertical turbulence measured by horizontally moving aircraft is assumed equal to the fine scale horizontal winds measured by vertically moving wind sensors. This assumption of isotropy has been shown to be reasonable for the wavelengths of interest. Houbolt, et. al. (1964) indicates the vertical spectrum can be approximated by

$$\frac{\Phi_W(K)}{\sigma_W^2} = \frac{L_W}{\pi} \frac{1 + \frac{8}{3}(1.339 K L_W)^2}{[1 + (1.339 K L_W)^2]^{11/6}} \qquad (2.31)$$

where

$$\sigma_w^2 = \int_0^\infty \Phi_w(\kappa)\, d\kappa$$

The function was multiplied by κ before it was plotted on semi-log paper in Figure 2-4 in order that the area under the curve be proportional to the integral. A value for L_w of 300 m was chosen.

A description of the tracking errors is also desired. The error of a tracking device is often quoted as a position error but it is convertible to a velocity error by the relation

$$\Phi_V = (\kappa V)^2\, \Phi_X \tag{2.32}$$

This formulation is easily derived by differentiating the position error to obtain

$$\frac{d(|\Delta X| e^{i2\pi f t})}{dt} = |\Delta X|\, i\kappa V e^{i\kappa V t} = |\Delta V|\, i\, e^{i\kappa V t}$$

from which the desired relation follows easily. The spectrum of the position error remains unknown, however, pending a detailed study of ranging errors. At that time, the variance and the spectrum of the propagation error, the inherent limit of any electromagnetic ranging device, should be investigated. Until then a reasonable assumption is that white noise exists, meaning Φ_X is constant.

To evaluate the first term in equation 2.25, equations 2.30 and 2.31 are employed, and $\Delta L_p/L_p$ and L_p are assumed to be 20% and 25 m. A 20% error is thought to be representative, but the value for L is large, hence conservative, compared to the values from 4 to 10 m found above for a two meter balloon. (This size balloon is commonly employed in high resolution wind measurements.) The spectrum of the first term is plotted in Figure 2-4. Integration of the error spectrum down to a height resolution of only ten meters yields a value of only 0.0034. Press (1957) indicates the probability of exceeding σ_w = 3 m/s is roughly one in a thousand. For this value the first term contributes only $3 \times \sqrt{0.0037} = 0.18$ m/s, a very small value.

The second term of equation 2.34 is evaluated by substituting in equations 2.29 and 2.32 and the white noise assumption. The result is

$$\int_0^{\kappa_c} [1 + (\kappa L)^2](\kappa V)^2\, \Phi_X\, d\kappa = \left[\frac{\kappa_c^3 V^2}{3} + \frac{\kappa_c^5 V^2 L^2}{5}\right] \Phi_X \tag{2.33}$$

where

$$\sigma_X^2 = \Phi_X\, \kappa_c$$

For a numerical example, take a two meter sphere with V = 8 m/s and L an average of 7 m. The term then contributes 3.8 σ_x^2 to the mean-square error if $\lambda_c = \frac{2\pi}{\lambda_c}$ = 25 m. The root-mean-square value of say 0.2 m/s would require the tracking root-mean-square errors be less than 0.1 m, a small value. Even if the wind sensor had instant response, the tracking error would have to be less than 0.17 m. High performance, single station, tracking radars such as the FPS-16 radar have minimum errors of a fraction of a meter per second with higher errors at long ranges. The above discussion suggests multistation radars such as a set of three Doppler radars because of the greatly reduced errors possible. A quantitative evaluation of the benefits to be derived must await a detailed study of ranging errors.

The evaluation of the last term in equation 2.25 is not attempted at this time. The tests reported to date do not provide sufficient data to describe the variance and the spectrum of the induced motions for a variety of Reynolds number. The spectrum is important, but only "hints" of the spectrum shape are available in the literature. What is available is described in the next section.

Before continuing, it is well to point out that other data processing techniques beyond the use of the equations of motion and digital filtering, as discussed herein, may reduce the errors. For example, the propagation error in radar could probably be reduced by a greater refinement of the index of refraction correction. Also it may be possible to remove the spectrum of the self-induced motions from the total spectrum due to wind and self-induced motions.

2.4 Self-Induced Motions

Self-induced motions appear to be due to the shedding of vortices. The shedding of a vortex street from a two-dimensional bluff body is a well known phenomena. Vortices detach themselves alternately from the sides of a cylinder in a regular manner beginning at Reynolds numbers of less than 100. At Reynolds numbers above 1000 the Strouhal number remains constant at 0.21 (Schlichting, 1960, p31). Vortices continue to be shed with unfailing regularity as the Reynolds number is increased until the flow becomes turbulent (Goldstein, 1938, p557). The flow behind a bluff body of revolution behaves in much the same way. Goldstein (1938, p579) states that no systematic investigation of the periodicity in the wake of three-dimensional bodies appears to have been made but Winny (1932) gives enough data for a sphere to indicate the main fluctuations occur at a Strouhal number of roughly 0.2. Since the Strouhal number $S = f\ell/V$ and $V = f\lambda$, then $S = \ell/\lambda$. f is the frequency, V the velocity, λ the wavelength and ℓ the diameter. A diameter-to-wavelength ratio of 1/5 is in the neighborhood of those observed by MacCready and Jex (1964) in their swimming pool tests. At subcritical Reynolds numbers they observed somewhat regular zigzags or spirals with a wavelength of the order of 12 diameters.

MacCready and Jex (1964) measured the amplitude of the self-induced motions and found the data would roughly fit the relationship

$$\frac{x_{max}}{\lambda/2} = \frac{0.37}{1 + 2\rho_s/\rho}$$

at subcritical Reynolds number where x_{max} is the double amplitude and ρ_s/ρ is the ratio of sphere density to fluid density. They derived the form of the equation by considering the spheres to be subject to impulses alternating in direction at regular intervals. Since the relation equals the ratio of lateral-to-vertical velocities, it indicates the self-induced horizontal velocities can be 40% of the vertical velocities for a smooth sphere.

At supercritical Reynolds numbers the self-induced motions were described as meandering spirals by MacCready and Jex (1964). Murrow and Henry give data for six runs with two meter smooth balloons released in a large hangar. The root-mean-square horizontal velocities averaged about 50% of the terminal velocities. Scoggins (1964) compared smooth spherical balloons and smoke trails to obtain spectra of the self-induced motions. These peak at a wavelength-to-diameter ratio of 100 in comparison to values the order of 12 for subcritical motion as discussed in a preceding paragraph.

The addition of small roughness elements was demonstrated by Murrow and Henry (1964) to have little effect at supercritical Reynolds numbers. Small roughness elements imbedded in the boundary layer might trip a laminar boundary layer into a turbulent condition, but the test Reynolds numbers were supercritical and turbulent separation had already occurred. It can be reasoned that large roughness elements, in contrast, should have an effect. One might suppose smaller vortices would be shed at higher frequencies because of the projections, compared to the vortices shed by a smooth sphere. Both Murrow and Henry (1964) and Scoggins (1964) demonstrate the amplitude can be reduced considerably by large roughness elements which suggest this line of reasoning may be correct. Conversations with Scoggins indicate the addition of a large number of elements of the proper design has reduced the self-induced motions to the point where they can no longer be observed with the FPS-16 radar. The present Jimsphere balloon configuration also has a weight to off-balance the center of gravity and discourage rotation.

A theory for self-induced motions is difficult because of the complex interaction between the boundary layer, the wake and the flow field, and reliance must be placed on tests. No tests have been conducted, however, on streamlined bodies, bodies with wings, or shapes with cutoff bases and trailing edges. It would appear the motions due to the shedding of vortices could be reduced by a sharp edge which would promote a stable line of separation and by having the separation occur at the rear of the body. This line of reasoning is only conjecture, however, until tests are completed.

2.5 Conclusions

1. The foregoing discussion of the three independent sources of errors leads to the following conclusions:

   a) The self-induced motions for a smooth, lightweight sphere are large. Tests still underway indicate these motions can be reduced to a root-mean-square value of a fraction of a meter per second by the addition of large roughness elements. Tests should be conducted on a variety of configurations to determine the spectrum as well as the variance of the motions.

   b) The wind error due to an error in the magnitude of the transfer function is usually small compared to the other two types of errors.

   c) A study should be conducted to investigate in detail the variance and the spectrum of the errors due to ranging. The root-mean-square error of an FPS-16 radar appears to be small, however, being only a fraction of a meter per second for a vertical resolution of 25 m at moderate ranges.

The overall error for a spherical balloon and FPS-16 radar system is a fraction of a meter per second for a vertical resolution of 25 m at moderate ranges. The error can be reduced even further by improved balloon configurations, improved data processing techniques and the use of multistation radar systems.

2. Unless the self-induced motions of a streamlined, fast-rising balloon are significantly less than those for spheres, the errors in a high resolution wind measuring system will increase if this type of balloon is employed.
3. A lifting wind sensor may reduce the errors in measuring the horizontal winds but probably will not change the errors in measuring the vertical winds.
4. A balloon has an advantage over a dropsonde in that the variation in the terminal velocity is less and greater response is possible at extreme altitudes.
5. Accelerometers can be installed in a wind sensor to obtain the fine scale trajectory data. Such an approach requires a carefully theoretical and experimental evaluation of the transfer functions, but there appears to be no reason why the errors in the trajectory data could not be reduced to a very low value. Nevertheless, this approach is limited by the weight, cost and complexity of the precision instrumentation required.
6. A sphere is twice as responsive to vertical winds as it is to the horizontal winds if the wind velocities are small compared to the terminal velocity.

2.6 References

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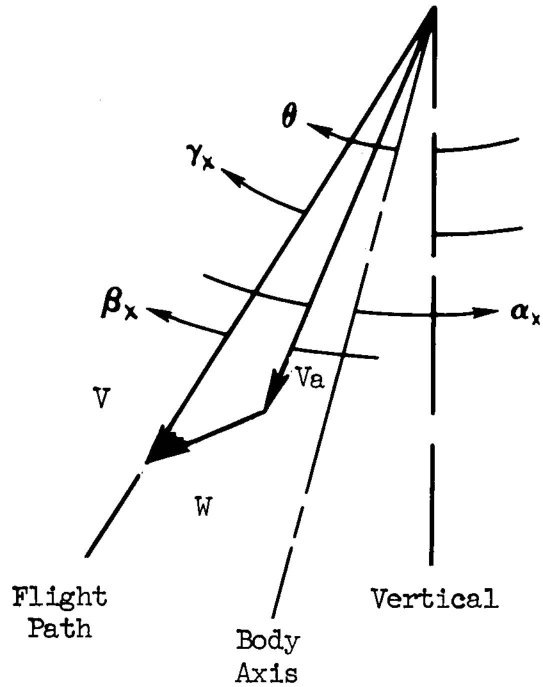

FIGURE 2-1 - POSITIVE DIRECTIONS FOR VELOCITIES AND ANGLES

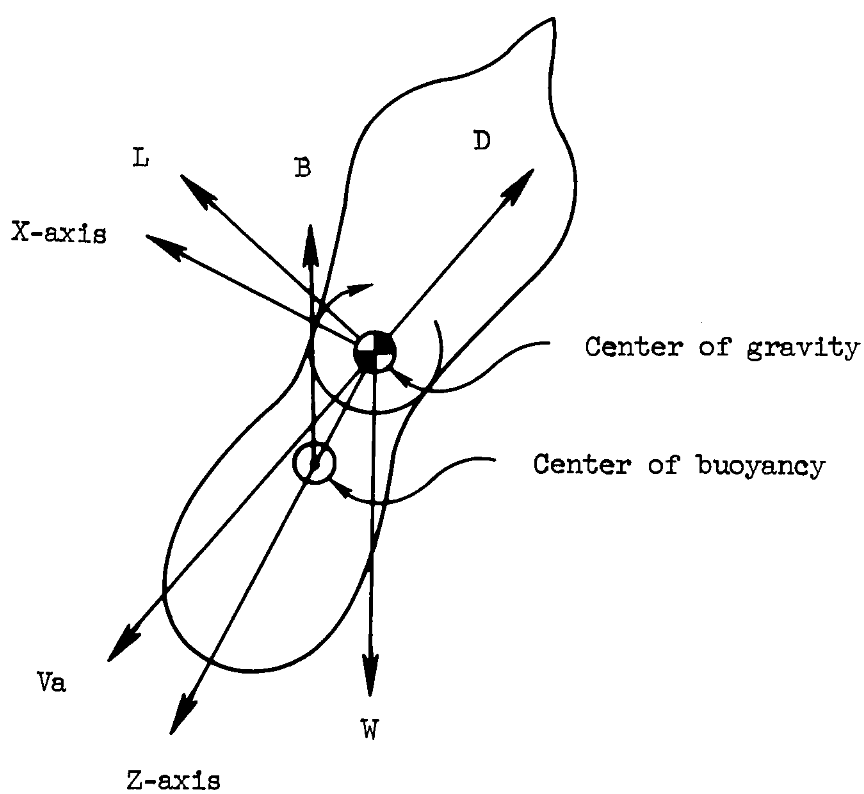

FIGURE 2-2 - POSITIVE DIRECTIONS FOR FORCES AND MOMENTS

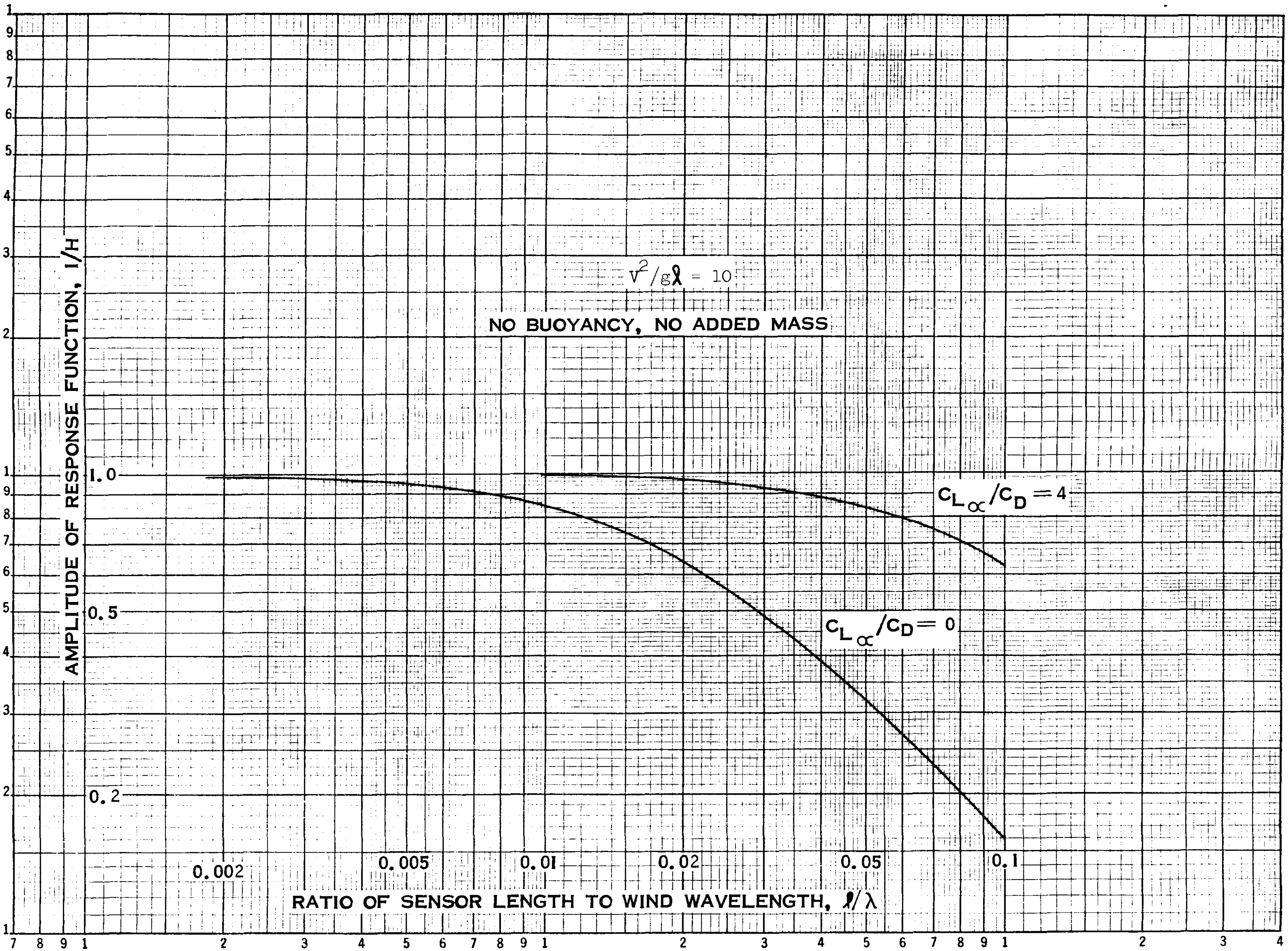

FIGURE 2-3 - SENSOR RESPONSE TO HORIZONTAL WINDS

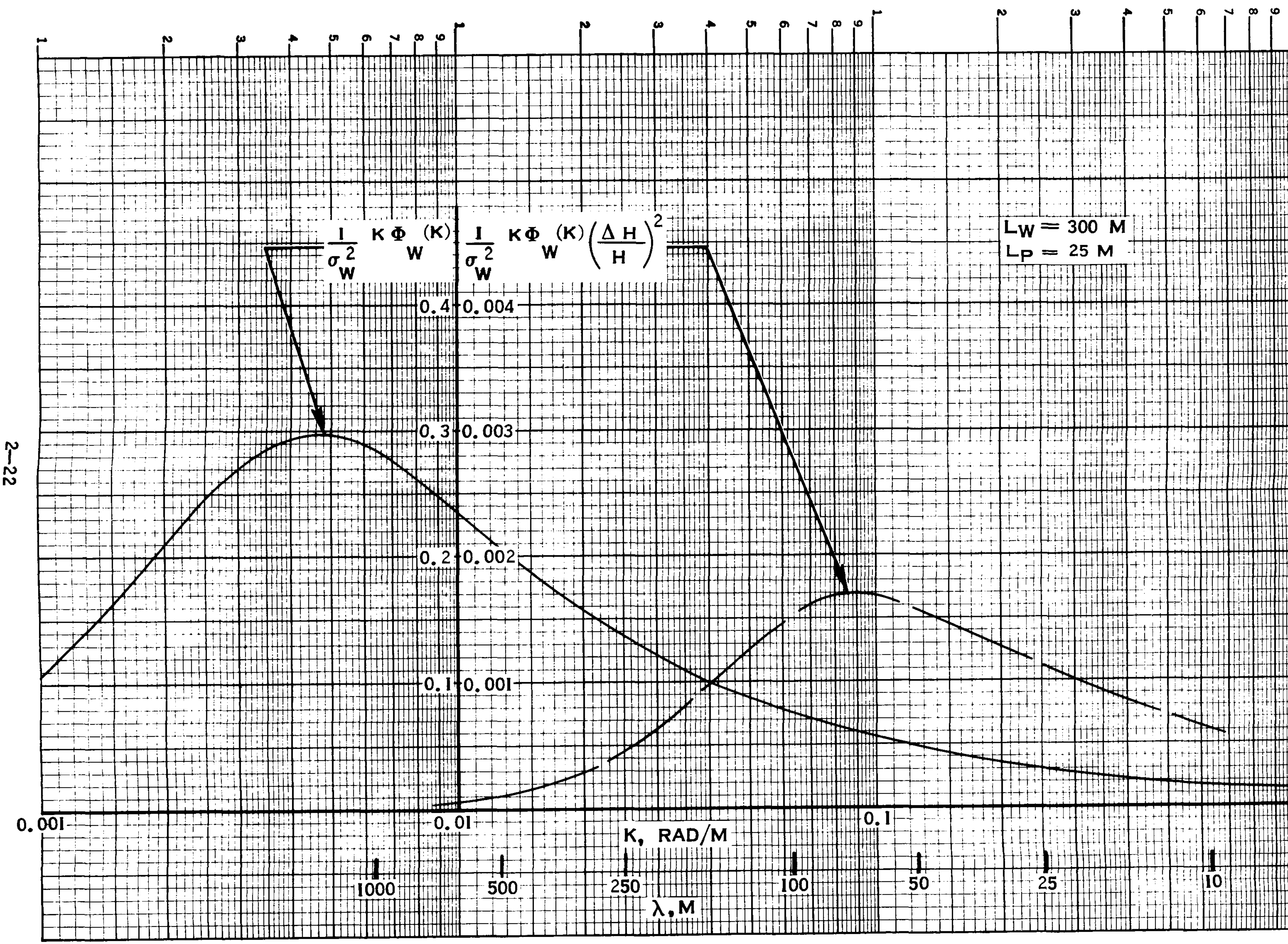

FIGURE 2—4 — SENSOR RESPONSE ERROR

3.0 ANALYSIS OF SONIC SYSTEMS

A variety of sonic systems and schemes have been conceived for measuring the winds aloft. The various possibilities were discussed in the Phase I report (Conner, Hildreth and Baer, 1964). Of these, only one system will be considered in this study as the others lack sufficient promise. The system of interest employs a sonic source (transmitter) in either a rising or falling probe and a microphone array (receiver) on the ground. The scheme can be thought of as a low altitude version of the rocket-grenade experiment (Weisner 1956, Groves 1956a, Otterman 1958) where a source capable of generating sine waves or pulses at a rapid rate is employed instead of grenades in the interest of obtaining greater vertical resolution. This method utilizes the trajectory of the sonic source and the travel time of the acoustical pulse and the attitude of the wavefronts at the microphones to calculate the mean wind in a layer.

3.1 Trajectory Determination

To find the mean winds, the space-time coordinates of each part of the acoustic wave must be established when the signal is transmitted and when it is received. The most obvious way of generating the aerial data is to use radar to determine the trajectory and telemetering to indicate the time of emission of each wavefront. It is apparent that modulation is required if the received phases are to be identified with the transmitted phases. The modulation could be accomplished by varying the amplitude of the source slowly or by turning the source on and off in a digital code.

To examine the radar accuracies required, one must first find the response length of the probe for vertical motions. (The horizontal motions are of secondary importance.) The desired relation for the response length is

$$L_z = V^2/2g \tag{3.1}$$

for a dense probe, the response length being the altitude required for a (1-1/e) response to a step input in the vertical winds. V is the vertical velocity and g the acceleration of gravity. The equation above is one half of equation 2.28 for a dense object where equation 2.28 gives the response length for horizontal inputs. It can be derived from equation 2.18 in the same manner as equation 2.28 was derived from equation 2.20 if $C_{D_{d\beta}}$ = 0. This derivative can be ignored since the probe is dense (μ_z is large) and the first order term in the denominator of equation 2.18 dominates over the first order term in the numerator.

To describe the trajectory errors, only the first term of equation 2.33 is employed as reproduced below

$$\sigma_{V_z}^2 = \frac{\kappa_c^2 V^2}{3} \sigma_z^2 \tag{3.2}$$

where

$$\sigma_z^2 = \Phi_z \kappa_c \tag{3.3}$$

The radar position error is σ_z and $\kappa_c = \frac{2\pi}{\lambda_c}$ where λ_c is the vertical resolution interval. The second term of equation 2.33 does not exist if only the trajectory errors are considered and not the errors in determining the input winds. Suppose V = 100 m/s. Then L_z = 500 m from equation 3.1 and a cutoff wavelength of 500 m is appropriate. Substituting these values in the equation above yields σ_z = 0.28 for a 0.2 m/s velocity error at a resolution of 500 m. A 0.2 m/s resolution in probe velocity is appropriate if a 0.2 m/s resolution is desired in the wind data. Equation 3.3 indicates an error of 0.28 m at a resolution of 500 m is equivalent to an error of 1.4 m at a wavelength of 20 m, the minimum resolution possible if the tracking data are produced at 10 data points per second. From the above numbers, it appears the requirement for tracking accuracy is stiff. However, not too large a relaxation in the velocity error requirement and an increase in the probe velocity to a larger fraction of the speed of sound will permit the employment of an FPS-16 precision radar, which is common to the nation's missile ranges.

3.2 Sonic Source Strength Requirements

The problem involved in a sonic system is to select practical characteristics for the transmitter and the receiver suitable for signaling from 20 km altitude. The computations made so far do not take into account the effect of scattering and reduced pressure at altitude on propagation loss. It is considered, however, that these effects, while not entirely negligible, are not of primary significance.

The passive equation for sound intensity may be stated in the following way:

$$L_{s/n} = L_s - N_w - L_n + N_{di} \tag{3.4}$$

where

$L_{s/n}$ is the signal differential, i.e., the difference in levels of the signal and of the interference as they exist in the receiving system,

L_s is the index level of the signal on the bearing of the receiving point,

L_n is the equivalent plane wave level of the interfering noise at the receiving point,

N_w is the propagation loss between the signal source and the receiving point, and

N_{di} is the directivity index of the receiver.

All of these terms are expressed in decibels and, of course, consistent reference quantities must be used.

For an illustrative calculation, let $L_{s/n} = 10$ dB , $N_{di} = 10$ dB , $L_n = 20$ dB T, and $L_s = 150$ dB T at 1 m (d BT = dB re 0.0002 microbar). Since $N_w = L_s - L_n + N_{di} - L_{s/n}$ then $N_w = 150 - 20 + 10 - 10 = 130$ d B .

This value must now be translated into an allowable upper limit on frequency. Assuming a non-directional source, spherical spreading loss is 86 dB . The remainder of the allowable transmission loss is, then, (130 - 86) dB or 44 dB. At some frequency the dissipation of sound in the atmosphere over a 20 km path nominally will be 44 dB; i.e., the dissipation coefficient will be 44/20,000 dB/m or 0.0022 dB/m approximately. The corresponding frequency is approximately 1000 cps according to the Kneser Nomogram for molecular absorption when the values 15°C in temperature and 50% in relative humidity are assumed. Any additional loss due to scattering is not accounted for in this calculation. Such loss might well be highly variable but not necessarily large for all meteorological conditions. An attempt was made to find relevant data on scattering in the technical literature, but such data apparently are readily available only for higher frequencies and essentially ground level altitudes. Similarly, effects of reduced pressures at high altitudes have not yet been accounted for since such data seem sparse.

The assumptions of $L_{s/n}$ = 10 dB and L_n = 20 dBT require some discussion. A signal-to-noise ratio of 10 dB is quite marginal and an interference level of 20 dBT at 1000 cps in a narrow band implies a rather quiet but not impossible microphone location. The frequency bandwidth of the microphone is assumed to be 100 cps. These values were assumed for trial in an attempt to meet certain other restrictions such as those on source level and receiver directivity.

Source levels greater than 150 dBT are not commonly found in small packages but diligent search or some development might accomplish this demand. For example, a 120 lb commercial siren supplied by a 5 hp compressor and rotor driven by a 1.5 hp motor has yielded levels just in excess of this magnitude in the vicinity of 5 kcps. Also, Hartmann generators (whistlers) have yielded levels in this vicinity although at somewhat higher frequencies apparently.

The assumption of N_{di} = 10 dB involves, of course, a receiving system having directional properties, thus implying an extended area system. A straightforward technique for achieving such directionality is by use of mirrors. For 10 dB directivity index the size of these mirrors would be practical. Line arrays with appropriate electrical delay lines could also be used.

The above illustrative computation is one of several carried out and it has been selected as perhaps the best point of departure at this stage of the investigation. If one seeks to relax one of the terms of the basic equation the result is, of course, that the deficit must be paid for in another term or terms. For example, relaxing the 150 dBT source level assumption alone leads to a lower allowable transmission loss which, in turn, implies a lower frequency; but a lower frequency demands, in general, larger component sizes and increased weight.

3.3 Errors

In order to determine the attitude of the wavefront and the wavespeed, at least four different microphones are needed (Groves 1956b). However, more microphones may be desirable. It will be shown that the time resolution required decreases with increasing distance between microphones. The number of microphones and the optimum array has yet to be determined but it is expected to be based on the resolution attainable by the overall system and the analytical method adopted. The analytical method in turn is expected to be based on the resolution ability of the acoustic system. It is anticipated that, in addition to the signal-to-noise aspects of the system, the effect of turbulence will be of importance in causing phase shifts and signal deformation which will decrease the precision and accuracy of the overall system.

An approximation of the accuracies required for a sonic system can be established from equations 6 through 9 of Weisner's work (1956). For a two-dimensional space, these equations reduce and combine to

$$W(t_2 - t_F) = Z_2 \cot \theta_2' - (t_F/t_1) Z_1 \cot \theta_1' \tag{3.5}$$

where

W is the wind velocity,

Z is the altitude,

θ' is the elevation of the wavefronts at the receiver, and

t is the time of the phase emission (grenade explosions).

1 and 2 are subscripts denoting phases emitted at the boundaries of the altitude interval of interest. The ratio t_F/t_1 will be assumed to be unity as Weisner indicates this ratio varies less than 5% from that value.

Next substitute $Z_2 = Z_1 + \Delta Z$ and $\theta_2' = \theta_1' + \Delta \theta'$ and consider $\Delta Z \ll Z_1$ and $\Delta \theta' \ll \theta_1'$. The above equation then reads

$$W \Delta t = \Delta Z \cot \theta' - Z \Delta \theta' \tag{3.6}$$

where $\Delta t = t_2 - t_1$ and $\Delta t = \Delta Z/V$ where V is the velocity of the probe. Now substitute typical values: W = 1 m/s, $\Delta Z = 100$ m, V = 100 m/s and $Z = 10^4$ m. If θ' = 90 deg, then $\Delta \theta' = 10^{-4}$ rad. As a result, for a wave speed C of 333 m/s, the time of arrival must be resolved down to a value of $\Delta\theta'/C = 3 \times 10^{-4}$ seconds per kilometer of spacing between a pair of microphones. An accuracy in the elevation angle measurement of $\Delta \theta'$ of 100 μ rad for a one meter per second wind over a 100 m altitude interval is extreme. Knowing that the propagation error for a single station radar is roughly 50 μ rad (see p24 of the Phase I report by Conner, Hildreth and Baer, 1964), and suspecting that the propagation error for sound is a good deal more, it is difficult to conceive of a sonic system with a "compact" array of microphones as being a high resolution wind measuring system.

Other methods of analysis exist, however, for which the errors may not be as severe. For example, the time t' that a phase is received can be written as

$$t' = t + \int_{0\ \text{along}\ \ell}^{Z} \frac{d\ell}{(C+W)_i \circ T_i} \tag{3.7}$$

where

t and Z are the time and altitude at which the phase was emitted,

$(C + W)_i = C + W_i$ is the speed of sound plus the wind velocity component,

T_i is the unit tangent vector to the ray path, and

$(C + W)_i \circ T_i = C + W_r$ where W_r is the wind velocity component along the ray path.

In a similar manner for another phase

$$t' + \Delta t' = t + \Delta t + \int_{0\ \text{along}\ \ell+\Delta\ell}^{Z} \frac{d\ell}{(C+W)_i \circ T_i} + \int_{Z\ \text{along}\ \ell+\Delta\ell}^{Z+\Delta Z} \frac{d\ell}{(C+W)_i \circ T_i} \tag{3.8}$$

The Δ's are assumed to be small and the integral from 0 to Z along ℓ is assumed equal to the integral from 0 to Z along $\ell + \Delta\ell$. Subtracting the first equations from the second yields

$$\Delta t' = \Delta t + \frac{\Delta Z}{C + W_r} \tag{3.9}$$

and if $W_r \ll C$

$$\Delta t' = \Delta t + \frac{\Delta Z}{C} - \frac{\Delta Z\, W_r}{C^2} \tag{3.10}$$

The integral over ΔZ was taken over the minimum altitude interval of interest for which C + W is taken as a constant. With four widely spaced microphones $C + W_{r1}$, $C + W_{r2}$, $C + W_{r3}$ and $C + W_{r4}$ are obtained and C, W_x, W_y and W_z can be calculated. To analyze the precision required, suppose $\Delta Z = 100$m, $W_r = 1$ m/s and C = 316 m/s. Then the increment in received time due to a one meter wind is 0.001 s. If the phases were emitted at 1000 Hz and Δt is 1 sec, then the required precision is one cycle. This precision seems to be more reasonable than the precision required for measuring the angle of an incoming wavefront but still the question of fluctuations in a turbulent medium must be raised. Experience gained by one of the authors in relating sonic boom signatures to meteorological conditions has indicated that the development of low level turbulence during the day has a profound effect on changing the shape of the typical N-signature of a sonic boom.

Almost no experiments have been reported on fluctuation in a turbulent atmosphere. Several Russian authors have explored the theory (Chernov, 1960). Theory can provide clues as to the shape of the spectrum for the phase and amplitude fluctuations and to the variations with path length and frequency but it cannot provide the actual magnitude.

3.4 Conclusions

The practicality of a sonic, high resolution wind measuring system rests on the magnitude of the fluctuations impressed upon a wavefront by a turbulent atmosphere. Until tests are completed, the question of practicality must remain in doubt.

A further investigation of the various methods of analysis is needed to establish the analytical and computational method which will result in the smallest error.

Further investigation should be conducted of the methods for reducing the measuring errors (bandpass filters, redundant microphones, etc.).

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4.0 COMPARISON OF POSSIBLE SYSTEMS

4.1 Discussion

The high resolution wind measuring systems to be considered are designed (1) to gather statistics concerning the wind environment for space vehicle design, (2) to monitor the winds prior to a launch, and (3) to conduct meteorological research, in that order of importance. In general, an altitude capability of 20 km is considered adequate for these purposes. At the present time, the only two high resolution systems in operation are the superpressure, two-meter, spherical balloon (Jimsphere) and FPS-16 radar system, and the smoke trail and precision camera system. The data from flow vanes mounted on space vehicles can be processed for the winds, but this method has not yet developed into a satisfactory high resolution system.

In the Phase I report it was concluded that the systems worthy of serious consideration employed either a probe (wind sensor), a tracer or sound. The possible systems are further subdivided into those employing an uninstrumented wind sensor (balloon or dropsonde), those employing an instrumented vehicle, those employing a chaff column, a smoke trail or natural aerosols, and those employing sound. The six types are illustrated in Figures 4-1 through 4-6 which also list varieties. A number of other possible systems were mentioned in the Phase I report which are not considered worthy of further evaluation. Included are schemes such as the tracking of a column of glass beads with laser (tracking a column of chaff with radar is better) and the tracking of the blast wave from an explosion aloft with radar (too many uncertain factors).

A comparison of the six types of systems is presented in Figure 4-7. No attempt is made to rate the importance of each factor or to develop a "rating score".

One system suffers severely in comparison with the others. The Doppler shift in the radiation backscattered by natural aerosols from a laser beam is the basis of an exotic scheme but examination reveals a large number of factors against such a system. Lasers with the high degree of monochromaticy required have power outputs less than a watt, many orders in magnitude less than that required for high resolution wind measurements. A hazy atmosphere ups the power requirement and clouds are more or less intolerable. The limitation imposed by haze and clouds could be tolerated if laser technology was well developed. Until research provides favorable answers to many questions, the severe demands of a high resolution wind measuring system discourages further study of laser systems.

High resolution wind data are obtained from smoke trails photographed by precision cameras. At the present time, measurements cannot be made at night, in haze or in clouds, nor can the vertical winds be determined. Chemiluminescent tracers may be useful at night and a trail coding device may permit the determination of the vertical winds. The limitation imposed by clouds is impossible to surmount. The remaining four systems to be discussed use radar and enjoy the advantage of being able to measure winds in heavy haze, at night and in clouds.

A chaff column system appears to suffer from one major disadvantage. A multi-station system composed of large Doppler radars must be designed and constructed before such a system can be operational. For example, with large, 13.7 by 4.7 m antennas the error due to mismatch in the altitudes sampled by a two radar system is greater than 2.2 m/s at a slant range of 40 km for 90% confidence limits (Jiusto, 1962).

The present Jimsphere and FPS-16 radar system suffers from errors due mainly to the limitation in accuracy of the FPS-16 radar at high altitudes and long ranges. Pending a comprehensive analysis of tracking errors, it appears the FPS-16 radar is approaching the limit for a single station radar which is imposed by fluctuations in the signal induced by a turbulent atmosphere. Such errors can be reduced to a much lower level if a multistation system can be employed. However, like the radar system for the chaff column, the cost of building such a system may be difficult to justify just for wind measurements. It should be noted that at times it is possible to employ more than one radar at widely separated locations with a consequent reduction in (and comparison of) the errors.

Two other factors are also important in a wind sensor system. First, balloons do not give a true vertical wind profile but rather a profile along a trajectory which extends horizontally more than it extends vertically. Second, the question of self-induced motions must be raised. Such errors are small for a Jimsphere, being a fraction of a meter per second, but they cannot be neglected.

An instrumented probe (or rocket) can be built around air velocity sensors such as flow vanes or inertial instruments such as accelerometers. The accuracy of velocity sensors is limited by the accuracy in angle of attack measurements of roughly 1/500 radians as discussed in the Phase I report. Vehicles with accelerometers are limited by the same self-induced forces which cause the self-induced motions observed for lightweight, uninstrumented wind sensors. Both approaches suffer from high operational costs which discourage such systems when thousands of wind profiles are to be measured. Also, the complexity in interpreting and processing the data is a source of errors. However, since the trend in electronics and instrumentation is toward smaller and smaller components and lower cost per component, it is expected instrumented wind sensors will become more interesting in the future.

A system with a sonic source in a rocket and ground microphones is promising since data could be gathered rapidly in clouds and at night, but the system is new and unproven. Costs per run cannot compare to those for a balloon, but only simple equipment is carried aloft and the operational cost should be reasonable. A sound system, however, is limited in accuracy by the fluctuation impressed on sound as it passes through a turbulent medium; the magnitude of which can only be established by suitable tests.

In theory, guns can replace rockets for launching wind probes (Staff, 1962 and 1963) at a large reduction in the cost per launch, but difficult problems arise. For one, severe demands exist on mechanical and electrical devices due to the thousands of "gees" experienced during a gun launch. Also, wind probes tend to be large in size and light in weight but a probe launched from a gun must be small and dense.

4.2 Conclusions

1. More meteorological research and technology development must be completed with favorable results before a laser system can be reconsidered for high resolution wind measurements.
2. The smoke trail system may be improved by a process of evolution to extend its operational capabilities. Extensive research and development efforts should not be undertaken because of inability to gather data in heavy haze, at night and in clouds.
3. A chaff column system is limited by the high costs of constructing a special, multistation system of large Doppler radars. Large radars must

be employed to reduce the measuring errors to a tolerable level.

4. Instrumented wind sensors appear to be limited mainly by their high operational costs and system complexity.

5. An uninstrumented balloon system is presently operational (Jimsphere and FPS-16 radar) and costs less than any other system or scheme. The only important disadvantage is the long time required to reach 20 km in altitude. Multistation radars, other shapes (balloon or dropsonde), and advanced data processing techniques can reduce the time of flight and the errors to a considerable extent. Tests are needed to measure the spectrum of the self-induced motions of wind sensors for a variety of shapes, Reynolds number, etc.

6. A system employing a sonic source in a rocket is promising enough to merit further investigation. Tests are necessary to establish the magnitude of the phase and amplitude fluctuations which arise as sound passes through a turbulent medium

4.3 References

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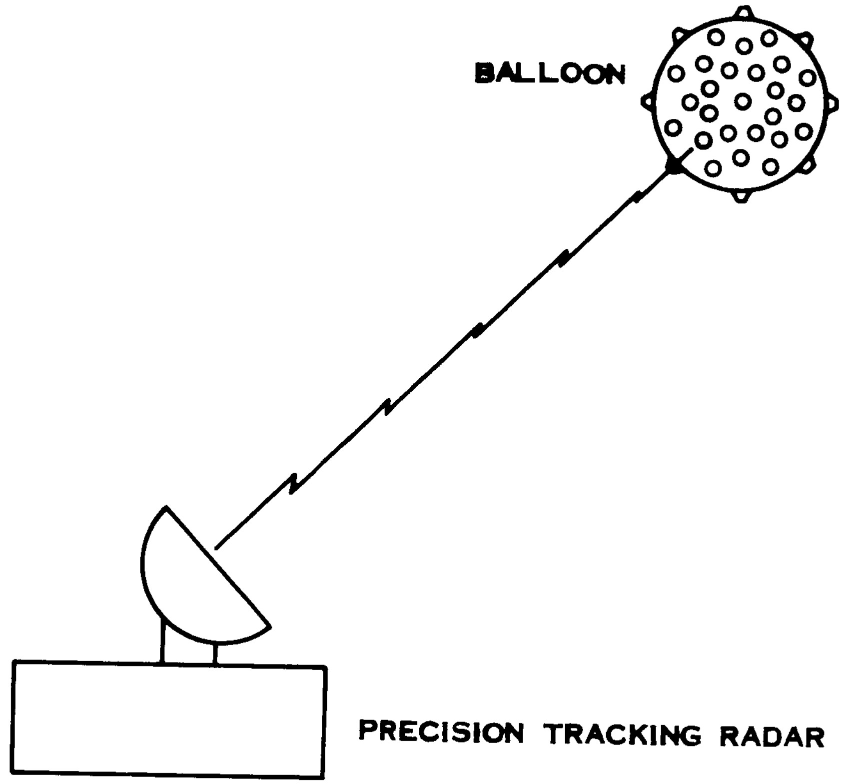


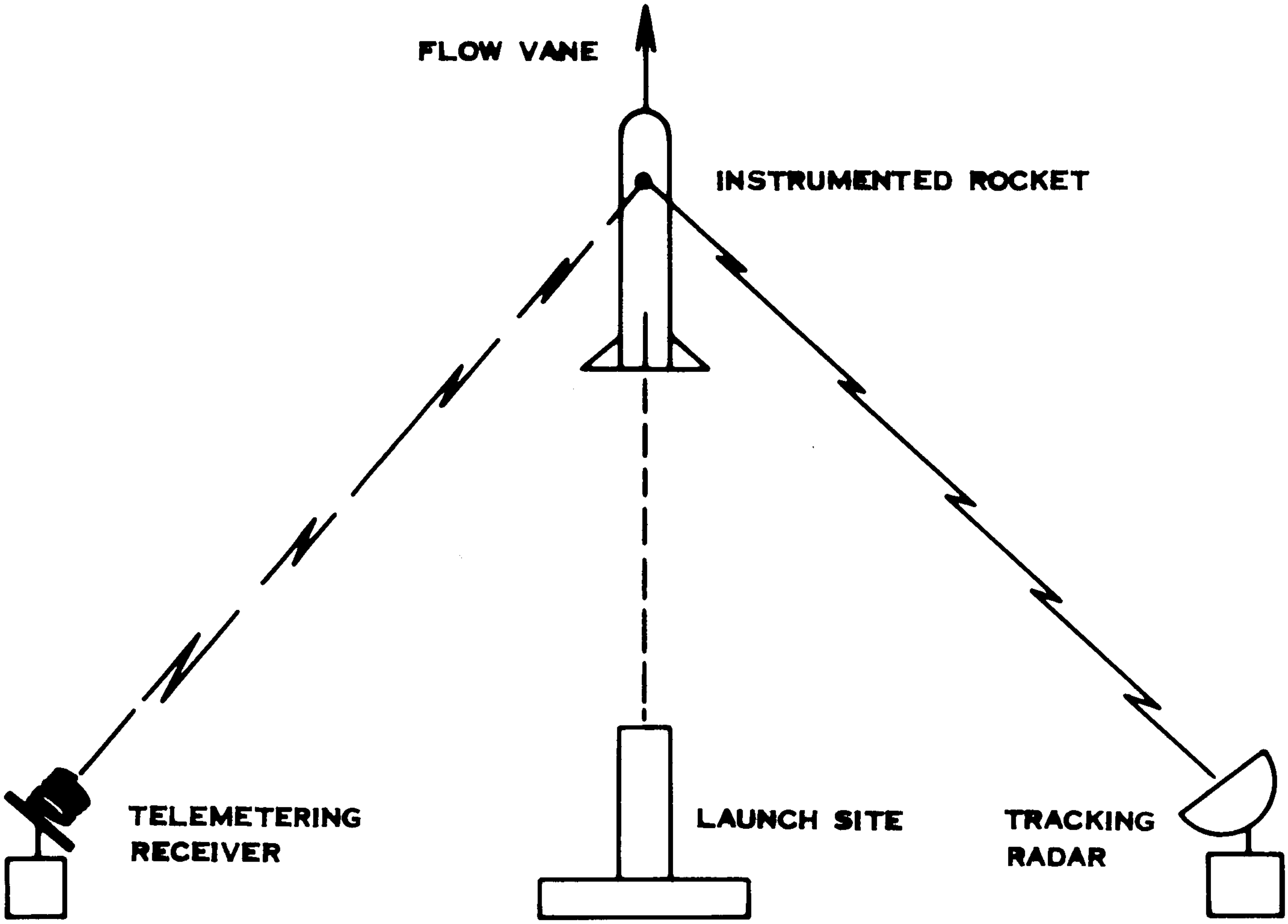
VARIATIONS

- Multistation Tracking Radar
- Other Shapes
- Dropsondes

STATUS

- First Method Used for Measuring Winds Aloft. System Being Refined by Efforts of NASA Marshall Space Flight Center and A.F. Cambridge Research Center.
- Jimsphere and FPS-16 Radar System Operational

FIGURE 4-1. WIND MEASUREMENT SYSTEM USING AN UNINSTRUMENTED WIND SENSOR



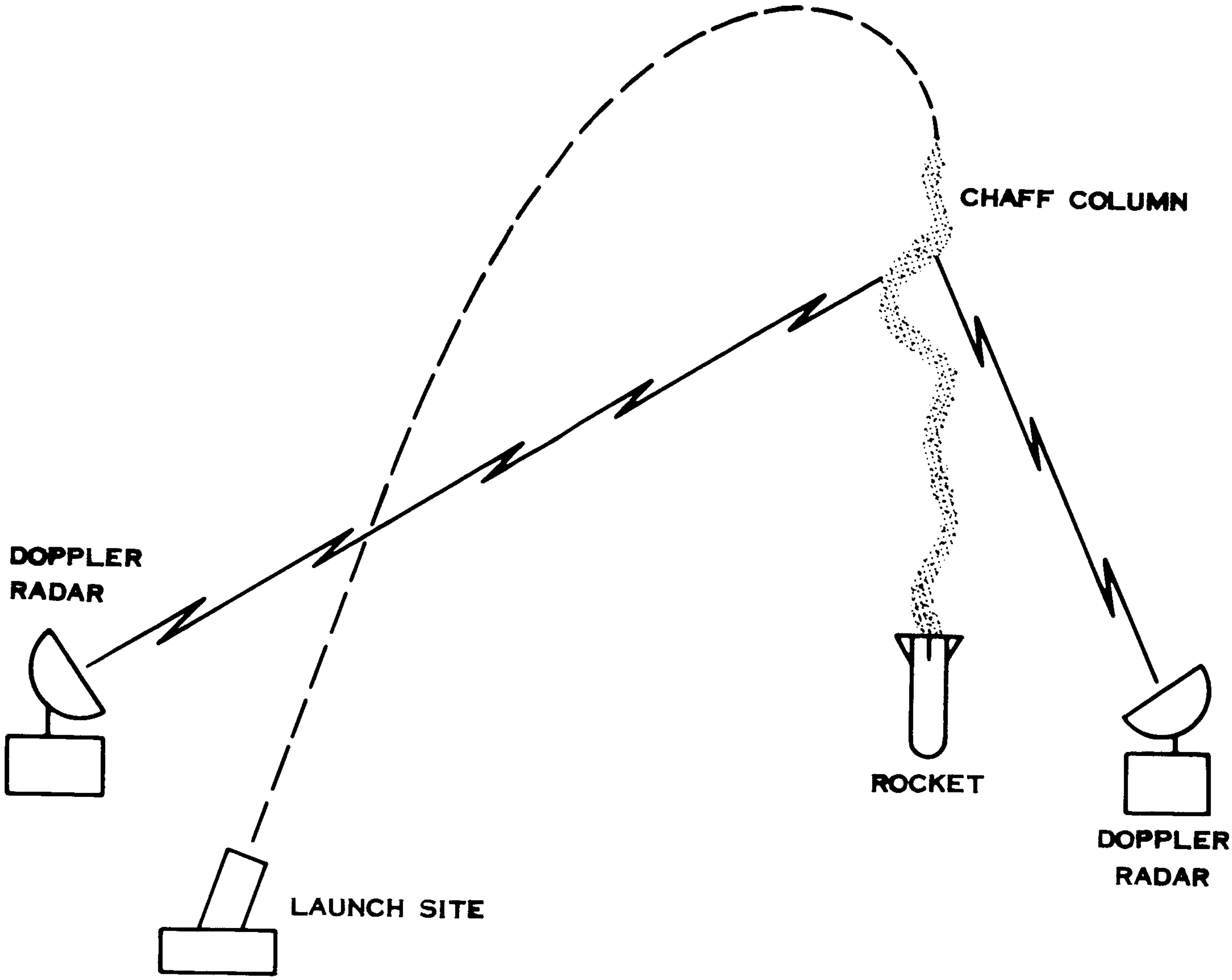
VARIATIONS

- High Response Vehicle with Accelerometers
- Other Types of Velocity Sensors
- Instrumented Space Boosters
- Gun Launch

STATUS

- Space Boosters Occasionally Instrumented and Wind Measurements are derived.
- Ring Wing, Wind Shear Dropsonde with Accelerometers Being Developed by U.S. Army Signal Research and Development Lab.

FIGURE 4-2. WIND MEASUREMENT SYSTEM USING AN INSTRUMENTED VEHICLE



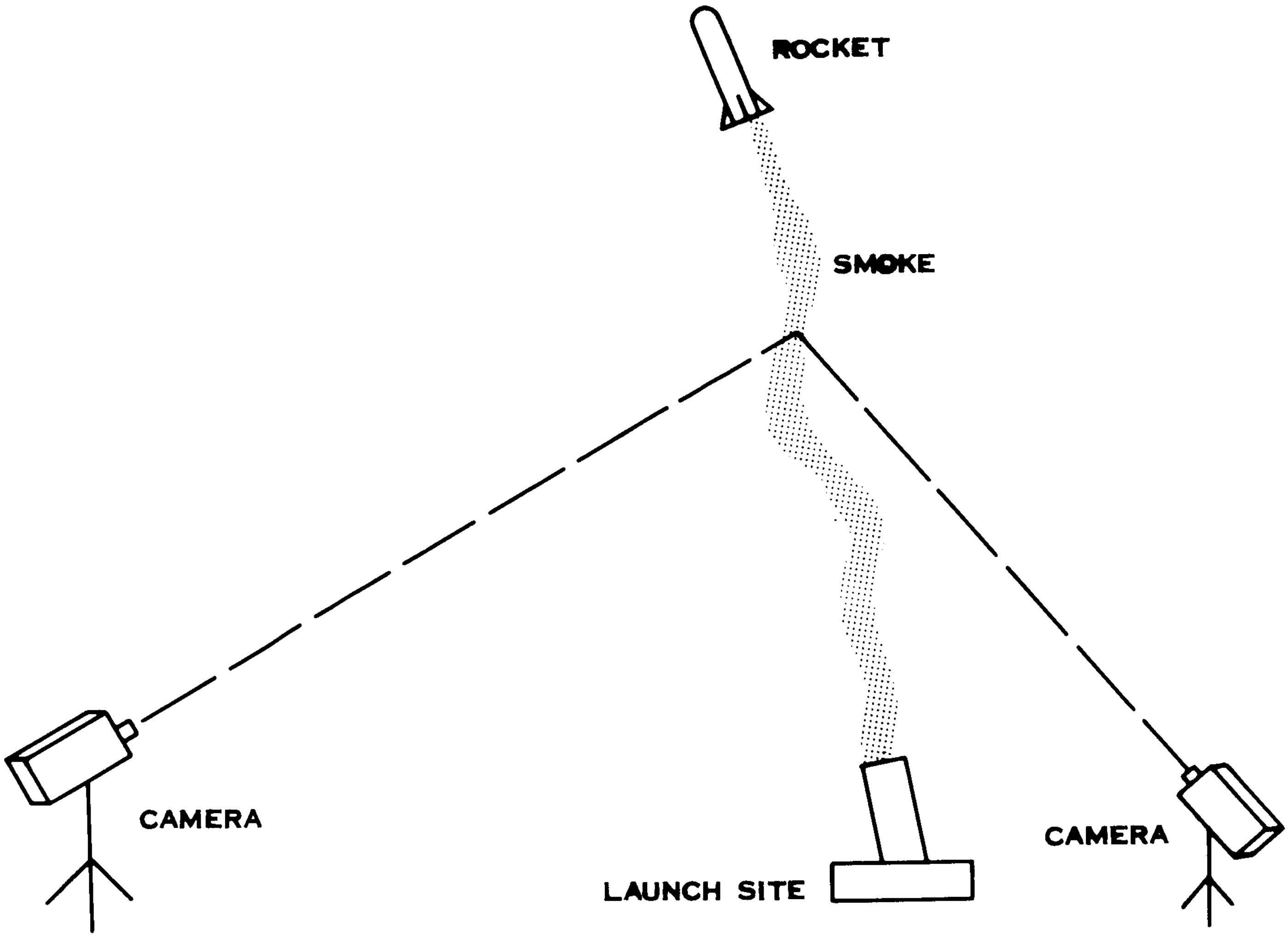
VARIATIONS

- Gun Launch
- Chaff Clouds

STATUS

- Design and Feasibility Tests Completed by Cornell Aeronautical Laboratory, Inc. for NASA Marshall Space Flight Center.

FIGURE 4-3. WIND MEASUREMENT SYSTEM USING A CHAFF COLUMN



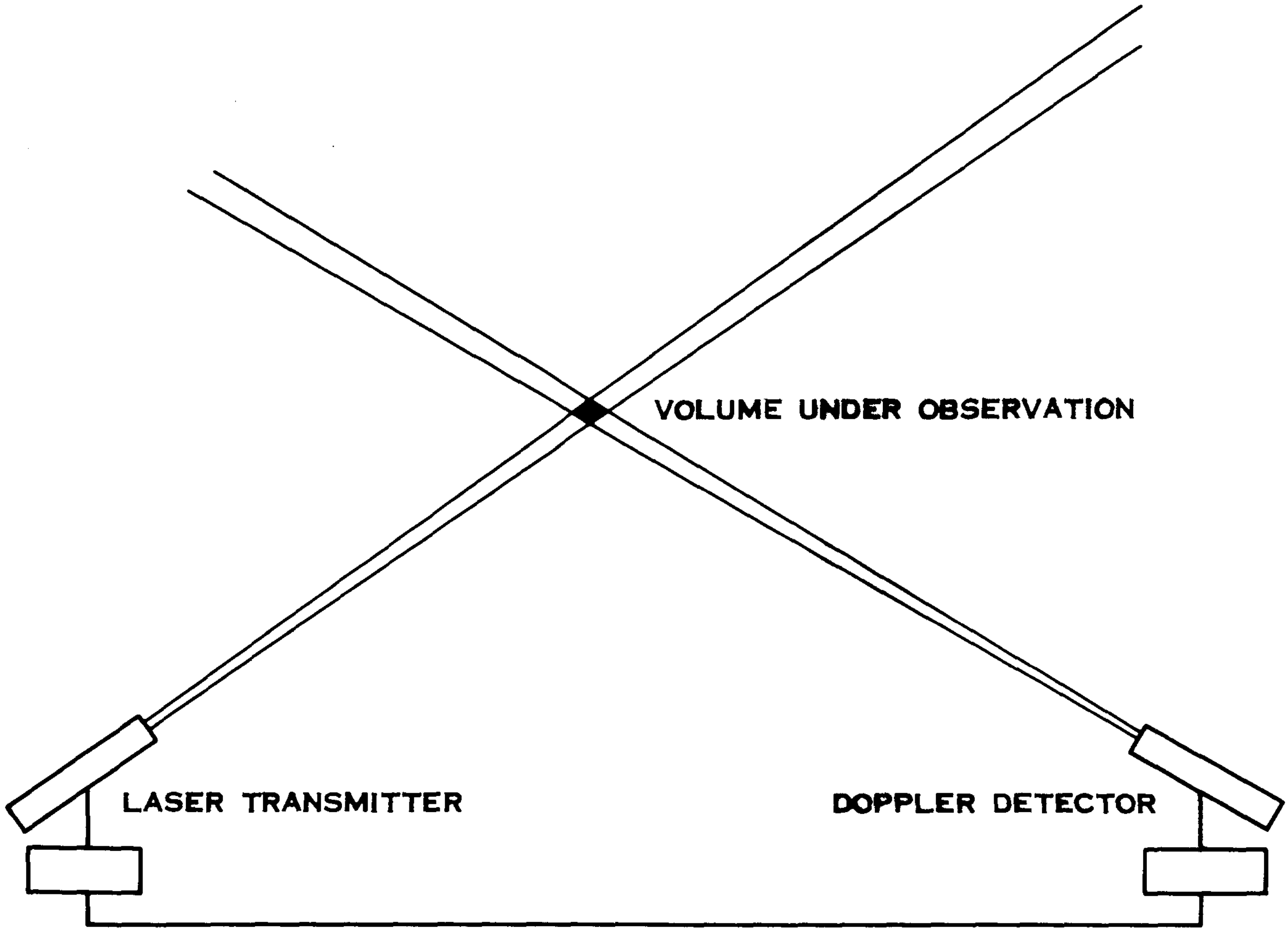
VARIATIONS

- Gun Launch
- Trail Coding
- Active Optical Tracking
- Chemiluminescent Tracer

STATUS

- Two Camera System Developed by NASA Langley Research Center and Used for Research

FIGURE 4-4. WIND MEASUREMENT SYSTEM USING A SMOKE TRAIL



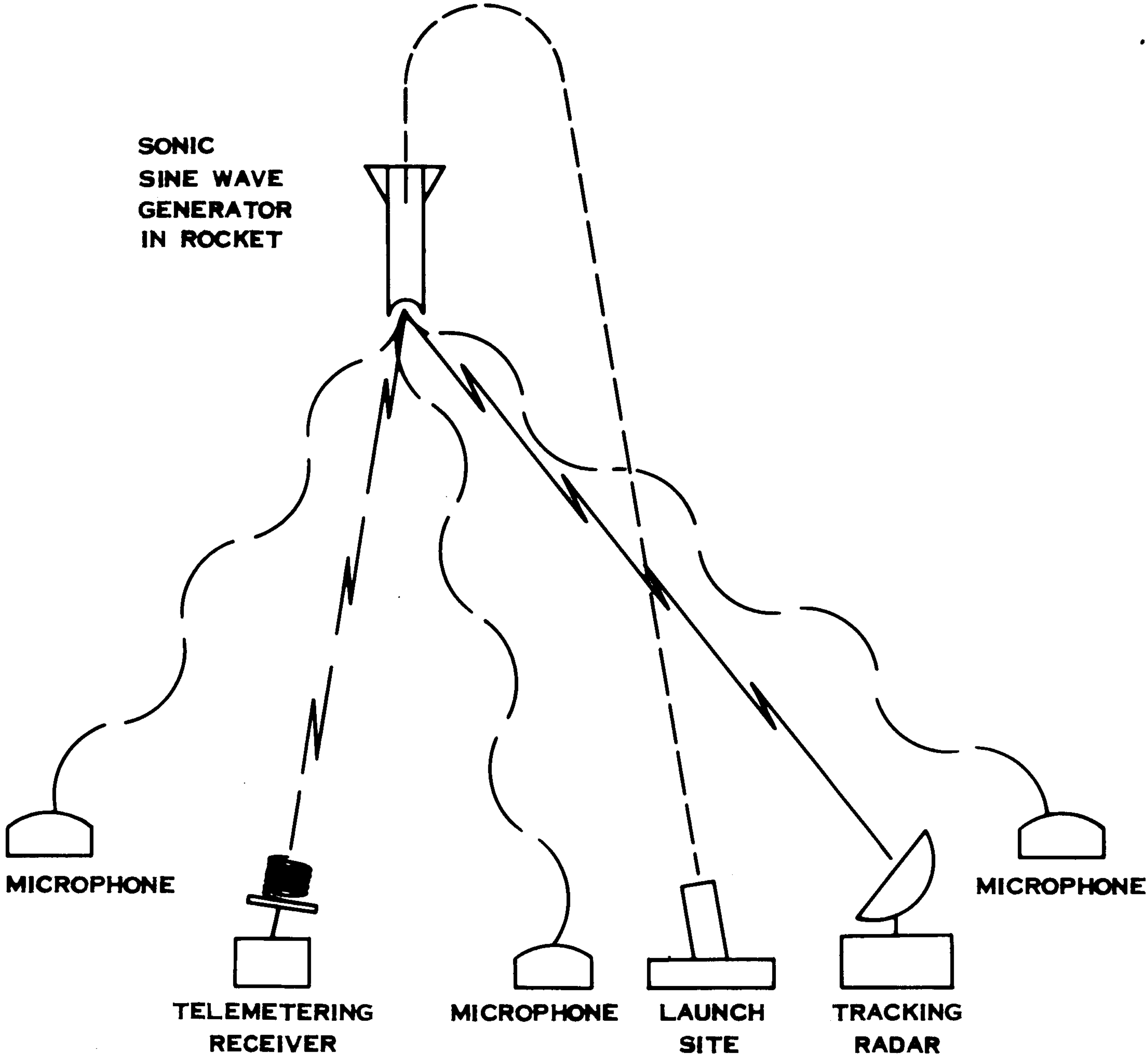
VARIATIONS

- Doppler Radar Backscattering

STATUS

- Similar Concept for Temperature Measurements Discussed in Reports from College of Engineering, New York University

FIGURE 4-5. WIND MEASUREMENT SYSTEM USING NATURAL AEROSOLS



VARIATIONS

- Gun Launch
- Elimination of Radar Requirement
- Explosions at a Rapid Rate
- Employment of Rocket Engine Noise

STATUS

- Low Resolution, Rocket Grenade System Developed by U.S. Army Signal Research and Development Lab.
- University of Michigan Conducting Research for NASA Marshall Space Flight Center for System Using Rocket Engine Noise

FIGURE 4-6. WIND MEASUREMENT SYSTEM USING SOUND

COMPARISON OF SYSTEMS *

WIND MEASURING SYSTEM USING

	Uninstrumented Probes	Instrumented Vehicles	Chaff Columns	Smoke Trails	Aerosols	Sound
OPERATIONS						
1. Operating Costs	Low	High	Moderate	Moderate	Low	Moderate
2. Reliability	High	Low	Moderate	Moderate	High	Moderate
3. Range Safety Limitation?	Yes	Yes	Yes	Yes	No	Yes
4. Wind profile directly above station of interest?	No	Yes	Yes	Yes	Yes	Yes
RANGING						
1. Measurements possible in poor visibility?	Yes	Yes	Yes	No	No	Yes
2. Single station ranging device satisfactory?	Yes	Yes	No	No	No	Yes
PRECISION AND RESOLUTION						
1. Feasible root-mean-square errors for a vertical resolution of 25 m	Fraction of a meter per second with "Jimspheres"	Roughly a meter per second or better	Several meters per second (depends on size of radar)	Fraction of a meter per second with cameras.	Intolerable unless break-through in the power output of highly monchromatic lasers.	Turbulent fluctuation limit accuracy.
STATUS						
1. Concept Proven?	Yes	Yes	Yes	Yes	No	No
2. Operational?	Yes	No	No	Yes	No	No

FIGURE 4-7 (Sheet 1 of 2)

COMPARISON OF SYSTEMS (Cont'd.)

	WIND MEASURING SYSTEM USING					
	Uninstrumented Probes	Instrumented Vehicles	Chaff Columns	Smoke Trails	Aerosols	Sound
OTHER						
1. Vertical Winds Easily Obtained?	Yes	No	Yes	No	Yes	No
2. Potential for Altitudes from 20 to 40 Km?	Yes	Yes	Yes	Yes	No	Yes

* Caution: This table is a highly condensed summary in the interest of presenting a quick comparison. It is not intended to stand alone but only in the context of the Phase I and II reports.

FIGURE 4-7 (Sheet 2 of 2)