AIR DATA SENSING FOR SPACE SHUTTLE

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FOREWORD

The presentation provides interim results of work by the authors on Contract NAS 8-26326 since August 1970. Monitoring and direction were provided by Alex Hafner, John Hamlet, and Tom Marshall of NASA-MSFC, Huntsville.

Acknowledgment is given for numerous helpful contacts with personnel at NASA, North American Rockwell, McDonnell Douglas, General Dynamics/Convair, and Honeywell. Also, many sources in the literature were drawn upon.

AUTHORS' INTRODUCTION

Under direction of K. E. Floren, Project Engineer, the Honeywell authors provided the following functions under the contract NAS 8-26326.

D. J. Sowada	-	System Integration and Analysis
F. A. Moynihan	-	Aerodynamics and Sensor Design
R. G. Bailey	-	Installation Design and System Definition

Alex Hafner was primary NASA Monitor, leading the design reviews.

PRESENT STATUS

Currently proceeding to a refined mechanization of the selected sphere nose sensor plus pitot/static probe concept in terms of sensor installation on current Shuttle vehicles, selection among available pressure transducers, assessment of expected performance, and detailing of associated electronics units.

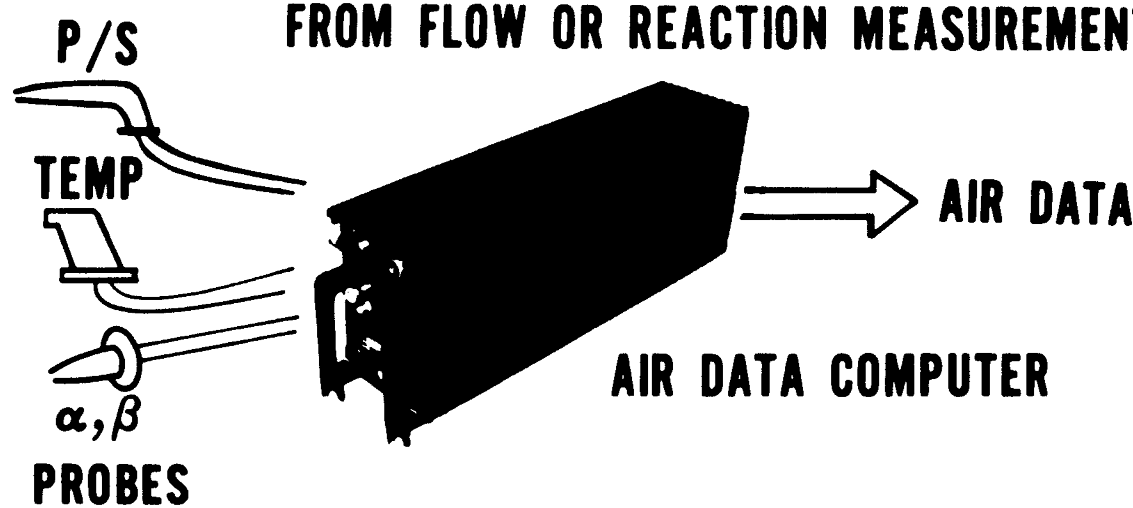
ABSTRACT

This Technology Study Report describes the feasible and useful air data sensing alternatives in terms of potential uses, practical mechanization, and primary impact related to the current configuration of the Space Shuttle vehicle and avionics. Recommendations are made to provide a baseline air data measurement (ADM) system for integration into the Shuttle vehicles. The state-of-the-art feasibility of the recommended system is substantiated by flight experience, wind tunnel tests, and simulation studies.

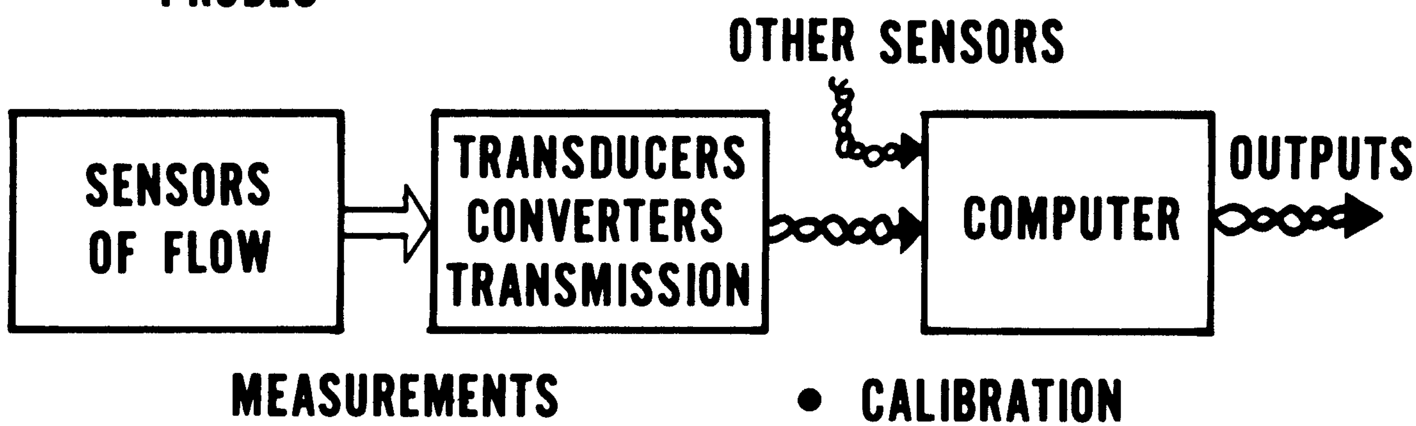
AIR DATA: ATMOSPHERIC FLIGHT PARAMETERS

FROM FLOW OR REACTION MEASUREMENTS

CONVENTIONAL



SHUTTLE



- CALIBRATION
- AIR DATA CONVERSION
- BLENDING
- USE OF AIR DATA

ATMOSPHERIC FLIGHT PHASES

The listed flight phases are those when flying through the sensible atmosphere. Needs are those functions essential to vehicle piloting and guidance, navigation, and control. For convenience, these can be divided into subsonic flight and re-entry/transition flight, combining later return and ferry phases.

The boost phase is short, timewise, and determined by guidance and control, rather than air data sensing. Special pressure sensing could be employed to alleviate loads; however, the special nature is best handled by integration with the special problem rather than the ADM system.

Subsonic and re-entry flight operation determine needs of the air data kind.

ATMOSPHERIC FLIGHT PHASES

COMBINED BOOST

BOOSTER RETURN
ORBITER RETURN → (RE-ENTRY TRANSITION CRUISE OR GLIDE LANDING)
ABORT RETURN

ORBITER FERRY → (TAKEOFF, CLIMB, SUBSONIC CRUISE, DESCENT, LANDING)

AIR DATA NEEDS

Thanks to many, after several iterations of what's needed?, what can be provided?, what's already aboard?, is it really needed?, etc., the listed needs survived the test of being essential. In the following list:

1, 3, and 5 are parameters that can be provided only by air data means; the need for near zero sideslip control during later phases of re-entry is critical for vehicle survival. Winds cause inertial navigation system (INS) determination of airspeed and flow direction to have serious error at the slower speeds.

2 and 9, altitude data, are useful for INS divergence clamping and for altimetry needs during subsonic flight; non-air-data sensing methods are possible.

6 and 8 provide for better guidance and control performance, if obtained by air data means.

The critical boost-loading problem (4) is solved better by non-air data means; direct monitoring of skin temperatures (7) is an intimate part of thermal protection system design, not air data. Skin temperature sensing has been pursued (e.g., ASSET program) as a form of air data sensing; these concepts need further development not consistent with 1972 technology base goal.

Can these needs be satisfied?

AIR DATA NEEDS

SUBSONIC FLIGHT

* 1. AIRSPEED (OR MACH)
2. PRESSURE ALTITUDE
* 3. α & β
** 4. HI-Q BOOST LOADING

RE-ENTRY & TRANSITION

* 5. SIDESLIP STABILIZATION
6. α REFERENCE
** 7. CRITICAL SKIN TEMP'S.
8. FLIGHT INTENSITY (q)
9. ALTITUDE REFERENCE

* MUST BE <u>AIR</u> DATA ---- FOR SURVIVAL

** NON-ADM

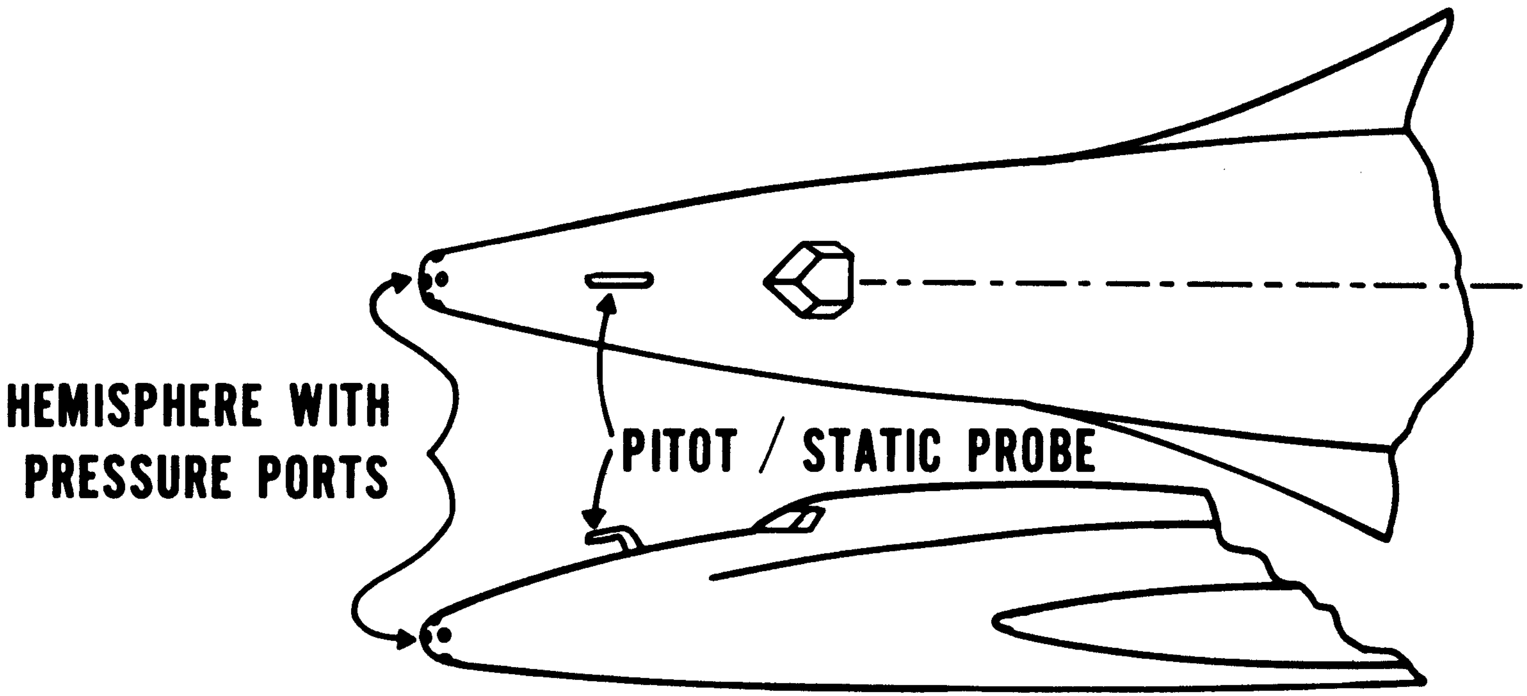
CONCEPTUAL SKETCH OF ADM SENSORS

The solution consists of a spherical nose with small pressure ports and a conventional subsonic pitot/static probe mounted permanently at a cool place on the vehicle.

Measurement of α and β by pressure ports on a sphere is an established technique but with movable spheres and only over a limited Mach number range. The Space Shuttle requirement of a large α range, along with use over a large Mach number range, from re-entry to landing, using a fixed sphere was shown to be possible. The spherical nose shape is more compatible with structure and heating problems than, for example, a nose boom. α and β can be determined, independent of Mach number and altitude, using a sphere.

The conventional pitot/static tube is for subsonic flight and landing where it would provide better accuracy of airspeed and pressure altitude than possible with the nose taps. Without vehicle shock waves, the subsonic probe can be mounted away from the nose area.

CONCEPTUAL SKETCH OF ADM SENSORS



ADM FUNCTIONS

Differential pressures from port pairs on the nose provide means to determine sideslip, β, and angle of attack, α, for all speeds after dynamic pressure, q, exceeds 15 PSF or 720 newtons/m^2 (near the point where sensible decelerations are evident in re-entry).

Addition of an absolute pressure measurement enables determination of stagnation pressure. At the higher speeds ($M > 2$), simple correlation provides dynamic pressure, q, for control scheduling. In turn, INS velocity can be used to determine ambient air density, ρ, which allows determination of density altitude for INS vertical channel clamping.

At subsonic speeds, the P/S probe enables the conventional determination of pressure altitude and forms of airspeed. The clamped, vertical INS channel is the best source of vertical speed.

ADM FUNCTIONS

MEASUREMENTS		OUTPUTS	CONDITION
SPHERE NOSE	DIFFERENTIAL	β - SIDESLIP α - ANG. OF ATT.	q >15 PSF ALL SPEEDS
PORT PRESSURES	ABSOLUTE	P_{t2} - STAG. PRESS.	q>15 PSF M >2
		$P_{t2} \rightarrow$ q - DYN. PRESS.	
		INS V $\dashrightarrow \rho \dashrightarrow$ HD FOR INS q $\dashrightarrow \rho$	
	STATIC PRESSURE	Hp $\dashrightarrow$ INS $\longrightarrow \dot{H}$	
P/S PROBE	TOTAL OR IMPACT PRESSURE	MACH OR COMPUTED AIRSPEED	SUBSONIC

FEATURES OF APPROACH

The approach is very attractive. Using flight proven concepts, clamping and blending improve the INS approach. The vehicle's thermal protection, structural, and aerodynamic characteristics are unchanged (compare with supersonic boom ahead of nose). Without deployment mechanisms, the approach is simple, reliable, and available throughout flight. Zero pressures of outer space provide opportunity for transducer offset calibration. With redundancy to survive in-flight failures, failure isolation is easy. The concept allows degraded gain, but good-null sideslip sensing backup, and needs no between-flight refurbishing.

Of course, it provides the necessary functions.

The spherical concept has flown on the X-15, Apollo, and various small probes. Currently produced transducers satisfy accuracy needs. The extension to entry usage has been shown on basis of analyses and wind tunnel tests over the past 10 years.

FEATURES OF APPROACH

- USES FLIGHT-PROVEN ELEMENTS
- AUGMENTS ON-BOARD INS AUTONOMY
- MINIMUM VEHICLE COMPROMISE
  (THERMAL PROTECTION, STRUCTURAL, AERODYNAMIC)
- AVAILABLE DURING ENTIRE FLIGHT
- CALIBRATION, FAILURE ISOLATION, & BACKUP OPTIONS
- NO MOVING PARTS - SIMPLE, RELIABLE
- NO BETWEEN-FLIGHT REFURBISHING
- PROVIDES NECESSARY FUNCTIONS

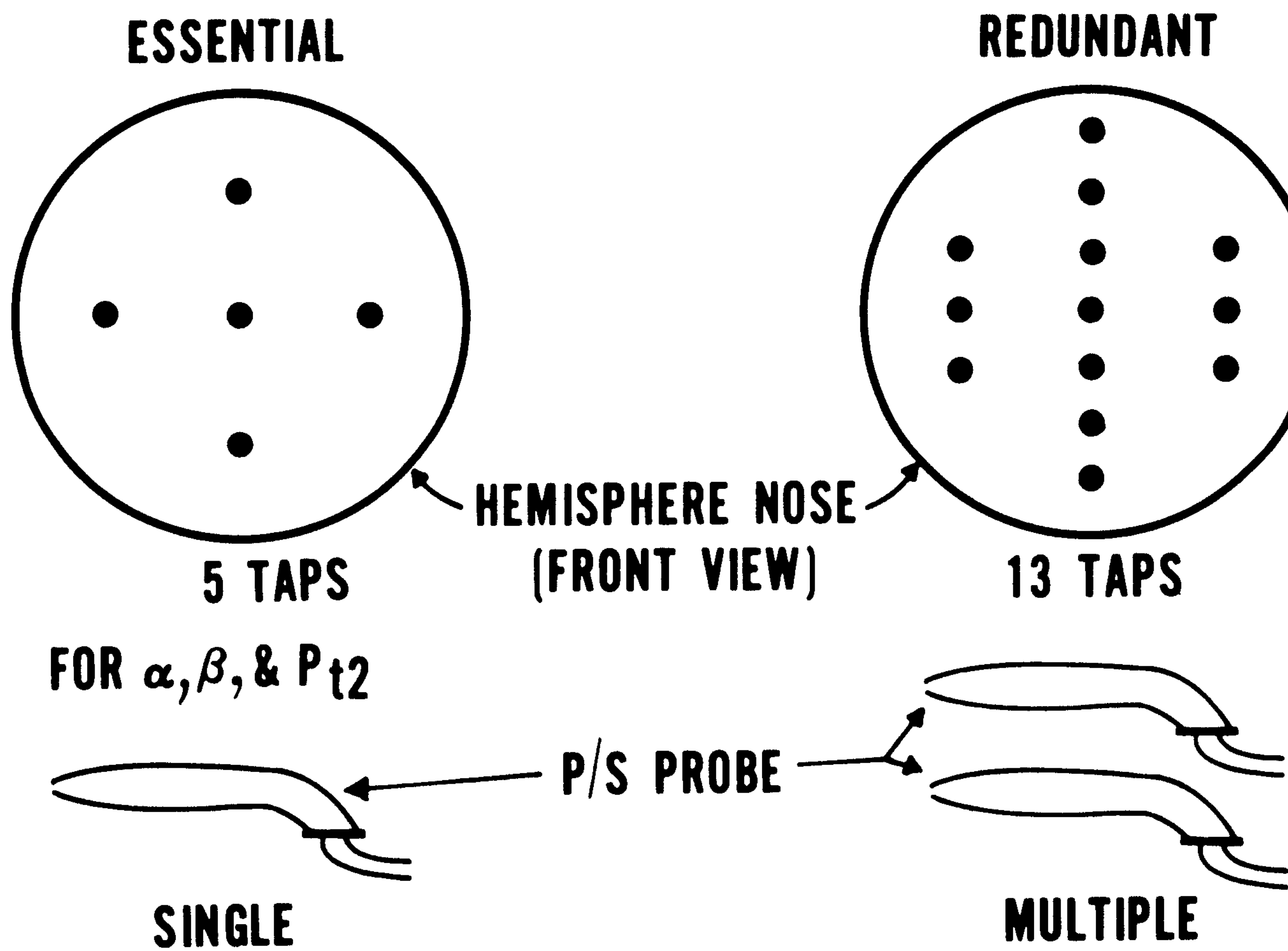
BASIC AND REDUNDANT CONFIGURATIONS

With five holes in the spherical nose, three differential transducers, and one absolute transducer, α, β, and P_{t2} are determined. By adding holes and transducers, the measurements are made redundant. With 13 holes and three identical sets of transducers, triple redundancy is provided. Accuracy is improved by scheduling the best of the redundant sets as function of angle of attack.

The pitot/static tube with transducer pair is made redundant with multiple transducer sets and multiple tubes.

After detailed vehicle installation, the failure probabilities (of blockage, line breakage, transducer failures, and electronic failures) together with means to avoid single-point failures and maintain identical transducer/electronics assemblies will need analysis to arrive at the best redundant configuration. The possibility of backup sideslip control sensing should allow less than full 3-channel redundancy.

CONFIGURATIONS



ALTITUDE/VELOCITY TRAJECTORIES (RE-ENTRY)

Now that we have reviewed the ADM measurement concept, let us take a closer look at how it is integrated into the Shuttle vehicle and avionics. First we consider integration of ADM and INS for performance benefit; then the added ADM hardware will be reviewed; finally the computational aspect will be reviewed.

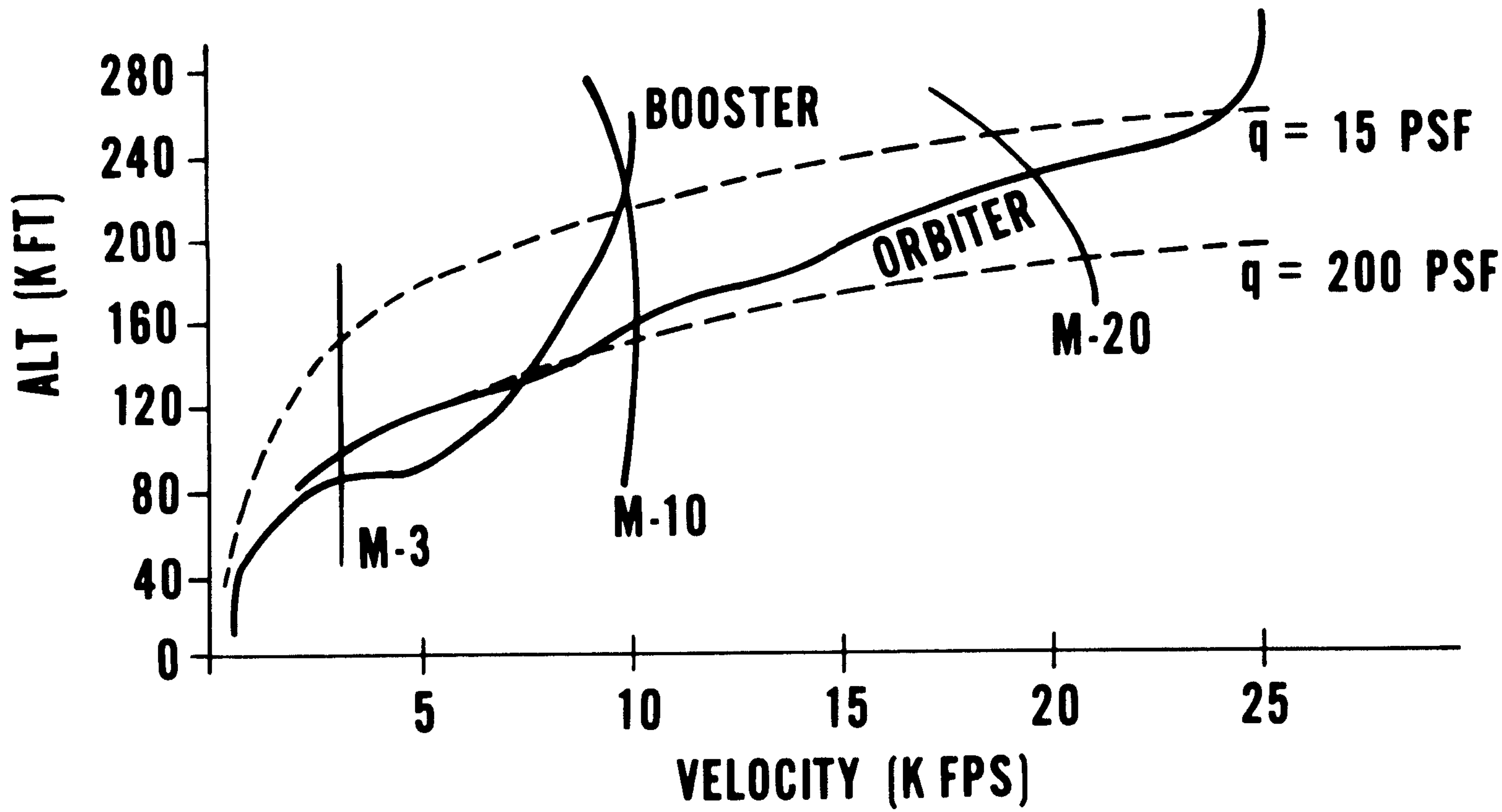
Notice that significant decelerations occur near the $q = 15$ PSF or 720 newtons/m^2 curve and that dynamic pressure, q, varies primarily with altitude at high speeds. Once decelerations are underway, dynamic pressure grows significantly higher than 15 PSF.

In brief, the INS will be shown to have significant increase in derived-air-data-parameter errors as speed decreases, during descent, because the INS cannot measure wind. On the other hand, the ADM becomes more sensitive as dynamic pressure increases. With such complementing of characteristics, blending is the obvious conclusion.

For International units:

KFT	40	80	120	160	200	240	280
KM	12	24	36.5	49	61	73	85
KFPS	5	10	15	20	25		
KMPS	1.5	3	4.6	6.1	7.6		
PSF	15	200					
Newtons/m^2	720	9576					

ALTITUDE/VELOCITY TRAJECTORIES
(RE-ENTRY)



WINDS

The following slide merely references wind magnitudes (mean and maximum) at various altitudes used in deriving data on the next slide. The expected mean winds above 30K feet are large.

Converted into International units:

Altitude (Meters)	Mean (MPS)	Maximum (MPS)
6K	24	38
9K-14K	90	128
30K-79K	73	104

Reference: Handbook of Geophysics, Revised Edition - 1960
United States Air Force
Air Research and Development Command
Air Force Research Division
Geophysics Research Directorate

WINDS

ALTITUDE (FEET)	MEAN (FPS)	MAX (FPS)
20K	80	125
30-45K	300	420
100-260K	240	340

INS WIND ERRORS

Without vertical clamping, errors would be larger at the transition point, about the same early in entry, and gross in subsonic flight. Thus, clamping should start during entry.

Early in entry, the INS provides the best available measurements; at transition, sideslip error becomes intolerable. For subsonic flight, INS measurement of air data parameters is not meaningful.

At transition, the altitude is about 100K feet or 30 KM, while the velocity is about 4 KFPS or 1.2 KMPS. The mean wind of 240 FPS or 73 MPS is about 6 percent of the vehicle velocity while the maximum wind is 8.5 percent of the velocity. If winds were from the side, either an α or β error, depending on bank angle, of 60 milliradians (mean wind) or 85 milliradians (maximum wind) would be caused. These angles correspond to 3.4° to 4.9°.

The values on the following slide are thus possible error magnitudes, including INS and mean wind errors.

With some manipulation of random-direction probabilities, these errors at transition could be converted to smaller probable errors that in turn justify another ADM solution. A supersonic/subsonic probe with pitot/static, α, and β capability could be deployed at transition and be used through landing.

INS WIND ERRORS
(VERTICAL CLAMPED)

PARAMETER	SUBSONIC	TRANSITION	EARLY BOOSTER ENTRY	EARLY ORBITER ENTRY
	$H < 45K$ FT $V < 1K$ FPS	$H \cong 100K$ FT $V = 4K$ FPS	$H = 200K$ FT $V = 10K$ FPS	$H = 250K$ FT $V = 25K$ FPS
α/β	5-20°	4°	1°	0.4°
RELATIVE WIND	10-30%	7.5%	2%	<1%

ERROR CHARACTERISTICS OF SPHERE/NOSE SENSOR

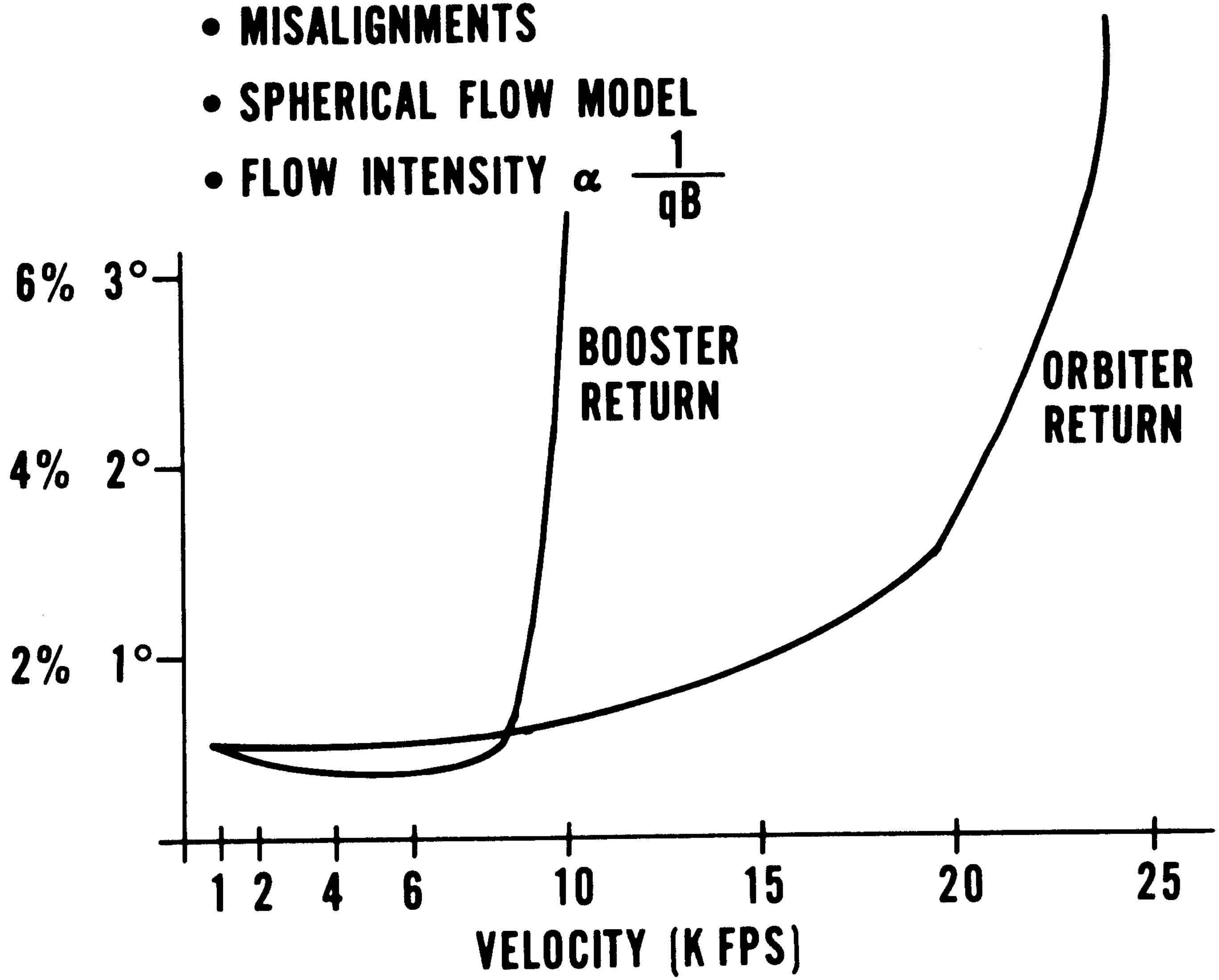
The flow direction sensor errors include misalignments of the nose section and imperfections of spherical pressure distributions which are partly calibratable for a given vehicle The effects of vehicle bending and distortion of the spherical shape result in α and β measurement errors that need to be controlled to about one degree (17.5 mrad).

The remaining errors decrease with increasing flow intensity. Replotting as a function of velocity for the entry trajectories, these errors are seen to decrease with velocity, during descent.

Since INS wind errors increase during descent, blending of measurements from ADM and INS is indicated.

ERROR CHARACTERISTICS OF NOSE SENSOR

- MISALIGNMENTS
- SPHERICAL FLOW MODEL
- FLOW INTENSITY $\alpha \frac{1}{qB}$



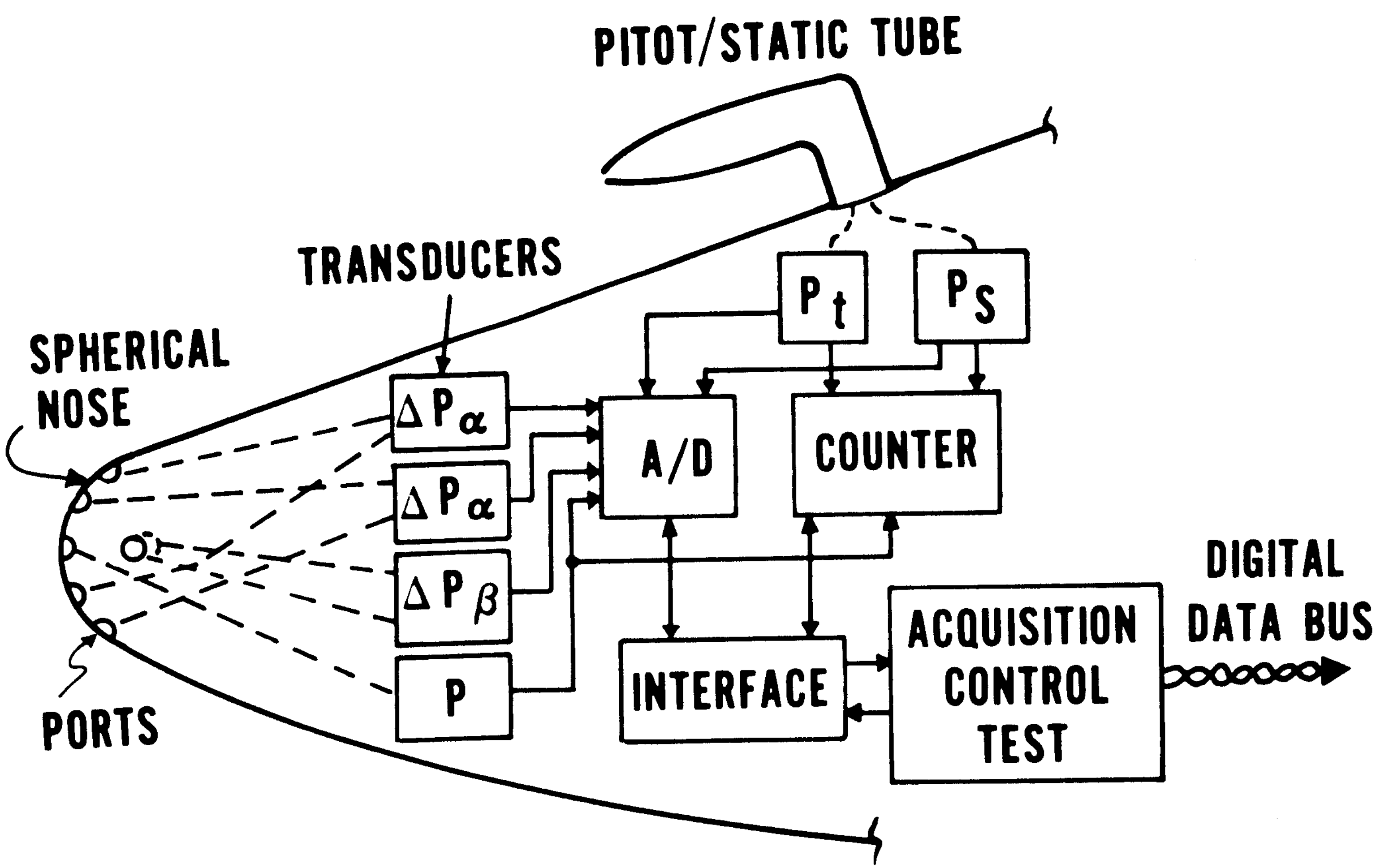
ADM HARDWARE

The ADM provides digital measurements of absolute and differential pressures to the data bus. The transducers and electronics can be located in a forward avionics bay with short pneumatic lines to minimize line-lag and thermal exposure. Such transducers require normalization to standard scale and temperature compensation; thus, correction constants and measurements of temperatures are additional items of data sent to the computer for processing.

Selection from available transducers is underway; design of electronic assembly can then be defined. Preliminary coordination with vehicle contractors established feasibility of spherical nose shape and means to attach plumbing.

Numerous combinations of number of ports, number of transducers of each type, and number of electronic units and types are possible. Specific installations can be optimized to suit performance and redundancy objectives in view of needs.

ADM HARDWARE



COMPUTATION FLOW

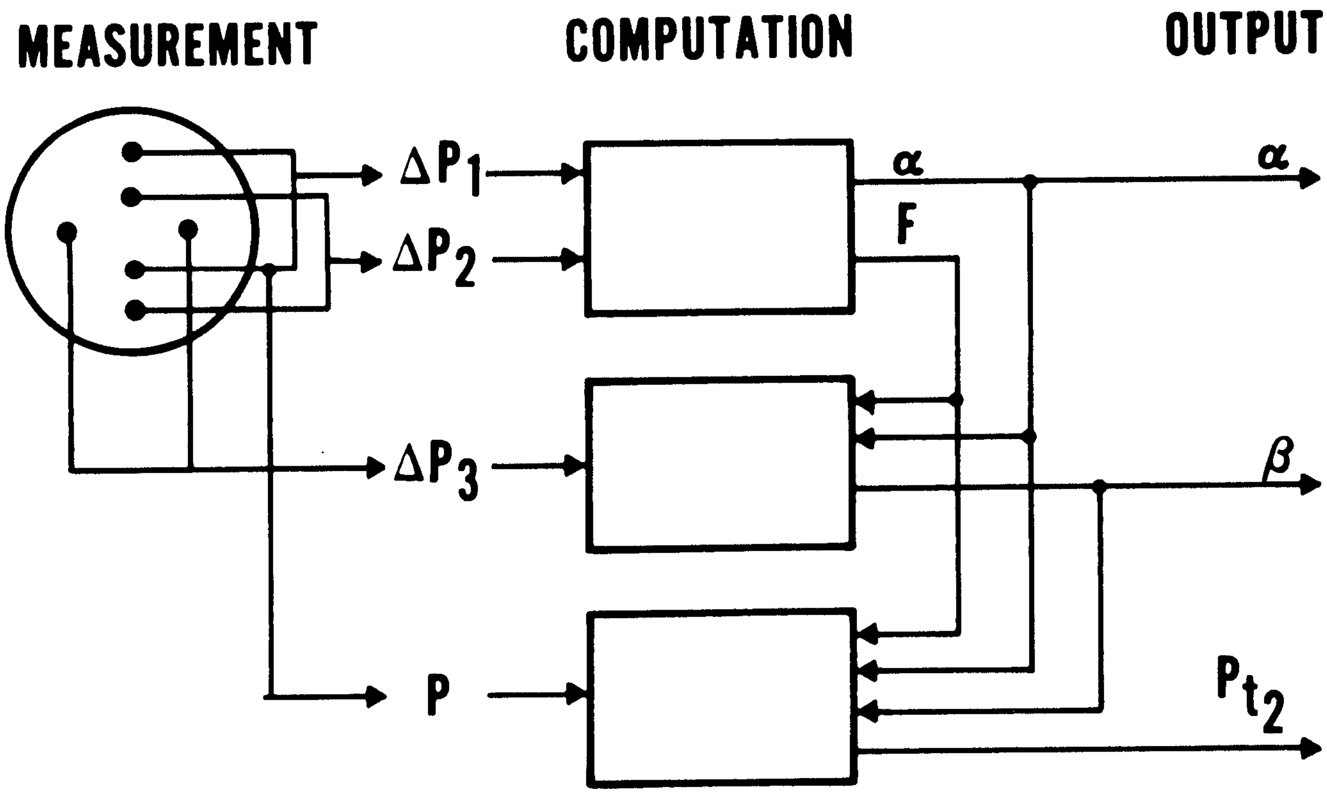
The computation of air data parameters α, β, and P_{t2} proceeds by using two pressure differences ΔP_1 and ΔP_2 to determine α and a pressure intensity function F. This approach does not require knowledge of flight conditions (like Mach number and altitude).

The third pressure difference, ΔP_3, is zero when $\beta = 0$ with sensitivity (gain) maximized but varying with angle of attack and flight intensity. For sideslip control (to null), ΔP_3 times a scheduled gain could be used. For β in angular units, α and F are used.

The absolute pressure measurement, P, at a particular point on the spherical nose is used to compute stagnation pressure, P_{t2}, using computed values of α, β, and F.

Correction constants are employed to compute the pressure values from transducer outputs. Improved system accuracy could be realized by automatically calibrating for zero output when above the sensible atmosphere.

COMPUTATION FLOW



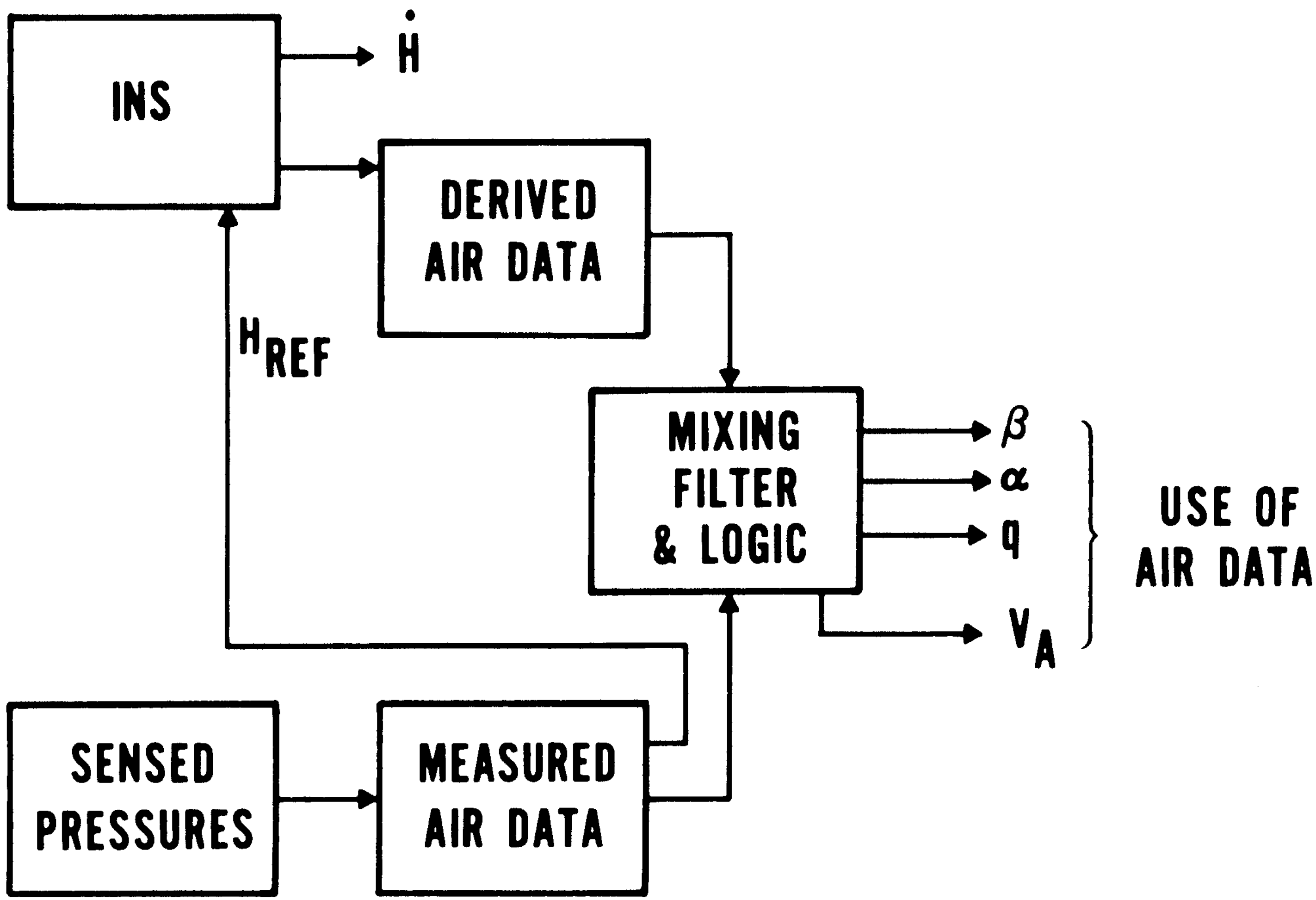
BLENDING OF MEASUREMENTS

To complete the description of computations, this slide illustrates the blending of INS and ADM measurements.

The altitude reference clamps the vertical channel of the INS to improve its performance and provide altitude rate, $\dot{H}$.

The mixing filter provides an improved estimate, or a logic chooses the best available source, thus providing digital words for air data use (by other programs or subsystems).

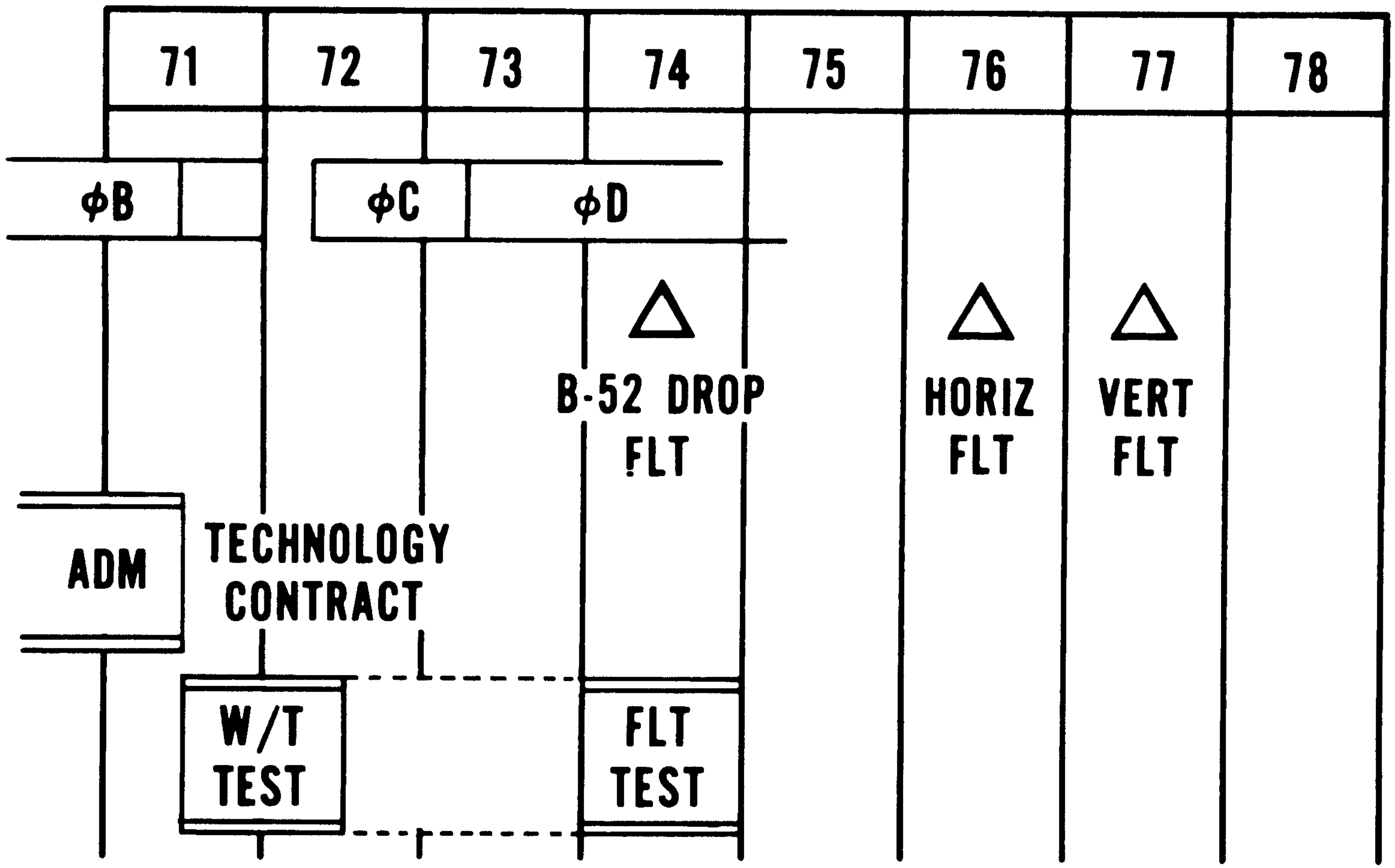
BLENDING OF MEASUREMENTS



SPACE SHUTTLE SCHEDULE

To influence vehicle design meaningfully, the ADM Technology Contract is currently providing supporting information to the Phase B Studies. It is expected that the sphere nose concept can be integrated into upcoming wind tunnel tests on vehicle models to give increased confidence in this approach for incorporation into vehicles.

SPACE SHUTTLE SCHEDULE



REMAINING WORK

To summarize, the sphere nose plus subsonic probe approach is feasible, useful, and attractive when compared to other approaches like supersonically deployed booms and subsonic probes only. Implementation depends on decision to do so and specifics of vehicle and avionics configurations.

The first three items are underway to the extent of preliminary design definition, under the ADM Technology Contract. The last three are extended Phase B and Phase C efforts.

REMAINING WORK

- INTEGRATION OF SPHERICAL NOSE
- INSTALLATION DESIGN
- TRANSDUCER SELECTION & ASSESSMENT
- PROOF - TESTING & SIMULATION
- INTEGRATION INTO VEHICLE & AVIONICS
- DESIGN & DEVELOPMENT