NOAA Technical Memorandum ERL RFC-7

DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

THE DETERMINATION OF NAVIGATIONAL AND METEOROLOGICAL VARIABLES MEASURED BY NOAA/RFC WP3D AIRCRAFT

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CONTENTS

1. INTRODUCTION

This technical memorandum provides a brief description of the way in which the principal navigational and meteorological variables measured aboard the NOAA WP3D aircraft are determined. For each variable, we describe the sensor inputs and equations used and provide an estimate of the error in the result. The report is divided into two sections: Quantities displayed on-board in real-time and additional quantities computed and available to the user on request in the final data set. An appendix describing the aircraft and much of their instrumentation is included. In some cases the equations used to compute a displayed variable in-flight differ from those used to compute the same variable in the final data set. In these cases, the equations presented here are those used for the final data set. The difference arises because of memory and computational speed limitations of the airborne computer. The data system records the unprocessed data. The data processing on-board is for real-time quick-look use only and does not affect the final product.

This description is not intended to be a complete, detailed and rigorous analysis of the RFC aircraft data collection system, but to provide users with a brief readable summary of what is measured and how. Greater detail about anything described in this work can be obtained from the appropriate people at RFC when required. Visitors to the RFC aircraft may find it useful to keep this technical memorandum at hand inflight. It answers many of the questions which frequently arise among new users of the aircraft.

2. VARIABLES DISPLAYED IN FLIGHT

The NOAA P3 data systems present a variety of navigational and meteorological variables on CRT displays throughout the aircraft. Table 1 shows the quantities displayed beside the corresponding CRT abbreviation. They are presented in alphabetical order and the units of measurements are given for easy reference in-flight. Details of the display system can be found in Brown (1978).

Table 1. ABBREVIATIONS AND UNITS OF QUANTITIES DISPLAYED BY RFC RAMS ONBOARD DISPLAYS

Abbreviation	Quantity	Units
AX or AXB	AXBT Temperature	degrees C
DA	Drift Angle	degrees
DV	"D" Value	meters
FWZ	Filtered Vertical Wind	meters/second
GS	Ground Speed	meters/second
HDG	Heading	degrees
HT	Height of Standard Surface Pressure	meters
LAT	Latitude	degrees
LONG	Longitude	degrees
LW	Liquid Water Content	grams/meter^3
PA	Pressure Altitude	meters
PQ	Differential Pressure	millibars
PS	Ambient Pressure	millibars
RA	Radar Altitude	meters
RH	Relative Humidity	percent
SN	Dropsonde ID Number	none
SP	Surface Pressure	millibars
SST	Sea Surface Temperature	degrees C
TA	Air Temperature	degrees C
TAS	True Airspeed	meters/second
TD	Dewpoint Temperature	degrees C
TRK	Track Angle	degrees
WD	Wind Direction	degrees
WS	Wind Speed	meters/second

The discussion following will appear in the same order as the variables found in Table 1. Many of the variables (e.g., TAS) are derived from others (e.g., PQ) and to avoid duplication, cross referencing will be used as needed.

2.1 AXBT Temperature (AX or AXB)

RFC operates an SSQ-36 air expendable bathythermograph system. The bathythermograph probe contains a precision thermistor and oscillator connected to a spool of fine wire. Changes in resistance of the thermistor due to temperature changes in the water cause a corresponding change in oscillator frequency, which is transmitted via a wire link to a VHF transmitter in the surface buoy. There a frequency modulated carrier is transmitted to the aircraft. The probe takes approximately 4.5 minutes to descend 475 m., the maximum length of wire supplied. Occasionally, the wire breaks at this point and transmission ceases. Otherwise, transmission continues until the unit scuttles itself after about 6.5 minutes. The output voltage from an electronics package aboard the aircraft is calibrated against the temperature sensed by the probe. The system operates over a temperature range from 0 to 30C with an accuracy of about 0.6C.

2.2 Drift Angle (DA)

The drift angle is the difference between the track angle (TRK) and the heading (HDG). It ranges from -180 to 180 degrees. The equations used are:

$$DA = TRK - HDG$$

$$\text{If } DA \geq 180 \text{ then } DA = DA - 360,$$

$$\text{If } DA < -180 \text{ then } DA = DA + 360.$$

The error is the sum of the errors in TRK and HDG or about 0.7 degrees. The drift angle is also available directly as an output from the inertial navigation system.

2.3 "D" Value (DV)

The "D" Value is defined as the difference (in meters) between the geopotential altitude (GA) and the pressure altitude (PA):

$$DV = GA - PA.$$

The error is approximately the sum of the errors in the PA and RA. Below about 1km altitude the error is less than 25 m. Above 1km the error is ±(10 m + 2% of altitude).

2.4 Filtered Vertical Wind (FWZ)

The vertical wind is computed from the difference between the vertical speed of the aircraft (VS) and the vertical airspeed relative to the aircraft (VA). The result is filtered by a first order autoregressive filter. The equations are:

$$WZ = VS - VA,$$

$$FWZ = (1 - BFIL)\ WZ + BFIL * FWZ.$$

BFIL is the filter constant, currently equal to 0.60653

VS is computed from the integrated vertical accelerometer output of the inertial navigation system. VA is computed from the angles of attack, sideslip pitch and roll.

The estimated error in the vertical wind is about 0.5 m/s based on aircraft intercomparisons.

2.5 Ground Speed (GS) and Heading (HDG)

Ground speed and heading are supplied by the inertial navigation system. This is described in more detail under LAT and LONG. Estimated errors are 0.5 m/s (GS) and 0.2 degrees (HDG) for 15 minute averages. Instantaneous values may have larger errors, especially in tight turns. These may be as large as 4 m/s and 0.4 degrees.

2.6 Height of Standard Pressure Surface (HT)

The height of standard pressure surface is derived from the pressure altitude (PA), virtual temperature (TV), and geopotential altitude (GA).

$$\text{Let } TSA = 288.15 - 0.0065\ PA. \quad \text{Then } HT = GA + (H\text{-}PA)\ TV/TSA$$

where H is a constant that selects the appropriate pressure surface. The values of H are given below:

STANDARD PRESSURE (mb)	NOMINAL ALTITUDE (K ft)	H (m)
850	5	1457
700	10	3012
500	18	5574
300	31	7185

The error is the sum of the errors in PA and GA plus the error due to TV. It is of the order of 15 meters.

2.7 Latitude (LAT) and Longitude (LONG)

Latitude and longitude as well as ground speed (GS), track (TRK), heading (HDG). pitch, roll and vertical aircraft acceleration are determined by an Omega-aided Inertial Navigation System. The system contains a three axis accelerometer mounted in a gyro-stabilized platform. Orientation of the aircraft with respect to the platform gives heading, pitch, and roll, while integration of the accelerometer outputs gives ground speed and track. Ground speed and track are integrated to give LAT and LONG. These are compared with values obtained from a radio navigation system (using VLF radio signals called Omega signals) in the navigation system computer. In this manner, drift in the inertial system can be corrected.

Position accuracy is usually good to within one minute of latitude or longitude (approximately 2km).

2.8 Liquid Water Content (LW)

Liquid water content of clouds is measured by a Johnson-Williams constant current hot-wire device. It is sensitive to drop sizes smaller than 50 microns but does not respond effectively to large droplets. The voltage from the instrument is filtered and digitized by the aircraft data system. The range of measurements is 0 - 6 g/m^3 with accuracy of about ±20% over the drop size range to which the instrument responds.

2.9 Pressure Altitude (PA)

The pressure altitude is derived from the static (ambient) pressure (PS) as follows:

$$PA\ (\text{meters}) = 44331\ (1 - (PS/1013.25)^{0.190263})$$

where PS is measured in millibars. This formula is taken from the definition of the ICAN standard atmosphere (see List (1958), page 268). The error is on the order of 10 m.

2.10 Differential Pressure (PQ)

Differential pressure is measured by a pitot-static tube and quartz oscillator type transducer located on the left wing tip. The range of measurement is 0 - 300 mb with an RMS error of 0.05 mb. A dynamic error correction is applied to the raw measurement. The formula is:

$$PQ\ (corrected) = PQ\ (raw) + ES2I + ES2S * PQ\ (raw)$$

where current values for the correction coefficients are derived for each aircraft based on in-flight and laboratory calibrations. ES2I is about 0.5 and ES2S is about -0.04.

2.11 Ambient Pressure (PS)

Static (ambient) pressure is measured by the same pitot-static tube used for PQ above. A quartz oscillator type transducer with a range of 250 - 1050 mb is used. The RMS error is 0.15 mb. A dynamic error correction is applied to the raw measurement. The formula is:

$$PS\ (corrected) = PS\ (raw) + ES1I + ES1S * PQ$$

where current values for the correction coefficients are derived for each aircraft based on inflight calibrations. ES1I is about 1 and ES1S is about 0.035.

2.12 Radar Altitude (RA)

Radar altitude is measured by a pulsed microwave radar having a range of 200 to 50,000 feet. The accuracy is the greater of 8 feet (3 m) or 1% according to the manufacturer but in-flight tests suggest errors as large as 50 feet (15 m) or 2% can occur. See Merceret et al (1980).

2.13 Relative Humidity (RH)

Relative humidity is computed from the ambient pressure (PA), temperature (TA), and dewpoint (TD). Intermediate quantities which must be computed are the ambient vapor pressure (EE) and saturation vapor pressure (EW). The formula is:

$$RH = \frac{100\ EE\ (PS - EW)}{EW\ (PS - EE)}$$

Appropriate corrections are made for Td < 0 (frost point). The accuracy is determined by the errors in PS, TA and TD and is on the order of ±10%. Note that the RH displayed in-flight is that measured by the Omega Dropwindsonde system, and not that based on the aircraft on-board sensors described above.

2.14 Surface Pressure (SP)

The estimated surface pressure is derived from the ICAN standard atmosphere in a manner similar to that used for height of standard surface (HT).

Let $TSA = 288.15 - 0.0065\ PA$ and

$PAS = PA - GA * TSA/TV.$ Then

$$SP = 1013.23\ (1 - PAS/44331)^{5.25588}$$

with an error on the order of 1 to 2 mb if measured below 1,500 feet (500 m) altitude. Surface pressures estimated from higher altitudes are less reliable. Errors could exceed 10 mb above 10,000 ft. (3km).

2.15 Sea Surface Temperature (SST)

Sea Surface Temperature is measured by a downward looking infrared radiometer (Barnes PRT-5) operating in the 9.5 - 11.5 micron window. The intensity of black body radiation from the sea surface is converted to a calibrated voltage by an RFC modified electronics package, filtered and digitized. The instrument operates in a pre-selected 20C range in the region -50 to +40C with an accuracy of 1 to 2C. The measurement is invalid when clouds obstruct the optical path between the instrument and the sea surface. Errors of 10C or more can occur in these circumstances.

2.16 Air Temperature (TA)

Air temperature is computed from total temperature (TT) measured by a platinum resistance thermometer and corrected for compressibility and exposure effects. The formula is

$$TA = ((TT + 273.16)/(1 + 0.2M^2)) + TE - 273.16$$

where M is the Mach number and TE is the temperature probe recovery error is given by

$$TE = 0.00109\ PQ^2/\sqrt{PS}.$$

The error is about +0.2C. In very wet environments additional error (cooling) due to wetting of the sensor has been observed (Lemone 1980).

2.17 True Airspeed (TAS)

True airspeed is derived from the Mach number (M) (which is derived from PS and PQ) and virtual temperature (TV). The formula is

$$TAS = 16.9435\ M\ \sqrt{GM*TV}$$

where GM is the ratio of specific heats (γ) for air and is approximately equal to 1.4. The range of measurement if 0 to 250 m/s with an RMS error of about 0.5 m/s.

2.18 Dewpoint Temperature

The dewpoint (frost point) is measured by a platinum resistance thermometer embedded in a thermo-electrically cooled mirror. The mirror temperature automatically adjusted until dew (or frost) just forms on its surface as measured by an optical sensor. The temperature of the mirror is reported as the dew (frost) point. If the measured temperature is below zero, the frost point (TW) is converted to vapor pressure (EE) using

$$EE = 6.1078 \exp (22.4716TW/(272.722 + TW))$$

The equivalent dewpoint is computed using

$$TD = 243.17 (\ln EE - 1.8096)/(19.4594 - \ln EE).$$

The range is -50 to 50C with an error of about 1C.

2.19 Track Angle (TRK)

The track angle is provided by the inertial navigation system. It can also be computed from the heading (HDG) and drift angle (DA) using

$TRK = HDG + DA$ and

If $TRK < 0$ then

$TRK = TRK + 360^{o}$.

The error is about ±0.5 degrees.

2.20 Wind Direction (WD) and Wind Speed (WS)

Wind direction and wind speed are derived from the true airspeed (TA), heading (HDG), sideslip angle (SA), ground speed (GS) and track angle (TRK). The TAS, SA and HDG give a vector airspeed $\tilde{A}$. The GS and TRK give a vector ground speed $\tilde{G}$. The vector wind $\tilde{W}$ is given by $\tilde{W} = \tilde{G} + \tilde{A}$. The range of each component (N-S and E-W) is ±150 m/s with an error of about 1 m/s for 15 minute averages. Errors for short records, especially in turns, can exceed 4 m/s.

3. VARIABLES COMPUTED BUT NOT DISPLAYED IN-FLIGHT

Table 2 presents those variables computed by the RFC software which are used to derive displayed quantities or which are of independent meteorological interest. It is in the same format on Table 1. It does not include all other quantities computed since many intermediate functions, correction factors and variables of purely engineering interest are computed whose inclusion here would contribute little to warrant their bulk.

Table 2. SELECTED UNDISPLAYED QUANTITIES COMPUTED BY RAMS ONBOARD SYSTEMS

Abbreviation	Quantity	Units
AA	Attack Angle	degrees
AMR	Mixing Ratio	gm/kg
EE	Vapor Pressure	mb
ET	Equivalent Potential Temperature	Kelvins
EW	Saturation Vapor Pressure	mb
GA	Geopotential Altitude	m
GM	Ratio of Specific Heats	none
M	Mach Number	none
PT	Potential Temperature	Kelvins
SA	Sideslip Angle	degrees
TV	Virtual Temperature	Kelvins

The discussion following will appear in the same order as the variables appear in Table 2 and as before, cross referencing will be used as needed.

3.1 Attack Angle (AA)

Angle of attack is measured by a differential pressure probe which senses a differential attack pressure (AP) between two pressure taps above and below the centerline of the probe. A correction for the dynamic pressure (PQ) is applied. The formula is

$$AA = AAI + AAS * AP/PQ$$

where AAI and AAS are constants determined for each aircraft each year during calibration. AAI is about 1.5 ± while the magnitude of AAS is about 6 ± 1. The sign of AAS is positive for N42RF and negative for N43RF because of differing internal connections to the pressure sensors. The range of measurement is ±12 degrees with an error of less than 0.5 degrees.

3.2 Mixing Ratio (AMR)

Mixing ratio is computed from the formula

$$AMR = 621.97\ EE/(PS - EE)$$

where PS is the ambient pressure and EE is the vapor pressure. The accuracy is the same as that of the vapor pressure below.

3.3 Vapor Pressure (EE)

Vapor pressure is determined from the dewpoint or frost point measured by a cooled mirror dewpoint hygrometer. Let TW be the mirror temperature, then

if $TW \geq 0C$,

$$EE = 6.1078 \exp (17.6498\ TW/(243.17 + TW));$$

if $TW < 0C$,

$$EE = 6.1078 \exp (22.4716\ TW/(272.722 + TW)).$$

The accuracy of TW is ±1C. The accuracy of EE is non-linear but is of order 10% in the range $-30 \leq TW \leq 30C$.

3.4 Equivalent Potential Temperature (ET)

Let TN be the air temperature in K (TN = TA + 273.16) and RH be the relative humidity. Let

$$A = \frac{EE \ln (RH/100)}{(PS - EE)} (1.03185\ TN - 1730.33) + 21130.51 + 11.087\ TN$$

and $B = (184.952 - 0.779402\ TN) \ln (RH/100) + 14.6777\ TN.$

Then $ET = PT \exp (A/B)$

where PT is the potential temperature. The error is on the same order as that in PT (±0.2K).

3.5 Saturation Vapor Pressure (EW)

If the air temperature is TA, then

$$EW = 6.1078 \exp (17.6498\ TA/(243.17 + TA))$$

with an error of about 2% over the range

$$-30 \leq TA \leq 30C$$

based on a temperature accuracy of ±0.2C.

3.6 Geopotential Altitude (GA)

GA is computed from the radar altitude (RA) and the latitude (LAT) as follows:

Let $G = 980.616 (1 - 0.0026373 \cos (2\ LAT))$, and

Let $R = 6482.01\ G$, then

$$GA = (G*R*RA)/(980 (R + RA)).$$

The error is approximately the same as the error in the radar altitude (15 m or

2%, whichever is greater). The difference between RA and GA is less than 0.5%, hence GA ≃ RA.

3.7 Ratio of Specific Heats (GM)

Let $E = EE/(PS - EE)$

then $GM = (1004.64 + 1148.16E)/(717.6 + 861.12E)$

which is approximately equal to 1.4.

3.8 Mach Number (M)

The Mach number is computed from GM above and the differential and static pressures PQ and PS.

Let $GO = GM - 1$

$$\text{then } M = \sqrt{\frac{2}{GO}\{(1 + PQ/PS)^{(GO/GM)} - 1\}}$$

The error is of order 1%.

3.9 Potential Temperature (PT)

Let TN be the absolute temperature (TN = TA + 273.16) and PS be the ambient pressure (PS). Then

$$PT = TN\ (1000/PS)^{0.285714}$$

with the same accuracy as TN (±0.2K).

3.10 Sideslip Angle (SA)

The sideslip angle is computed from differential pressure (with laterally displaced taps) in the same manner as attack angle (AA). The equation is

$$SA = SAI + SAS\ (BP/PQ)$$

where BP is the differential sideslip pressure, SAI is currently near zero and SAS is about -6.6 for both aircraft. The range is ±12 degrees, with an error not exceeding ±0.5 degrees.

3.11 Virtual Temperature

Let TN be the absolute temperature (TN = TA + 273.16), PS be the static pressure and EE the vapor pressure. Then

$$TV = PS*TN/(PS - 0.37803\ EE)$$

with an error of about ±0.3K.

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APPENDIX A

Summary Description of the WP3D Aircraft

The RFC P3's were produced by Lockheed Aircraft Corporation on special order for the RFC. N42RF was delivered in June 1975 and N43RF was delivered in February 1976. They are four engined turboprop aircraft having a maximum operating range of about 3,000 miles at a cruising altitude of 20,000 feet or 2,200 miles at 500 feet. Maximum ferry range is about 4,200 nautical miles. They normally operate at a true airspeed near 300 kt. in smooth air. In turbulent air, speed is reduced to about 220 kt. Maximum endurance is 8 to 10 hours depending on altitude and aircraft gross weight. Seating capacity varies from around thirteen to about seventeen depending on weight and balance limitations. When heavy expendables like AXBT's are carried then fuel or seats or both must be reduced to stay within acceptable load limits.

APPENDIX B

Description of Certain Sensors Providing Input to the Quantities Described in this Paper

B.1 The Inertial Navigation System (INS)

The INS on the NOAA P3 aircraft has three major position determining components: an inertial platform, an Omega (radio) navigation receiver, and a Doppler radar navigation system.

The inertial platform is gyro-stabilized to maintain its orientation about three axes in an inertial reference frame. This is corrected for motion about the Earth's surface so that one plane of the gyro system stays level with reference to the surface of the Earth. A three axis accelerometer affixed to the platform provides acceleration information in the reference coordinates which can be integrated to yield velocity and position.

The Omega system receives VLF radio signals from several transmitting stations of known position and triangulates position based on phase relations among the signals.

The Doppler radar determines ground speed from the Doppler shift in the ground return from a radar pulse. This, with heading information, can be integrated to yield position from a known starting point.

All three position sources are routed to a Kalman filter in the INS control computer which generates a "best-fit" position that compensates for inertial platform drift, Omega propogation anomalies and Doppler errors.

B.2 Total Temperature

On the RFC aircraft the free air temperature sensor is a Rosemount Model 102CH2AF total temperature probe with fast response (~1 sec.). The sensing element is a precision platinum wire having 500 ohms resistance at 0^oC. The resistance is a known function of temperature. The relationship, known as the Callender-Van Dusen equation (see Benedict (1977) Ch. 4, 6.), is linearized in the amplifier/signal conditioner described below.

The probe is designed to control boundary layer growth on its interior surfaces. The pressure within the probe is higher than that outside so that air is drawn off via ports in the sensor housing. This also causes the flow to make an abrupt turn to pass over the sensing element while water droplets in the flow are routed directly out of the probe. Flow separation at the turn is prevented by boundary layer removal at the inside of the turn. The inertial trapping of water droplets is not always sufficient to keep the probe dry so some evaporative cooling occurs in very wet environments (Lemone 1980).

There is an electric heater built into the sensor housing permitting accurate temperature measurements even during atmospheric icing conditions. The heater is of the temperature compensation type which reduces the heat generated when the housing becomes warm, thus permitting operation in still air without damage.

The Amplifier/Signal conditioner (Model 510DY1) is used with the total temperature probe. Output voltage is proportional to the sensed temperature within ±0.15% from -5 to +5V, for the temperature range -60 to $+60^oC$. For calibration check purposes, the unit has built-in capability to replace the sensor with two selectable resistors having extremely low temperature coefficients (typically of the order of 5×10^{-6}/C). The stated output voltages are connected to an electronic multiplexer with high input impedance.

Accuracy	- ±0.29C
Range	- -60^o to $+60^oC$
Limits	- Temperature -90 to 350^oC for sensing element and a maximum of 250^oC for the resistor housing receptable.
Speed	- 0 to 3 Mach number
Altitude	- 0 to 100,000 ft.
Humidity	- 0 to 100% RH

B.3 Pressure (Static and Dynamic)

Pressure is sampled with a wing-tip mounted pitot-static tube with internal electrical de-icing. The transducer is located in the wing tip as well to keep pneumatic lines short to the maximize frequency response of the measurement.

Pressure is measured by monitoring the deflection of a fused quartz deflection diaphragm. The deflection of the diaphragm is a function of the pressure applied, causing a change in the capacitance between electrodes deposited in the diaphragm. This capacitance is the frequency determining element in the LC oscillator circuit of the sensor. As the capacitance varies with pressure a variable frequency signal is generated. Temperature compensation is accomplished using a temperature sensor attached to the housing.

The pressure encoders sense the absolute value of pressure (Ps), the positive differential (Pq) pressure, and the internal temperature of the sensing device. The sensed temperature in analog form is converted to digital format by a dual ramp A/D converter to provide thermal compensation for the pressure sensor. The differential pressure encoders use Ps to compensate for dielectric changes. The sensed Ps in analog form is converted to digital format through the use of the same dual-ramp A/D converter.

B.4 Dewpoint

Dewpoint is measured using a cooled-mirror dewpoint hygrometer. When power is applied to the instrument, the mirror surface of the cooling module is dry and at ambient temperature. Light from a solid state source is reflected by the mirror to a DIRECT photoresistor and a portion of the light controlled by the bias from the lamp is detected by a BIAS photoresistor. The photoresistors feed a Control Amplifier and the power output circuit causing current to flow to the module. This cools the mirror to a point where condensation occurs on the mirror surface. As condensation occurs, the light reflected to the DIRECT photoresistor is scattered and therefore reduced in intensity.

The imbalance is detected by the Control Amplifier, resulting in a decrease of cooling current and a subsequent increase in mirror temperature. The operation is that of a servo system utilizing proportional control to continually adjust itself to maintain a constant dew layer thickness on the mirror surface. When the dew on the mirror is of constant thickness it is in equilibrium with the partial pressure of the water vapor in the air sample. Under these conditions the temperature of the mirror is the dewpoint temperature.

The mirror temperature is measured by a precision platinum resistance thermometer embedded inside the mirror. The resistance of the thermometer forms part of a bridge circuit which provides a linearized 0-5 vdc output.

Under conditions where the dewpoint is below $0^{o}C$, the instrument may initially cool to the supercooled dewpoint. However, this is a highly unstable situation and the system will quickly come to frost point equilibrium.

The exposure of the dewpoint sensor appears to be adequate to respond to the free environment without contamination by liquid water in the flow. This prevents humidity errors of the type reported by Lemone (1980) and

Lenschow and Pennell (1974).

B.5 Angles of Attack and Sideslip

These angles are measured using a sensor with five ports positioned on a hemispherical head pointed into the airstream. This measures flow angles by measuring pressure differentials between various combinations of ports. The ports are located one above center, one below center, one left, one right, and one on center. They provide a pneumatic signal proportional to the non-alignment with the relative airflow. These pressures are transferred from the ports by internal pneumatic tubes to transducers. One pair of ports provides the total pressure while the other pair gives values representative of the angle. When the aircraft flies at zero angle of attack, the top and bottom ports sense equal pressures. As the aircraft rotates to a positive angle of attack, the pressure of the lower port becomes greater than the pressure at the upper port. The greater the angle of the aircraft in reference to the relative airflow, the greater the pressure differential between the two ports.

The sideslip sensor works identically but in the horizontal plane. The pressure differential increases at lower altitudes and higher airspeeds, therefore a normalizing function must be introduced to account for the changes in altitude and airspeed. The port located in the center of the sensor head provides a local pitot pressure source for this purpose. The probe is heated to prevent ice accumulation.

B.6 Cloud Liquid Water

The Johnson-Williams liquid water indicator consists of a heated sensing head with a supporting strut mounted in the airstream, a power unit, and a control unit containing the power, range and airspeed controls, an indicating meter and all other components of the measuring circuit.

A calibrated resistance wire is mounted with its axis perpendicular to the airstream. The element is connected as one arm of a balanced bridge circuit. As water droplets in a cloud impinge on the heated wire they are evaporated. The cooling effect of evaporation on the wire decreases its electrical resistance. The change in resistance causes the bridge to become unbalanced. The degree of unbalance is a function of the liquid water content in the airstream.

A second resistance wire, mounted on its axis parallel to the airstream direction, and hence not subject to water drop impingement, is connected as an adjacent arm of the bridge. This wire serves to compensate for variations in airspeed, altitude and air temperature. The output of the bridge is therefore proportional to the rate of impingement of water on the sensing wire. This signal is converted to concentration of water per unit volume of air using an adjustment for true airspeed.

B.7 Radar Altitude

The APN-159 Radar Altimeter comprises four basic components: receiver-transmitter, power supply, indicators, and two antennas mounted on the underside of the airplane. The receiver-transmitter (R-T) develops recurring RF pulses which are radiated from the transmitting antenna to the ground. The signal which is reflected back up to the receiving antenna is amplified, detected, and shaped in the receiver for use in the computer portion of the system. It is compared to a reference pulse which occurs at the time of transmission. The comparison is used to drive a servo loop which is positioned according to the altitude-induced pulse delay. A pair of synchros supply analog signals for positioning of the indicator pointer and digital readout. The indicator presents this information as a pointer indication (100s of feet) and as a digital display (1000s of feet) at the various positions in the airplane where it is required. In addition, several remote outputs are available for interfacing to the external equipment. A built-in test (BIT) capability gives a lamp and/or pointer indication to check receiver sensitivity, transmitter frequency, transmitter power, and system tracking accuracy. An automatic calibration (AUTOCAL) is performed for one second every third minute of operation to insure that the system is tracking properly and to correct any small inaccuracies which may have developed.

B.8 Sea Surface Temperature

The modified Model PRT-5 Precision Radiation Thermometer is a non-contact, direct reading, temperature-measuring instrument. The PRT rapidly responds to the naturally-emitted radiation from surfaces which fill its field of view.

The PRT-5 consists of an Optical Unit and an Electronics Unit. The Optical Unit continuously compares the amount of energy emitted by the target with that emitted by an internal, controlled, reference environment. The Electronics Unit converts this optical comparison into a voltage which is directly related to the energy difference between the target and the reference.

Precision and stability are achieved by using a very sensitive hyper-immersed thermistor bolometer as the radiation detector mounted in a tightly controlled reference temperature cavity. The optical elements are also located in the temperature controlled reference cavity. The electronic circuits are ambient temperature stabilized, and large amounts of negative feedback are employed which produce a gain stability of better than 0.1%.

Radiation emitted from a target first arrives at an optical chopper which alternately blocks the radiation and passes it to the detector. When the detector path is blocked, the detector effectively sees itself. Like all elements in the optical path, the detector is at the reference temperature, hence the detector alternately receives radiation from the target and from its own temperature-controlled environment. It produces an electrical output signal proportional to their difference.

The detector signal is amplified and then processed by a band-pass filter network having a center frequency of 100 cps, the optical chopping rate. The signal then goes to a post amplifier whose gain is set to give the correct span. The output of the post amplifier is coupled to a demodulator where the signal is synchronously rectified to produce a d-c voltage which is related in magnitude and polarity to the difference between the target and reference. The d-c voltage from the demodulator is calibrated in terms of temperature.

APPENDIX C

Description of Aircraft Systems Not Directly Providing Sensor Inputs to the Variables Described in this Report

C.1 The Data Recording Systems

There are several recording systems aboard the WP-3D aircraft: one system is dedicated to the meteorological, radiation, and some cloud physics sensors, another system is dedicated to the nose, lower fuselage and tail radars, and others to cloud physics and dropwindsonde systems. Only the first system mentioned above is described here. It records all of the data used to compute the variables described in this paper.

The WP-3D meteorological data acquisition system samples 64 ADC channels at a rate of 40 samples per second per channel. It also collects information from the aircraft navigation system at the same rate. This information is filtered and then recorded on magnetic tape.

There are two HP-2100A computers: one used for data collection and recording, the other for real-time analysis, graphics and disc storage. Each has 32K of memory.

The recording is done in two formats. In the digital format, the rate is one per second; in the analog format, the rate is determined by the investigator and may be as high as 40 per second. Rates up to 2000 per second can be obtained by connecting the same signal to multiple channels.

Filtered data are further processed to calculate flight level meteorological parameters. These are displayed on CRTs throughout the aircraft.

The data analysis system has been designed with flexibility in order to meet present and future investigator requirements. Through interactive terminals the investigator has control of the data reduction he wishes to perform in real-time. A graphic sub-system exists which allows a wide range of versatility in the representation of the data.

The graphics computer receives sensor information at a rate of one per second. This information is stored on the disc in a history file which can accommodate up to 18 hours of recording. Thus, the investigator is afforded the convenience of calling data of a previous flight pattern, or data taken on a previous day.

A block diagram of the data acquisition and display system is shown on the following page.

DATA SYSTEMS

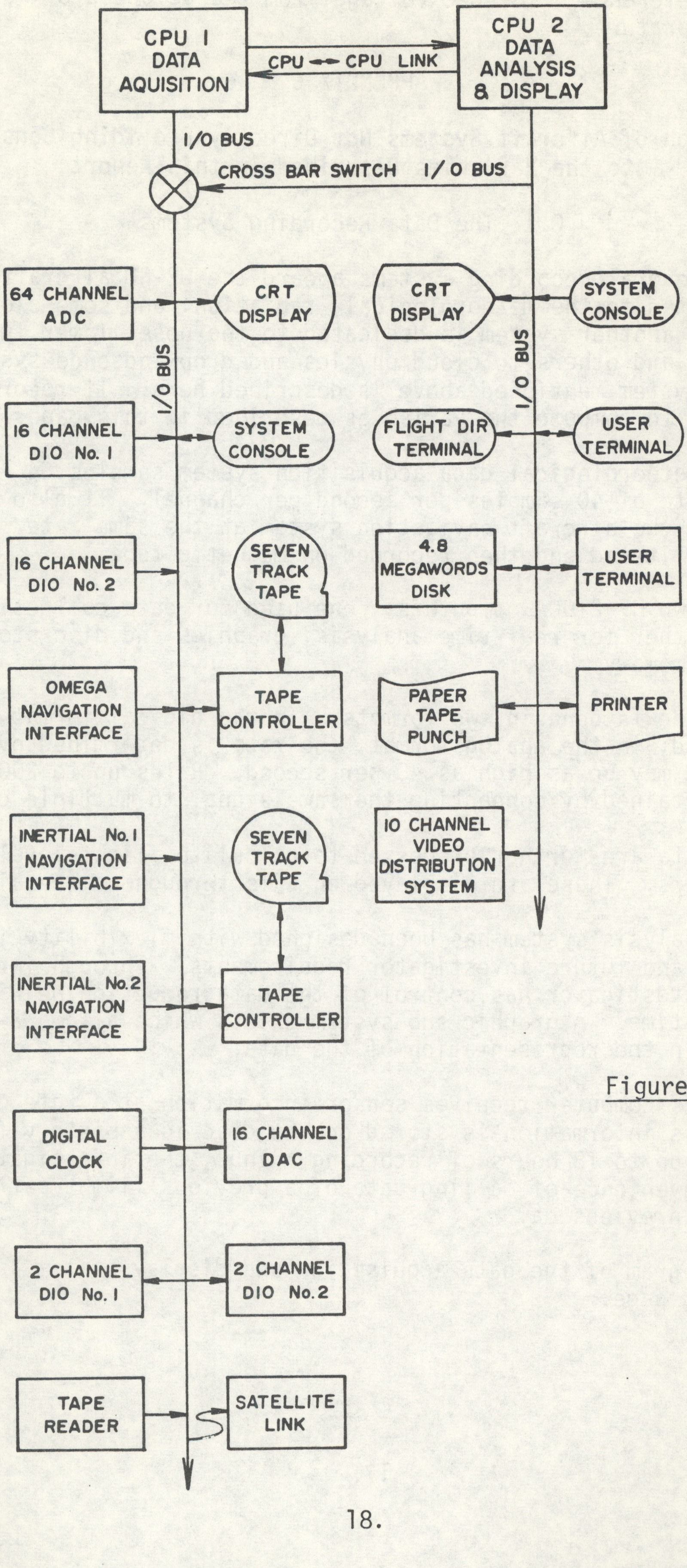

Figure 1

C.2 The Radar System

The WP3D has three meteorological radar systems: nose, lower fuselage, and tail. These are used to measure the radar reflectivity of cloud and rain areas from which their liquid water content or rainfall rate can be inferred (see Battan (1973), Ch. 7).

The table on the following page shows their individual characteristics.

The data from these radar systems is recorded on digital tape after processing in a Digital Video Integrator Processor (DVIP) and an HP-2100A mini-computer.

The nose and lower fuselage radars can be used by the flight crew for severe weather avoidance or penetration as desired. Both provide a plan position indicator (PPI) display of the position and intensity of meteorological radar targets. The tail radar scans about an axis aligned with the motion of the aircraft and produces a range-height indication (RHI) output useful for estimating cloud depth.

Controls located at the radar operator's station allow manual control of the displays to "zoom in" on selected features and magnify them.

C.3 The Hydrometeor Spectrometers

The PMS (Knollenburg) probes which measure particle spectra are located in pods under the wing tip. Their data are recorded on a dedicated recorder (Data Acquisition System Model DAS-2D). The sensors include the Forward Scattering Spectrometer Probe Model FSSP-100, the Optical Array Spectrometer Probe Model OAP-2D-C, and the Optical Array Spectrometer Probe Model OAP-2D-P.

The forward scattering probe (FSSP-100) measures particle sizes by the amount of light scattered into the collecting optics aperture during particle passage through a focused laser beam. The scattering signal pulses are A-C coupled to a pulse height detector which compares their maximum amplitude with a reference voltage derived from a separate measurement of the DC light signal illuminating the particles. The output of the pulse height detector is encoded to give the particle size in binary code. This system is capable of sizing particles from 0.5 to 45 microns diameter. The system resolves particles into 15 equally spaced sizes. It is capable of sizing particles having relative velocities from 10 to 125 m sec^{-1}. The probe also has a gate output signal which is a measure of particle transit time. The system automatically rejects particles with transit times less than average since these are susceptible to edge effect errors and result from particles passing through regions of less than maximum intensity.

The optical array spectrometer probe (OAP-2D-P) is a 2-D particle size spectrometer which uses a photodiode array and photo detection electronics similar to the 1-D PMS optical probes. However, the system contains a high speed front end data storage register which enables each photo detector element to transmit up to 1024 bits of shadow information rather than 1 bit from each

Table 3 - RADAR CHARACTERISTICS

	NOSE RADAR	LOWER FUSELAGE RADAR	TAIL RADAR
Transmitter Frequency	5445 ± 6.6 MHz	5370 ± 6.7 MHz	9315 ± 11.6 MHz
Transmitter Pulse Length	3.0 μsec	6.0 μsec	0.5 μsec
PRF	400 pps	200 pps	1600 pps
Power Output	70 KW (Min)	70 KW	60 KW
Power Amplifier	Magnetron	Magnetron	Magnetron
Receiver Curve	Logarithmic	Logarithmic	Logarithmic
Receiver Dynamic Range	80 dB	80 dB	80 dB
Noise Figure	6 dB	6 dB	6 dB
Receiver B. W.	425 KHz	233 KHz	2 MHz
Intermediate Frequency	30 MHz	30 MHz	30 MHz
Antenna Polarization	Linear, Horizontal	Linear, Horizontal	Linear, Vertical
Gain, Main Beam	34 dB	37 dB	40 dB
Beam Width	Az., El., 3.6^o	Horiz. 1.1^o Vertical 4.1^o	Horiz. 1.35^o Vertical 1.9^o
Sidelobe Gain	23 dB down	23 dB down	23 dB down
Azimuth Coverage	Variable to ±220^o	360^o	±50^o
Elevation Coverage	40^o	20^o	360
Antenna Stabilization	Pitch & Roll	Pitch & Roll	Grd. Trk. & Pitch

particle. The particle's transit serves to scan the array and "image slices" are recorded across the shadow to develop a true two-dimensional image.

The technique employed to achieve 2-D information from particles passing through the probe is to take image slices of each particle as it progresses through the sampling volume of a single linear photodiode array. The system employs 32 active photodiode elements in the array and takes image slices at a rate of up to 4 million per second when a particle passes through. The 2-D clock is variable below this maximum rate and can be set so that the size resolution across the array (particle width) is identical to the image slice resolution through the array (particle length).

The beam emerges from the laser as a spot 1 to 2 mm diameter. The beam is modified by a lens system in the telescope attached to the front of the laser to provide a beam at the sample area of an optimum size and shape for the size of the particles to be observed. The laser beam is deviated through a mirror system to arrive at the sample area. A similar mirror system is between the diode array and the sample area. After the sample area there is an objective lens which images the particle into a microscope eyepiece which images the particle onto the diode array.

The probe is housed in a cylindrical pod and interfaces with a PMS Model DAS-2D dual 2-D Data Acquisition System (DAS). The probe can collect particle image information at the rate of 128 million bits per second. Data are recorded only when particles are present and thus automatic data compression results.

The DAS-2D accepts data from the two PMS 2-D particle imaging probes and the FSSP-100 probe along with various other input data and makes it all available for writing on computer compatible magnetic tape. A selectable four digit decimal display is standard and allows viewing any single word in the slow data format as desired. There is also provision for three manual event entries into the data and a six digit decimal display of time in hours, minutes and seconds.

Data written on the output computer tape are not affected by selection of words for viewing on this display. A particle image display is available to allow real-time viewing of image data from either 2-D probe as desired.