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Variables and Algorithms Used for RAF's Production Output Data Products

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Contents

1 INTRODUCTION

1.1 Alphabetical List of Variables

The index to this appendix includes all variables described in this Appendix, with links to where they are discussed. The index also includes some variables not discussed here; where possible, reference to those variables and information on the project(s) where they were used has been included also.

It will be useful to understand the RAF naming conventions as described in the next sub-section to be able to use this index effectively.

1.2 General Comments

This Appendix describes the basic measurements made on RAF aircraft and, where appropriate, includes the equations used by the RAF's "nimbus" software to calculate the derived measurements – those resulting from the use of one or more other measurements (raw and/or derived). Since 1993, data from research flights have been archived in NETCDF format, and the NETCDF header for recent projects will include detailed information on the measurements present in the file, how they depend on other measurements, units, etc.

Before 1993, data were processed by a different program, "GENPRO," and a different output format (also named GENPRO) was used for archived datasets. Some variable names shown below, esp. in section 15, refer to obsolete variable names, some used with GENPRO and others referring to instruments that are now retired. These names are included here so that this Appendix can be a reference for older archived data as well as for current data files.

There are some cases where redundant measurements are present, often for key measurements like pressure or temperature. When these are used in subsequent calculation of derived variables like potential temperature, some choice is often made regarding which measurement is considered most reliable. It is useful to record which measurement was so designated, so a reference measurement, chosen from a group of redundant measurements, usually has a variable name ending with the letter(s) X or XC. Some do not follow that convention: base_time, time_offset, ATTACK, SSLIP and EDPC. (See their individual descriptions below.)

There are references in the following descriptions to the data system in use, because this has changed several times. The data systems in use were, approximately, as given in the following table:

data system	start	end
ADS-1		
ADS-2		
ADS-3		
NIDAS	2005	present

1.3 System of Units and Values Used For Constants

This document will favor the SI system of units, but there are many exceptions. Among them are the following:

1. The millibar (mb) or hectopascal (hPa) is used for pressure.
2. Many variables are presented in the units most often used for that variable, even when they involve CGS units or mixed CGS-MKS units, as for example [$g\,m^{-3}$] for liquid water content or [cm^{-3}] for droplet concentration.
3. Flow rates are often quoted in liters per minute (LPM) or standard liters per minute (SLPM) because those terms are linked to properties of commercially available instruments with flow control. One liter is $10^{-3}\,m^3$. Because there is considerable ambiguity in the definition of "standard" conditions (regarding choice of the reference pressure and temperature), the particular usage will be documented in each case.
4. The International Bureau of Weights and Measures recommends against use of units like percent or parts per million, but these are so conventional in atmospheric chemistry and elsewhere that data filesl continue to use those units for relative humidity or the concentration of chemical species. Typical units are ppmv or ppbv for parts per million by volume or parts per billion by volume. Care must be taken to interpret ppbv especially, because "billion" has different meaning in different languages and different countries; herein, 1 ppbv means a volumetric ratio of 1:10^9. Many measurements produce native results in terms of a mass ratio, often described as a mixing ratio r_m in terms of mass of the measured gas per unit mass of "air" (where the weight of the "air" does not include the variable constituents, usually only significant for water vapor). The perfect gas law relates the density ratio of two gases ($\rho_1 : \rho_2$) to the ratio of their partial pressures ($p_1 : p_2$) or number densities ($n_1 : n_2$), as follows:

   $$r_m = \frac{\rho_1}{\rho_2} = \frac{p_1 M_1}{p_2 M_2} = \frac{n_1 M_1}{n_2 M_2}$$

   where M_1 and M_2 are respective molecular weights for the two gases. The ratio of number densities or, equivalently, partial pressures, denoted here as r_v because it is also the volumetric mixing ratio, is related to the mass mixing ratio according to the following equation:

   $$r_v = \frac{n_1}{n_2} = \left(\frac{M_2}{M_1}\right) r_m$$

   When concentrations are recorded with units of "ppmv" or "pptv", these units refer to (respectively) $10^6 r_v$ or $10^9 r_v$ as given by the above equation.

5. The unit “hertz” (abbreviation Hz) is the proper unit for a periodic sampling frequency and will be used here in place of the more awkward term, “samples per second.” That is the usage favored by the International Bureau of Weights and Measures (cf. `http://www.bipm.org/en/si/si_brochure/chapter2/2-2/table3.html#notes`) when the frequency represented refers to the rate of sampling.

6. In some cases, particularly for older data files, speed has been recorded in units of knots (= 0.514444 m/s) and distance in nautical miles (= 1852 m).

The following are values used for some constants in this document:[1]

π = 3.1415926536...
C_{dr} = conversion factor, degrees to radians, = $2\pi/180^\circ$
g = acceleration of gravity[a], 9.7959 m s^{-2}
T_0 = temperature in kelvin corresponding to $0^\circ C$ = 273.15 K
T_t = temperature corresponding to the triple point of water = 273.16 K
M_a= molecular weight of dry air, 28.9644 kg kmol^{-1}
M_w = molecular weight of water, 18.01528 kg kmol^{-1}
R_0 = universal gas constant[b] = 8.314472×10^3 J kmol^{-1}K
$R_d = (R_0/M_d)$ = gas constant for dry air
R_E = radius of the Earth = 6.371229×10^6 m
c_p = specific heat of dry air at constant pressure = $\frac{7}{2}R_d$ =1.00470×10^3 J kg^{-1}K^{-1}
(value at $0^\circ C$; small variations with temperature are not included here)
c_v = specific heat at constant volume = $\frac{5}{2}R_d$ =0.717646×10^3 J kg^{-1}K^{-1}
(value at $0^\circ C$; small variations with temperature are not included here)
γ = ratio of specific heats, c_p/c_v, taken to be 1.4 (dimensionless) for dry air
Ω = angular rotation rate of the Earth = 7.292116×10^6 radians/s
Ω_{Sch} = angular frequency of the Schuler oscillation = $\sqrt{\frac{g}{R_E}}$
σ = Stephan-Boltzmann Constant = 5.6704×10^{-8}W m^{-2}K^{-4}

[a] for calculating altitude in the International Standard Atmosphere, g is 9.80665 m s^{-2}as specified by the ISA

[b] an exception to this value of R occurs in the calculation of pressure altitude, where the value R=8.31432×10^3J kmol^{-1}K^{-1} is used because that is required by the definition of the standard atmosphere

1.4 Abbreviations

The next table defines some abbreviations used in this appendix, in addition to the standard abbreviations for the mks system of units:[2]

[1] reference for R_0 and σ: http://physics.nist.gov/cuu/Constants/index.html

[2] where the symbol $\equiv$ is used, the relationship is exact by definition

CEP circular error probable: confidence level is 50% to be this close to the correct value (used to characterize the accuracy of IRS/INS position measurements)

$^\circ$ degree, angle measurement $\equiv (\pi/180)$ radian

ft foot $\equiv$ 0.3048 m

mb millibar $\equiv$ 100 Pa $\equiv$ 1 hPa

ppmv parts per million by volume (see section 4)

ppbv parts per billion (10^9) by volume

pptv parts per trillion (10^{12}) by volume

n mi nautical mile $\equiv$1852 m

kt knot $\equiv$ (1852/3600) m/s = 0.514444... m/s

1.5 Other Comments On Terminology

1.5.1 Variable Names In Equations

This Appendix often uses variable names in equations, and sometimes there is potential for confusion because the variable names consist of multiple characters. In many cases, to denote that the variable name is considered as the variable in the equation (as opposed to each of the letters in the variable name representing quantities to be multiplied together), the variable name has been enclosed in brackets, as in {TASX}. In addition, variable names always are displayed with upright Roman character sets, while other nomenclature in equations is represented by slanted (script) character sets as is conventional for mathematical equations. In cases where code segments (usually expressed in C code) are included to document how calculations are performed, typewriter character sets indicate that the segment is a representation of how the processing is coded. Such a code segment is not always a direct copy of the code in use, but such code is often the most convenient way to express the algorithm in use.

1.5.2 Distiinction Between Original Measurements and Derived Measurements

Many of the variables in the data files and in this Appendix are derived from combinations of measurements. The term "raw" measurement is often used for a minimally processed output received directly from a sensor or instrument. Such measurements may be subject to calibration coefficients or other conversion to new units, but otherwise they are a direct representation of the measured quantity.[3] In contrast, derived

[3]Calibration coefficients, e.g. those used to convert from voltage output from an analog sensor to a measured quantity with physical units like $^\circ C$), are not included or discussed in this appendix but are part of project reports and, in recent years, are included in the header of the NETCDF file.

variables (e.g., potential temperature) depend on one or more “raw” measurements and are not direct results of output from an instrument. For most derived measurements, a box that follows an introductory comment is used to document the processing algorithm. The box has a line dividing top from bottom; in the top are definitions used and explanations (usually with links) regarding variables that enter the calculation, while the bottom portion contains the equation, algorithm, or code segment that documents how the variable is calculated.

1.5.3 Dimensions in Equations

An effort has been made to avoid dimensions in equations except where it would be awkward otherwise. Some scale factors are introduced for only this purpose (e.g., to avoid dimensions in arguments to logarithms or exponentials), and some effort was made to isolate dimensions to defined constants rather than requiring that variables in equations be used with specific units. Some exceptions, however, remain, to be consistent with historical usage.

2 VARIABLES RELATED TO TIME

The data in all modern output files are referenced to Coordinated Universal Time (UTC), although there are some exceptions in old archived data files. The system time and date are synchronized to the Global Positioning System (GPS) at the beginning of each flight, and for data acquired by the present ADS-3 (NIDAS) data acquisition system time is synchronized continuously with the GPS time. Time variables are often different for older archived data files; some of the following are obsolete, but are included here for reference because they are important to those wanting to use those archives.

Time (s): <u>Time</u>

This is the reference-time *counter* for the output data files, used by data system versions beginning with ADS-3. It is an integer output at 1 sample per second *and has an initial value of zero at the start of the flight.* Add this to the "Time:units" attribute found in the NETCDF header section for this variable to obtain the UTC measurement time.

Example attribute:

`Time:units = ‘‘seconds since 2006-04-26 12:55:00 +0000’’ ;`

For code examples that show how to use "Time" see:

`http://www.eol.ucar.edu/raf/Software/TimeExamp.html`

Reference Start Time (s): <u>base_time</u> (Obsolete)

This is the reference time for the NETCDF output data files (data system versions before ADS-3). It represents the time of the first data record. Its format is Unix time (elapsed seconds after midnight 1 January 1970). Use this measurement and add time_offset to obtain the time for each data record. (Note: base_time is a single scalar, not a "record" variable, so it occurs just once in the output file.)

Time Offset from Reference Start Time (s): <u>time_offset</u> (Obsolete)

This is the time offset from base_time of each data record used for the NETCDF output files produced by data system versions before ADS-3. It starts at zero (0) and increments each second, so it can also be thought of as a record counter. Use this measurement and add base_time to obtain the time for each data record.

Raw Tape Time (hour, minute, s): <u>HOUR</u>, <u>MINUTE</u>, <u>SECOND</u> (obsolete)

(versions before ADS-3 only)

These three time variables are recorded directly from the aircraft's data system. Since ADS-3, this information is replaced by the "Time" variable and the "Time:units" attribute of that variable.

Date (m, d, y): <u>MONTH</u>, <u>DAY</u>, <u>YEAR</u> (obsolete)

(versions before ADS-3 only)

These three variables represent the date when the aircraft's data system began recording data. They are repeated as 1 Hz variables but are NOT incremented if the time rolls over to the next day. Use base_time and time_offset for reference timing. Since ADS-3, this information is replaced by the “Time” variable and the “Time:units” attribute of that variable.

3 VARIABLES OBTAINED FROM AN INERTIAL REFERENCE SYSTEM

An Inertial Reference System (IRS) provides measurements of aircraft position, orientation, velocity, acceleration and attitude. For the GV, the system is a Honeywell Laseref III/IV Inertial Reference System. Data from the IRS come via a serial digital bit stream (the ARINC digital bus) to the ADS (Aircraft Data System). Because there is some delay in transmission and recording of these variables, adjustments for this delay are made when the measurements are merged into the processed data files, as documented in the NETCDF header files. Some of the variables are recorded only on the original "raw" data tapes and are not usually included on final archived data files; these are discussed at the end of this section. See also Section XXX for information on results from inertial systems that were used prior to installation of the present Honeywell systems.

An Inertial Reference System "aligns" while the aircraft is stationary by measurement of the variations in its reference frame caused by the rotation of the Earth. Small inaccuracy in that alignment lead to a "Schuler oscillation" that produces oscillatory errors in position and other measurements, with a period τ_{Sch} of about 84 minutes ($\tau_{Sch} = 2\pi\sqrt{R_e/g}$). Position errors of less than 1.0 n mi/hr are within normal operating specifications. See Section 5 for discussion of additional variables, similar to the following, for which corrections are made for these errors via reference to data from a Global Positioning System. **Latitude (°): LAT**
This is the aircraft latitude, output from the IRS at 10 Hz. Positive values are north of the equator; negative values are south. The resolution is 0.00017° and the accuracy is reported by the manufacturer to be 0.164° after 6 h of flight.

Longitude (°): LON
This is the aircraft longitude, output from the IRS at 10 Hz. Positive values are east of the prime meridian; negative values are west. The resolution is 0.00017° and the accuracy is reported by the manufacturer to be 0.164° after 6 h of flight.

Aircraft True Heading (°): THDG
This is the aircraft's true heading, output from the IRS at 25 Hz. The resolution is 0.00017° and the accuracy is quoted by the manufacturer as 0.2° after 6 h of flight. "True" distinguishes the heading from the magnetic heading, the heading that would be measured by a magnetic-compass needle.

Aircraft Pitch Attitude Angle (°): PITCH
This is the aircraft's pitch angle, provided from the IRS at 50 Hz. Positive values correspond to the nose of the aircraft pointing above the horizon. The resolution is 0.00017° and the accuracy is quoted by the manufacturer as 0.05° after 6 h of flight.

Aircraft Roll Attitude Angle (°): ROLL
This is the aircraft's roll angle, output from the IRS at 50 Hz. Positive angles occur with the starboard (right) wing down ((i.e., a clockwise rotation from level

when facing forward in the aircraft). The resolution is 0.00017° and the accuracy is quoted by the manufacturer as 0.05° after 6 h of flight..

Aircraft Vertical Acceleration ($\mathrm{m\,s^{-2}}$): ACINS

This is the output from the IRS vertical accelerometer with its internal drift removed via pressure damping.[4] The sample rate is 50 Hz and the resolution is $0.0024\ \mathrm{m\,s^{-2}}$.

Computed Aircraft Vertical Velocity (m/s): VSPD

This is the upward velocity of the aircraft provided directly by the IRS. It is determined in the IRS by integration of the vertical acceleration, with damping based on measured pressure to correct for accumulated errors in the integration of acceleration. The sample rate is 50 Hz with a resolution of 0.00016 m/s. The Honeywell Laseref IRS employs a baro-inertial loop, similar to that described below for WP3 and the Litton LTN-51, to update the value of the acceleration. It is also filtered within the IRS so that there is little variance with frequency higher than 0.1 Hz.

Pressure-Damped Aircraft Vertical Velocity (m/s): WP3 (obsolete)

This was a derived output incorporating a third-order damping feedback loop to remove the drift from the inertial system's vertical accelerometer (ACINS or VZI) using pressure altitude (PALT) as a long-term, stable reference. Positive values are up. The Honeywell IRS now in use provides its own version of this measurement, VSPD, and WP3 is now considered obsolete (and in any case should not be calculated from ACINS as provided by the Honeywell Laseref IRS because ACINS already incorporates pressure damping). Documentation is included here because many old data files include this variable. WP3 was calculated by the data-processing software, as follows:[5]

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[4]For earlier projects using the Litton LTN-51 INS, this is a direct measurement without adjustment for changes in gravity during flight and without pressure-damping. Previous use employed a baro-inertial loop to compensate for drift in the integrated measurement. See the discussion of WP3 below.

[5]Regarding signs, note that ACINS is a number near zero, not near g, and so already has the estimated acceleration of gravity removed. It appears that the assumption made in the following is that the INS will report values adjusted for the gravitational acceleration at the point of alignment, which would be G_L. If g_F, the estimate for gravity at the flight altitude (palt) and latitude (lat), is *smaller* than G_L then the difference $(G_L - g_f)$ will be positive; this will correct for the value ACINS being the sensed gravity - G_L when it should actually be the sensed gravity - g_f, so to obtain (sensed gravity - g_f) it is necessary to add $(G_L - g_f)$ to ACINS, *increasing* acz in this case. However, the situation with "vcorac" is apparently reversed. "vcorac" is a positive term for all eastward flight, for example, but in that case the motion of the aircraft makes objects seem lighter (i.e., they experience less acceleration of gravity) than without such flight. ACINS is positive upward so represents a net acceleration of the aircraft upward (as imposed by the combination of gravity and the lift force of the aircraft). To accomplish level flight in these circumstances, the aircraft must actually accelerate downward so the accelerometer will experience a negative excursion relative to slower flight. To compensate, "vcorac" must make a positive contribution to remove that negative excursion from "acz". In the extreme that the aircraft flew fast enough for the interior to appear weightless, ACINS would reduce to -1*$G_L$and vcorac would increase to +G_L, leaving acz near zero as required if the aircraft were to remain in level flight in the rotating frame

g_1 = 9.780356 m s^{-2}
a_1 = 0.31391116$\times$10^{-6} s^{-2}
a_2 = .0052885 (dimensionless)
VEW = eastward groundspeed of the aircraft
VNS = northward groundspeed of the aircraft
LAT = latitude measured by the IRS [°]
$C_{dr} = 2\pi/180^\circ$ = conversion factor, degrees to radians
PALT = pressure altitude of the aircraft
Ω = angular rotation of the earth = 7.292116$\times$10^6 radians/s
R_E = radius of the Earth = 6.371229$\times$10^6 m
g_f = local gravity corrected for latitude and altitude
V_c = correction to gravity for the motion of the aircraft
G_L = local gravity at the location of INS alignment, corrected to zero altitude
$\{C[0], C[1], C[2]\}$ = feedback coefficients, {0.15, 0.0075, 0.000125} for 125-s response

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1. From the pressure altitude PALT (in m) and the latitude LAT (converted to radians), estimate the acceleration of gravity:

$$g_f = g_1\left(1 + a_2 \sin^2(\mathrm{C_{dr}}\{\mathrm{LAT}\}) + a_1\{\mathrm{PALT}\}\right)$$

2. Determine corrections for Coriolis acceleration and centrifugal acceleration, based on motion of the aircraft:

$$V_c = 2\Omega\{\mathrm{VEW}\}\cos(C_r\{\mathrm{LAT}\}) + \frac{\{\mathrm{VEW}\}^2 + \{\mathrm{VNS}\}^2}{R_E}$$

3. Estimate the acceleration experienced by the aircraft as follows:

$$a_z = \{\mathrm{ACINS}\} + G_L - g_f + V_c$$

4. Use a feedback loop to update the integrated value of the acceleration to obtain a new value of the vertical motion of the aircraft. The following code segment uses acz=a_z, deltaT[] to represent the time between updates, and hi3, hx, and hxx to store the feedback terms:
```
wp3[FeedBack] += (acz - C[1] * hx[FeedBack]
   - C[2] * hxx[FeedBack]) * deltaT[FeedBack];
```
5. Update the feedback terms:
```
hi3[FeedBack] = hi3[FeedBack] + (wp3[FeedBack]
    - C[0] * hx[FeedBack]) * deltaT[FeedBack];
hx[FeedBack]  = hi3[FeedBack] - palt;
hxx[FeedBack] = hxx[FeedBack]
              + hx[FeedBack] * deltaT[FeedBack];
```
6. Set WP3 to the average of the last wp3 result and the current wp3 result.

Inertial Altitude (m): ALT

This is the aircraft altitude as provided by the IRS, with pressure damping applied within the IRS to the integrated aircraft vertical velocity to avoid the accumulation of errors. The sample rate is 25 Hz with a resolution of 0.038 m.

Aircraft Ground Speed (m/s): GSF

This is the aircraft's ground speed as provided by the IRS (at 10 Hz). The resolution is 0.0020 m/s.

Aircraft Ground Speed East Component (m/s): VEW

This is the output from the IRS (10 Hz) of the east component of ground speed. The resolution is 0.0020 m/s.

Aircraft Ground Speed North Component (m/s) VNS

This is the output from the IRS (10 Hz) of the north component of ground speed. The resolution is 0.0020 m/s.

–RAW IRS VARIABLES NOT INCLUDED IN NORMAL DATA FILES:–

The following IRS variables are not normally included in archived data files, but their values are recorded by the ADS and can be obtained from the original "raw" data files:

Raw Lateral Body Acceleration (m/s^2): BLATA

This is the raw output from the IRS lateral accelerometer. Positive values are toward the front, parallel to the aircraft center line. The sample rate is 50 Hz with a resolution of 0.0024 m/s2.

Raw Longitudinal Body Acceleration (m/s^2): BLONA

This is the raw output from the IRS longitudinal accelerometer. Positive values are toward the right, normal to the aircraft center line. The sample rate is 50 Hz with a resolution of 0.0024 m/s2.

Raw Normal Body Acceleration (m/s^2): BNORMA

This is the raw output from the IRS vertical accelerometer. Positive values are up, normal to the aircraft center line. The sample rate is 50 Hz with a resolution of 0.0024 m/s2

Raw Body Pitch Rate (°/s): BPITCHR

This is the raw output of the IRS pitch rate gyro. Positive values are up, normal to the aircraft's lateral axis. The sample rate is 50 Hz with a resolution of 0.0039°/s.

Raw Body Roll Rate (°/s): BROLLR

This is the raw output of the IRS roll rate gyro. Positive values are right wing down, normal to the aircraft center line. The sample rate is 50 Hz with a resolution of 0.0039°/s.

Raw Body Yaw Rate (°/s): BYAWR

This is the raw output of the IRS yaw rate gyro. Positive values are nose turning to the right, normal to the aircraft's vertical axis. The sample rate is 50 Hz with a resolution of 0.0039°/s.

4 VARIABLES OBTAINED FROM A GLOBAL POSITIONING SYSTEM (GPS)

GPS variables aboard RAF aircraft are provided by a Trimble TANS-III GPS receiver. It has the ability to track up to 6 satellites at a time but needs only 4 to provide 3-dimensional position and velocity data (3 satellites for 2-dimensions). The accuracy of the position measurements is stated to be 25 meters (horizontal) and 35 meters (vertical) under "steady-state conditions."[6] Likewise, velocity measurements are within 0.2 m/s for all axes. Measurement resolution is that of 4-byte IEEE format (about 6 significant digits). All variables are output at a sample rate of 1 Hz.

Some of the following variables are also available from a second unit and are qualified by the name of that unit; e.g., GGLAT_GMN for GGLAT as measured by a Garmin GPS unit.

GPS Latitude (°)**: GGLAT**, **LAT_G**; also formerly **GLAT**
: The aircraft latitude output from the GPS. Positive values are north of the equator;negative are south. GGLAT is provided by the data-system GPS; LAT_G and LATF_G are from the avionics system GPS. LATF_G is a fine-resolution measurement.

GPS Longitude (°)**: GGLON**, **LON_G**; also formerly **GLON**
: The aircraft longitude output from the GPS. Positive values are east of the prime meridian; negative are west. GGLON is provided by the data-system GPS;LON_G and LONF_G are from the avionics system GPS. LONF_G is a fine-resolution measurement.

GPS Ground Speed (m/s): GSF_G, GGSPD
: The aircraft ground speed output from the GPS. GSF_G originates from the avionics-system GPS; GGSPD originates from the data-system GPS.

GPS Ground Speed Vector East Component (m/s): GGVEW, **VEW_G**
: The east component of ground speed as measured by the GPS . VEW_G originates from the avionics-system GPS; GGVEW originates from the data-system GPS.

GPS Ground Speed Vector North Component (m/s): GGVNS, **VNS_G**
: The GPS output of the aircraft north component of ground speed. VNS_G originates from the avionics-system GPS; GGVNS originates from the data-system GPS.

GPS-Computed Aircraft Vertical Velocity (m/s): VSPD_G, (obsolete) **GVZI**
: The aircraft vertical velocity output from the GPS. Positive values are up.

[6] Note: The GPS signals at one time suffered from "selective availability," a US DOD term for a dithered signal that degrades GPS absolute accuracy to 100 meters. This was especially noticeable in the altitude measurement, so GALT normally was not useful. As of 1 May 2000, selective availability was deactivated to allow everyone to obtain better position measurements. (See the Interagency GPS Executive Board web site for more information.)

GPS Altitude (m): GGALT, ALT_G
The aircraft altitude output from the GPS. The measurement is with respect to a geopotential surface (MSL) defined by the GPS's built-in earth model. Positive values are up. GGALT originates from the data-system GPS; ALT_G originates from the avionics-system GPS.

GPS Aircraft Track Angle (°): GGTRK, TKAT_G
The direction of the aircraft track (degrees clockwise from true north), as measured by the data-system GPS (GGTRK) or the avionics-system GPS (TKAT_G).

GPS Height of the Geoid (m): GGEOIDHT
Height of geoid (MSL) above WGS84 ellipsoid.

GPS Satellites Tracked: GGNSAT
The number of satellites tracked by the GPS unit.

GPS Mode (none): GGQUAL
Quality flag: 0, 1, 2 for invalid, normal GPS, and differential GPS, respectively.

GPS Mode: GMODE (obsolete)
This is the former output from the GPS indicating itss mode of operation. The normal value is 4, indicating automatic (not manual) mode and that the receiver is operating in 4-satellite (as opposed to fewer) mode.

GPS Status (none): GGSTATUS, GSTAT_G, (obsolete) **GSTAT**
The status of the GPS receiver. A value of 1 indicates that the receiver is operating normally; a value of 0 indicates a warning regarding data quality. GGSTATUS indicates the status of the data-system GPS; GSTAT_G indicates the status of the avionics-system GPS. The obsolete variable GSTAT, formerly used for the same purpose, has the reverse meaning: A value of 0 indicates normal operation and any other code indicates a malfunction or warning regarding poor data accuracy.

5 COMBINED OUTPUT FROM AN INERTIAL REFERENCE SYSTEM (IRS) AND A GLOBAL POSITIONING SYSTEM (GPS)

In some cases, measurements from the global positioning and inertial reference systems are combined to produce new variables that take advantage of the strengths of each, the long-term stability of the GPS and the short-term resolution of the IRS. This section describes some variables that result from this blending of variables. These corrected variables are usually the best available when the GPS and IRS are both functioning. The GPS can suffer from noise spikes and missing data during aircraft maneuvering or poor satellite geometry. When the GPS data are lost, the algorithm in use slowly reverts from the last "best" measurements to the pure IRS measurements.

One can determine if the GPS is functioning by examining the GPS status variables described in the previous section or by looking for spikes or "flat-lines" in the data. If the GPS data are missing for a short time (a few seconds to a minute), accuracy is not affected. However, longer dropouts will result in accuracies approaching those of the IRS. Without the GPS or another ground reference, the IRS error cannot be determined empirically, and one should assume that it is within the manufacturer's specification (1 nautical mile of error per hour of flight, 90% CEP). When the GPS is active, RAF estimates that the correction algorithm produces a position with an error less than 100 meters. Due to the nature of the algorithm, the error will increase from the 100 meters to the IRS specification in about one-half hour. **GPS-Corrected Inertial Ground Speed Vector, (m/s): VEWC, VNSC**

These variables result from combining GPS and IRS output of the east and north components of ground speed from the complementary-filter algorithm. Positive values are toward the east and north, respectively. The smooth, high-resolution, continuous measurements from the inertial navigation system, {VNS, VEW}, which can slowly accumulate errors over time, are combined with the highly accurate but occasionally noisy or discontinuous measurements from the GPS, {GVNS, GVEW}, via an approach based on a complementary filter. A low-pass filter, $F_L(\{\mathrm{GVNS}, \mathrm{GVEW}\})$, is applied to the GPS measurements of groundspeed, which are assumed to be valid for frequencies at or lower than the cutoff frequency f_c of the filter. Then the complementary high-pass filter, denoted $(1-F_L)(\{\mathrm{VNS}, \mathrm{VEW}\})$, is applied to the IRS measurements of groundspeed, which are assumed valid for frequencies at or higher than f_c. Ideally, the transition frequency would be selected where the GPS errors (increasing with frequency) are equal to the IRS errors (decreasing with frequency). The filter used is a three-pole Butterworth lowpass filter, coded following the algorithm described in Bosic, S. M., 1980: *Digital and Kalman filtering : An Introduction to Discrete-Time Filtering and Optimum Linear Estimation,* p. 49. The digital filter used is recursive, not centered, to permit calculation during a single pass through the data. If the cutoff frequency lies where both the GPS and INS measurements are valid and almost the same, then the detailed characteristics of the filter in the transition region (e.g., phase shift) do not matter because the complementary filters have cancelling effects when applied to the same signal. The transition frequency f_c was chosen to be (1/600) Hz. The

Butterworth filter was chosen because it provides flat response away from the transition. The net result then is the sum of these two filtered signals, calculated as described in the following box:

VEW = IRS-measured east component of the aircraft ground speed
VNS = IRS-measured north component of the aircraft ground speed
GVEW = GPS-measured east component of the aircraft ground speed
GVNS = GPS-measured north component of the aircraft ground speed
$F_L()$ = three-pole Butterworth lowpass recursive digital filter

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$$\{\mathrm{VNSC}\} = F_L(\{\mathrm{GVNS}\}) + (1 - F_L)(\{\mathrm{VNS}\})$$

$$\{\mathrm{VEWC}\} = F_L(\{\mathrm{GVEW}\}) + (1 - F_L)(\{\mathrm{VEW}\})$$

This result is used as long as the GPS signals are continuous and flagged as being valid. When that is not the case, some means is needed to avoid sudden discontinuities in velocity (and hence windspeed), which would introduce spurious effects into variance spectra and other properties dependent on a continuously valid measurement of wind. To extrapolate measurements through periods when the GPS signals are lost (as sometimes occurs, for example, in turns) a fit is determined to the difference between the best-estimate variables {VNSC,VEWC} and the IRS variables {VNS,VEW} for the period before GPS reception was lost, and that fit is used to extrapolate through periods when GPS reception is not available. The procedure is as follows:

1. If GPS reception has never been valid earlier in the flight, the IRS values are used without correction.

2. If GPS reception is lost after a valid complementary-filter correction has been obtained earlier using the procedure described above, but no valid Schuler-oscillation fit has been accumulated as described in [3.] below, the correction factors from the complementary filter are reduced by a factor of 0.997 each second, producing an exponential decay back toward the IRS values with decay time constant of about 5.6 min.

3. When GPS reception is good, update a least-squares fit to the difference between the GPS and INS groundspeeds, for each component. The errors are assumed to result primarily from a Schuler oscillation, so the three-term fit is of the form $\Delta = a_1 + a_2 \sin(\Omega_{Sch} t) + a_3 \cos(\Omega_{Sch} t)$, where Ω_{Sch} is the angular frequency of the Schuler oscillation (taken to be $2\pi/(5067\,s)$) and t is the time since the start of the flight. A sseparate fit is used for each component of the velocity and each component of the position (discussed below under LATC and LONC). The fit matrix used to determine these coefficients is updated each time step but the accumulated fit factors decay exponentially with a 30-min decay constant, so the terms used to determine the fit are exponentially weighted over the period of valid data with a time constant that decays exponentially into the past with a characteristic time of 30 min. This is long enough to determine a significant portion of the Schuler oscillation but short enough to emphasize recent measurements of the correction.

4. When GPS data become invalid, if sufficient data (spanning 30 min) have been accumulated, invert the accumulated fit matrices to determine the coefficients $\{a_1, a_2, a_3\}$ and then use the formula for Δ in the preceding step to extrapolate the correction to the IRS measurements while the GPS measurements remain invalid. Doing so immediately would introduce a discontinuity in {VNSC,VEWC}, however, so the correction Δ is introduced smoothly by adjusting {VNSC,VEWC} smoothly as follows: Δ'=$(1-\eta)$(VNSC$_0$-GVNS$_0$)+$\eta\Delta$ where Δ' is the sequentially adjusted correction, (VNSC$_0$-GVNS$_0$) is the difference preserved from the last time the GPS groundspeed was valid, and $\eta = 0.997\,s^{-1}$ is chosen to give a decaying transition with a time constant of about 5.5 min. This has the potential to introduce some artificial variance at this scale and so should be considered in cases where variance spectra are analyzed in detail, but it has much less influence on such spectra than would introducing a discontinuous transition. Ideally, the current fit and the last filtered discrepancy (VNSC$_0$-GVNS$_0$) should be about equal, so this should not introduce a significant change.

GPS-Corrected Inertial Latitude and Longitude (°): <u>LATC</u>, <u>LONC</u>

Combined GPS and IRS output of latitude and longitude from the complementary-filter algorithm. Positive values are north and east, respectively. These variables are the best estimate of position, obtained by the following approach:

LAT = latitude measured by the IRS
LON = longitude measured by the IRS
GLAT = latitude measured by the GPS
GLON = longitude measured by the GPS
VNSC = aircraft ground speed, north component, corrected
VEWC = aircraft ground speed, east component, corrected

---

1. Initialize the corrected position at the IRS position at the start of the flight or after any large change (>5°) in the IRS position.

2. Integrate forward from that position using the aircraft groundspeed with components {VNSC,VEWC}. Note that in the absence of GPS information this will introduce long-term errors because it does not account for the Earth's spherical geometry. It provides good short-term accuracy, but the GPS updating in the next step is needed to compensate for the difference between a rectilinear frame and the Earth's spherical coordinate frame and provides a smooth yet accurate track.

3. Use an exponential adjustment to the GPS position, with time constant that is typically about 100 s.[a]

4. To handle periods when the GPS becomes invalid, use an approach analogous to that for groundspeed, whereby a Schuler-oscillation fit to the difference between the GPS and IRS measurements is developed and used to extrapolate through periods when the GPS is invalid.

[a] specifically, LATC += η(GLAT-LATC) with $\eta = 2\pi/(600\,\mathrm{s})$

6 ALTITUDE AND POSITION VARIABLES

Altitude, Reference (MSL): ALTX, GALTC

This is the derived altitude above the geopotential surface obtained primarily from GALT, the GPS Altitude, with help from another Reference altitude, typically ALT, the Inertial Altitude. The GPS signals, at times, are degraded, most often during aircraft turns. Two GPS status measurements are used to detect this, but sometimes the information comes too late. A 10-second running average is calculated of the difference between the GPS altitude and the Reference altitude. When the sample-to-sample altitude difference changes more than 50 meters or when the GPS status detects a degraded signal, the altitude from this measurement changes from GPS altitude to an adjusted Reference altitude (Reference altitude plus the running difference average). When the GPS altitude is again "good" and to avoid a sudden altitude transition, the output linearly steps back to the GPS altitude over the next 10 seconds.

revise this as described in the GGALTC algorithm note of 10 Dec

ISA Pressure Altitude (m): PALT

The derived altitude obtained from the reference barometric (static) pressure measurement using the International Standard Atmosphere (ISA), equivalent to the reference atmosphere for aviation operations worldwide.[7] The pressure altitude is best interpreted as a variable equivalent to the measured pressure, not as a geometric altitude. In the following description of the algorithm, some constants (identified by the symbol †) are specified as part of the ISA and so should not be "improved" to more modern values (e.g., R_0').[8] A note at this URL describes the pressure altitude in more detail and documents the change that was implemented in November 2010.

Revised Nov 2010

[7] see "U.S. Standard Atmosphere, 1976", NASA-TM-A-74335, available for download at http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19770009539_1977009539.pdf

[8] Prior to and including some projects in 2010, processing used slightly different coefficients: for aircraft other than the GV, T_0/λ was represented by -43308.83, the reference pressure p_0 was taken to be 1013.246, and the exponent x was represented numerically by 0.190284. For the GV, the value of T_0/λ was taken to be 44308.0, the transition pressure p_T was 226.1551 hPa, x = 0.190284, and coefficient $\frac{R_0' T_T}{g M_d}$ was taken to be 6340.70 m instead of 6341.620 m as obtained below. The difference between these older values and the ones recommended below is everywhere less than 10 m and so is small compared to the expected uncertainty in pressure measurements, because 1 hPa change in pressure leads to a change in pressure altitude that varies from about 8–40 m over the altitude range of the GV .)

T_0= 288.15 K, reference temperature†
λ = -0.0065 K/m = the lapse rate for the troposphere†
P_s = measured static pressure, hPa, usually from PSXC
P_0 = 1013.25 hPa, reference pressure for PALT=0†
M_d = 28.9644 $kg/kmol$= molecular weight of dry air, ISA definition†
g = 9.80665 m s^{-2}, acceleration of gravity†
R'_0 = universal gas constant, defined† as 8.31432×10^3 $J\,\mathrm{kmol}^{-1}\,\mathrm{K}^{-1}$
z_T = altitude of the assumed tropopause = 11,000 m†
$x = R'_0\lambda/(M_d g) \approx 0.1902632$ (dimensionless)[a]

For pressure > 226.3206 hPa (equivalent to a pressure altitude < z_T):

$$\mathrm{PALT} = -\left(\frac{T_0}{\lambda}\right)\left(1 - \left(\frac{P_s}{P_0}\right)^x\right)$$

otherwise, if T_T and p_T are respectively the temperature and pressure at the altitude z_T:

$$T_T = T_0 + \lambda z_T = 216.65\,\mathrm{K}$$

$$p_T = p_0\left(\frac{T_0}{T_T}\right)^{\frac{gM_d}{\lambda R'_0}} = 226.3206\,\mathrm{hPa}$$

$$\mathrm{PALT} = z_T + \frac{R'_0 T_T}{gM_d}\ln\left(\frac{p_T}{p_s}\right)$$

which, after conversion from natural to base-10 logarithm, is coded to be equivalent to the following:

```
// transition pressure at the assumed ISA tropopause:
#define ISAP1 226.3206
        // reference pressure for standard atmosphere:
#define ISAP0 1013.25
if (psxc > ISAP1)

    palt = 44330.77 * (1.0 - pow(psxc/ISAP0, 0.1902632));
else

    palt = 11000.0 + 14602.12 * log10(ISAP1/psxc);
```

[a] This is the value, rounded to seven significant figures, that is used for data processing.

Geometric Radio Altitude (m): HGM

This is the distance to the surface below the aircraft, measured by a radio altimeter.

The maximum range is 762m (2,500 ft). The instrument changes in accuracy at an altitude of 152 m: The estimated error from 152 m to 762 m is 7%, while the estimated error for altitudes below 152 m is 1.5 m or 5%, whichever is greater.

Geometric Radar Altitude (Extended Range) (APN-159) (m): HGME

There are two outputs from an APN-159 radar altimeter, one with coarse resolution (CHGME) and one with fine resolution (HGME). Both raw outputs cycle through the range 0-360 degrees, where one cycle corresponds to 4,000 feet for HGME and to 100,000 feet for CHGME. To resolve the ambiguity arising from these cycles, 4,000-foot increments are added to HGME to maintain agreement with CHGME. This preserves the fine resolution of HGME (1.86 m) throughout the altitude range of the APN-159.

Geometric Radar Altitude (Extended Range) (APN-232) (m): HGM232

Altitude above ground as measured by an APN-232 radar altimeter.

Pressure-Damped Inertial Altitude (m): HI3 (obsolete)

The aircraft altitude obtained from the twice-integrated INS acceleration (ACINS), pressure-adjusted to obtain long-term agreement with PALT. Note that this variable has mixed character, producing short-term variations that accurately track the altitude but with adjustment to the pressure altitude, which is not a true altitude. The variable is not appropriate for estimates of true altitude, but proves useful in the updating algorithm used with the LTN-51 INS for vertical wind. See the discussion of WP3. This variable is now obsolete.

Distance East/North of a Reference (km): DEI/DNI

These are derived outputs obtained by subtracting a fixed reference position from the current position, determined from measurements of latitude and longitude and converted from degrees to distance in a rectilinear coordinate system. The reference position can be either the starting location of the flight or a user-defined reference point (e.g., the location of a project radar). The accuracy of these values is dependent on the accuracy of the source latitude and longitude measurements, and the calculations are only appropriate for short distances because they do not take into account the spherical geometry of the Earth..

LON_{ref} = reference longitude (°)
LAT_{ref} = reference latitude (°)
SF_{ref} = reference scale factor = 111.12 km /°

$$\mathrm{DEI} = (\{\mathrm{LON}\} - \{\mathrm{LON}_{ref}\})\mathrm{SF}_{ref}\cos(\{\mathrm{LAT}\})$$

$$\mathrm{DNI} = (\{\mathrm{LAT}\} = \{\mathrm{LAT}_{\mathrm{ref}}\})\mathrm{SF}_{\mathrm{ref}}$$

Radial Azimuth/Distance from Fixed Reference: FXAZIM, FXDIST

Derived calculations of the radial azimuth (°) and distance (km) from a fixed reference position (a user-specified reference latitude and longitude) to the aircraft's location. It is calculated by rectangular-to-polar conversion of DEI/DNI.

7 AIRCRAFT AND METEOROLOGICAL STATE VARIABLES

Measurements of meteorological state variables often are made at various locations on an aircraft. To distinguish among similar measurements, many variable names incorporate an indication of where the measurement was made. In this document, locations in variable names are represented by “x”, where “x” may represent the following:

Character	Location
B	bottom (or bottom-most)
B	(obsolete) boom
F	fuselage
G	(obsolete) gust probe
R	radome
T	top (or top-most)
W	wing

In addition, a true letter ’X’ (not replaced by the above letters) may be appended to a measurement to indicate that it is the preferred choice used for derived calculations. Other suffixes sometimes used to distinguish among measurements are these: ’D’ for a digital sensor; ’H’ for a heated (usually, deiced) sensor, ’L’ for port side, and ’R’ for starboard side.

RAF uses the radome gust-sensing technique (Friehe XXXX) as the reference system to measure incidence angles (angles of attack and sideslip). The pressure difference between sensing ports above and below the center line of the radome is used, along with the dynamic pressure measured at a port on the centerline and referenced to the static pressure, to determine the angle of attack, and similarly for the sideslip angle. A Rosemount Model 858AJ gust probe is occasionally used for specialized measurements. The radome measurements are made by differential pressure sensors located in the nose area of the aircraft and connected to the radome by semi-rigid tubing. **Static Pressure (mb): <u>PSx</u>, <u>PSxC</u>**
The atmospheric pressure at the flight level of the aircraft, measured by a calibrated absolute (barometric) transducer at location x. PSx is the measured static pressure, and may be affected by local flow-field distortion. PSxC is corrected for local flow-field distortion. (See Bulletin No. 21.) For output variables PSFD and PSFDC, the letter “D” indicates that the transducer used was a Rosemount Model 1501 digital absolute pressure transducer. For output variable PSFRD, the letters “RD” indicate that the pressure transducer used was a Ruska Model 7885-1B digital absolute pressure transducer. Other static pressure measurements are made by a Rosemount Model 1201 absolute pressure transducer, an analog transducer used with appropriate calibration coefficients.

Dynamic Pressure (mb): <u>QCx</u>, <u>QCxC</u>
Dynamic pressure is the difference between the pitot (total) pressure resulting

from the flight speed of the aircraft and the static pressure that would be present in the absence of motion. The QCxC value is corrected for local flow-field distortion, as described in RAF Bulletin 21. A Rosemount Model 1221 differential pressure transducer is used for all measurements of dynamic pressure. This measurement enters the calculation of true airspeed and Mach Number and so is needed to calculate many derived variables.

Total Temperature (°C): <u>TTx</u>, <u>TTxH</u>

The recovery temperature is the temperature sensed by a temperature probe that is exposed to the atmosphere. In flight, the temperature is heated above the ambient temperature because it senses the temperature of air near the sensor that has been heated adiabatically during compression as it is brought near the airspeed of the aircraft. These variables are the measurements of that recovery temperature from calibrated temperature sensors at location x. (The name is misleading, but is kept to comply with long-standing practice. These are not true total temperature measurements, for which the air would be at the same speed as the aircraft.) For Rosemount temperature probes, the recovery temperature is near the total temperature, but all probes must be corrected to obtain either true total temperature or true ambient temperature. In the standard output, the "total" temperature (and ambient temperature) variable name also conveys the sensor type. TTx is the measurement from a Rosemount Model 102 non-deiced temperature sensor, while TTxH is the measurement from a Rosemount Model 102 deiced (heated) temperature sensor. *Some past experiments used a reverse-flow temperature housing; the associated variable name for this probe is TTRF.*

Dew/Frost Point (°C): <u>DPx</u>

The dew point or frost point measured by either an EG&G Model 137, a General Eastern Model 1011B or a Buck Model 1011C dew-point hygrometer. Below 0°**C** the instrument is assumed to be measuring the frost point, although occasionally in climbs there is a short transition near the freezing level before the condensate on the mirror of the instrument freezes. These are the uncorrected values, so they represent directly what the instrument senses. The dew point is a measure of water vapor pressure, and so is dependent on the vapor pressure in the housing being equal to that in the ambient air. This is achieved by appropriate orientation of the sensor housing.

Corrected Dew Point (C): DPxC

The corrected dew point is the dew point estimated from the original measurement, referenced to the equilibrium vapor pressure over a plane water surface in the absence of other gases. Dew/frost point hygrometers measure the equilibrium point in the presence of air, and this affects the measurement in a minor way. Calculation of this variable removes this dependence, so the vapor pressure obtained from the corrected dew or frost point is that vapor pressure corresponding to equilibrium in the absence of air. In addition, if the measurement is below 0°C, it is assumed to be a measurement of frost point and a corresponding dew point is calculated from the measurement (with correction for the influence of the total pressure on the measurement. changed 2011

The relationship between water vapor pressure and dew or frost point is based on the Murphy and Koop (2005) equations. They express the equilibrium vapor pressure as a function of frost point or dew point *and at a total air pressure p* in relationships that are equivalent to the following equations:

$$e = e_{s,i}(T_{FP}) = \quad b_0' \exp(b_1 \frac{(T_0 - T_{FP})}{T_0 T_{FP}} + b_2 \ln(\frac{T_{FP}}{T_0}) + b_3(T_{FP} - T_0)) \tag{1}$$

$$e = e_{s,w}(T_{DP}) = e_0 \exp\left((\alpha - 1)e_6 + d_2(\frac{T_0 - T_{DP}}{T_{DP}T_0}\right) + d_3 \ln(\frac{T_{DP}}{T_0}) + d_4(T_{DP} - T_0) \tag{2}$$

$$f(p, T_P) = 1 + p(f_1 + f_2 T_p + f_3 T_P^2)) \tag{3}$$

where e is the water vapor pressure, T_{FP} or T_{DP} is the frost or dew point, respectively, expressed in kelvin, T_0=273.15 K, $e_{s,i}(T_{FP})$ is the equilibrium vapor pressure over a plane ice surface at the temperature T_{FP}, $e_{s,w}(T_{DP})$ is the equilibrium vapor pressure over a plane water surface at the temperature T_{DP} (above or below 0°C), and $f(p, T_P)$is the enhancement factor at total air pressure p and temperature T_p, with T_P equal to T_{DP} when above 0°C and T_{FP} when below 0°C . The coefficients used in the above formulas are given in the following tables, with the additional definitions that $\alpha = \tanh(e_5(T - T_x))$, T_X = 218.8 K, and $d_i = e_i + \alpha e_{i+5}$ for i = {2,3,4}:

Coefficient	**Value**
b_0'	6.11536 hPa
b_1	$-5723.265\,K$,
b_2	3.53068
b_3	-0.00728332 K^{-1}
f_1	4.923×10^{-5} hPa^{-1}
f_2	-3.25×10^{-7}hPa^{-1}K^{-1}
f_3	5.84×10^{-10}hPa^{-1}K^{-2}

coefficient	**value**
e_0	6.091886 hPa
e_1	6.564725
e_2	-6763.22 K
e_3	-4.210
e_4	0.000367 K^{-1}
e_5	0.0415 K^{-1}
e_6	-0.1525967
e_7	-1331.22 K
e_8	-9.44523
e_9	0.014025 K^{-1}

Because processing to obtain the corrected dew point from the vapor pressure would require inversion of the above formulas, interpolation is used instead. A table constructed from (1) and another constructed from (2), giving vapor pressure as a function of dew point temperature in 1°C increments from -100 to +50°C, is then used for three-point Lagrange interpolation (via a function described below as $T_{DP} = F_D(e)$) to find dew point temperature from vapor pressure.[9] Tests of these interpolation formulas against high-accuracy numerical inversion of formulas (1) and (2) showed that the maximum

[9]prior to 2011 the conversion was made using the formula $\mathrm{DPxC} = 0.009109 + \mathrm{DPx}(1.134055 + 0.001038\mathrm{DPx})$. For instruments producing measurements of

error introduced by the interpolation formula was about 0.004°C and the standard error about 0.001°C.

For other instruments that measure vapor density, such as Lyman-alpha or tunable diode laser hygrometers, a similar conversion is made from vapor density to dew point, as documented below:
DPx = uncorrected dew/ point measurement directly from an instrument, $°C$
RHO = vapor density measurement directly from the instrument, g/m^3
ATX = reference ambient temperature ($°C$)
T = temperature in kelvin = ATX+T_0
PSXC = reference ambient pressure (hPa) = p
e_t = intermediate vapor pressure used for calculation only
M_w= molecular weight of water
$R*$ = universal gas constant

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for dew/frost point hygrometers, producing the measurement DPx:
if DPx < 0°C:
obtain e_t from (1) using T_{FP}=DPx + T_0
else (i.e., DPx $\geq$ 0°C):
obtain e_t from (2) using $T_{DP} = DPx + T_0$
correct e_t for enhancement factor to get actual vapor pressure e:
$e = f(p,T)\, e_t$
obtain DPxC by finding the dew point corresponding to the vapor pressure e:
DPxC=$F_{DP}(e)$
for other instruments producing measurements of vapor density (RHO, g/m^3):[a]
find the water vapor pressure in units of hPa:
e =({RHO} R* T/M_w)$\times 10^{-5}$
find the equivalent dew point:
DPxC=$F_{DP}(e)$

[a] prior to 2011 the following formula was used:

$$Z = \frac{\ln((\mathrm{ATX} + 273.15)\,\mathrm{RHO}}{1322.3}$$

$$\mathrm{DPxC} = \frac{273.0Z}{(22.51 - Z)}$$

Attack Differential Pressure (mb): ADIFR[10]

This variable records the pressure difference between the top and bottom pressure

vapor density (RHO), the previous Bulletin 9 section incorrectly gave the conversion formula as $DPxC = 273.0Z/(22.51 - Z)$, a conversion that would apply to frost point, not dew point. However, the code in use shows that the conversion was instead $237.3Z/(17.27 - Z)$, where Z in both cases is $Z = \ln((\mathrm{ATX} + 273.15)\mathrm{RHO}/1322.3)$.

[10] **Obsolete variable ADIF is a similar variable used for old gust-boom systems or for Rosemount Model 858AJ flow-angle sensors.**

ports of the radome gust-sensing system.

Sideslip Differential Pressure (mb): BDIFR[11]

This variable records the pressure difference between starboard and port pressure inlets of the radome gust-sensing system, in the horizontal plane of the aircraft's flow-angle sensor system.

Attack Angle, Radome (°): AKRD

This derived output represents the angle of attack of the aircraft. It is obtained from ADIFR and a dynamic pressure using a sensitivity function that has been determined empirically for each aircraft.

ADIFR = attack differential pressure, radome
QCXC = reference dynamic pressure
XMACH2 = square of the Mach number
c_0, c_1 = sensitivity coefficients determined empirically
= {0.3843, (1/0.06653) °} for the C-130
= {0.2571, (1/0.04724) °} for the GV
c_3, c_4 = additional coefficients for the GV
= {0.6195°, -1.02758°} for XMACH2 > 0.194
= {0.42°, 0} for XMACH2 $\leq$ 0.194

For the C-130:

$$\mathrm{AKRD} = c_1 \left(\frac{\{\mathrm{ADIFR}\}}{\{\mathrm{QCXC}\}} + c_0 \right)$$

For the GV:

$$\mathrm{AKRD} = c_1 \left(\frac{\{\mathrm{ADIFR}\}}{\{\mathrm{QCXC}\}} + c_0 \right) + c_3 + c_4\{\mathrm{XMACH2}\}$$

Reference Attack Angle (°): ATTACK

This variable is the reference selected from other measurements of angle of attack in the data set. In most projects, it is equal to AKRD. It is used where attack angle is needed for other derived calculations (e.g., wind measurements).

Sideslip Angle (Differential Pressure) (°): SSRD

This variable is derived from BDIFR and a dynamic pressure using a sensitivity function that has been determined empirically for each aircraft.

[11] **Obsolete variable BDIF is a similar variable used for old gust-boom systems or for Rosemount Model 858AJ flow-angle sensors.**

M = Aircraft Mach Number BDIFR = differential pressure between sideslip pressure ports, radome (mb) QCXC = dynamic pressure (mb) c_0, c_1 = empirical coefficients dependent on the aircraft and radome configuration = {-0.000983, (1/0.09189)° } for the C-130 ______ = {-0.0023, (1/0.04727)°} for the GV
$$\text{SSRD} = c_1\left(\frac{\{BDIFR\}}{\{\text{QCXC}\}} - c_0\right)$$

Reference Sideslip Angle (°): SSLIP

This variable is the reference selected from other measurements of angle of attack in the data set. In most projects, it is equal to SSRD. It is used where attack angle is needed for other derived calculations (e.g., wind measurements).

Cabin Pressure (mb): PCAB

The pressure in the interior of the aircraft cabin, measured by a Rosemount Model 1201 absolute pressure transducer.

Cryogenic Hygrometer Inlet Pressure (mb) and Frost Point Temperature (°C): CRHP and VCRH

These are measurements made directly in the chamber of the cryogenic hygrometer, a cabin-mounted instrument connected to outside air by an inlet line. CRHP is the pressure and VCRH is the frost-point temperature inside that chamber. VCRH is determined from a third-order calibration equation applied to the voltage measured by the instrument.

Corrected Cryogenic Frost Point Temperature and Dew Point Temperature (°C) - FPCRC and DPCRC [obsolete]

To obtain estimates of the ambient frost point and dew point, the measurements made inside the chamber of the cryogenic hygrometer (CVRH and CRHP) must be corrected for the difference in water vapor pressure between that chamber and ambient conditions. The ratio of the chamber pressure to the ambient pressure is assumed to be the same as the ratio of the chamber vapor pressure to the ambient vapor pressure. The vapor pressure in the chamber is determined from the Goff-Gratch (1946) equation for saturation vapor pressure with respect to a plane ice surface. This vapor pressure is then used with CRHP and a measure of the ambient pressure (PSXC) to determine the vapor pressure in the outside air, after which the Goff-Gratch equation is again used to convert that vapor pressure to an equivalent frost point and an equivalent dew point. The instrument is only used for measurements of frost point less than -15°C because it does not function well above that frost point. The steps are documented below:

VCRH = frost point inside the cryogenic hygrometer ($^\circ C$)
CRHP = pressure inside the chamber of the cryogenic hygrometer (mb)
PSXC = reference ambient pressure (mb)
f_i = enhancement factor (see Appendix C of Bulletin 9)
$F_1(T_d)$ =Goff-Gratch formula for vapor pressure at dew point T_d
$F_2(T_f)$ = Goff-Gratch formula for vapor pressure at frost point T_f
T_3 = temperature at the triple point of water = 273.16 K

---

chamber vapor pressure e_{ic} (mb):

$$e_{ic} = (6.1071\,\text{mb}) \times 10^A$$

$$\begin{aligned}
\text{where } A &= -9.09718\left(\frac{T_3}{\text{VCRH}+T_3} - 1\right) \\
&+ 3.56654\log_{10}\left(\frac{T_3}{\text{VCRH}+T_3}\right) \\
&+ 0.876793\left(1 - \frac{\text{VCRH}+T_3}{T_3}\right)
\end{aligned}$$

ambient vapor pressure e_a (mb):

$$e_a = e_{ic}\left(\frac{\text{PSXC}}{\text{CRHP}}\right) f_i$$

ambient dew and frost point DPCRC and FPCRC: (iterative solution)

$$\begin{aligned}
e_a &= F_1\,(\text{DPCRC}) \\
&= F_2\,(\text{FPCRC})
\end{aligned}$$

Voltage Output From the Lyman-alpha Sensor (V): <u>VLA</u>, <u>VLA1</u>

The voltage output from the Lyman-alpha absorption hygrometer, which provides fast-response, high-resolution water vapor density measurements. (If a second sensor is used, a 1 is added to its name.)

8 THERMODYNAMIC VARIABLES

Ambient Temperature (°C): ATx, ATxH

The name of the variable used for ambient temperature, ATx conveys the same information regarding sensor type and location as the variable name used with total (recovery) temperature. See the discussion in Aircraft and Meteorological State Variables (Section 7) above. The ambient temperature (also known as the static air temperature) is calculated from the measured recovery temperature, which includes dynamic heating effects caused by the airspeed of the aircraft. The calculated temperature therefore depends on the recovery temperature TTx as well as the dynamic and static pressure, usually respectively QCXC and PSXC. The pressures are first corrected from the raw measurements QCX and PSX to account for deviations caused by airflow around the aircraft and/or position-dependent systematic errors. The basic equations use conservation of energy for a perfect gas undergoing an adiabatic compression.

The following section combines discussion of the calculations of temperature and airspeed, to reflect the linkage between these derived measurements.

Aircraft temperature sensors do not measure the total temperature, but measure the temperature of the air immediately in contact with the sensing element. This air will not have undergone an adiabatic deceleration to zero velocity and hence will have a temperature T_r somewhat less than T_t. This temperature is the measured or "recovery" temperature. The ratio of the actual temperature difference attained to the temperature difference relative to the total temperature is defined to be the recovery factor α :

$$\alpha = \frac{T_r - T_a}{T_t - T_a} \tag{4}$$

From conservation of energy:

$$\frac{U_a^2}{2} + c_p T_a = \frac{U_r^2}{2} + c_p T_r = \frac{U_t^2}{2} + c_p T_t \tag{5}$$

where $\{U_a, U_r, U_t\}$ are respectively the aircraft true airspeed, the airspeed relative to the aircraft of the air in thermal contact with the sensor, and the airspeed of air relative to the aircraft when fully brought to the motion of the sensor (i.e., zero). The corresponding absolute temperatures (expressed in kelvin) for the same conditions are $\{T_a, T_r, T_t\}$, the ambient, recovery, and total temperatures.

Then, from (5),

$$T_a = T_r - \alpha \frac{U_a^2}{2c_p} \tag{6}$$

The temperature sensors used on RAF aircraft are designed to decelerate the air adiabatically to near zero velocity. Recovery factors determined from wind tunnel testing for the Rosemount sensors are 0.95 (non-deiced model) and 0.98 (deiced model). The recovery factor determined for the NCAR reverse-flow sensor is 0.6.[12] Recovery factors have also been determined from flight maneuvers, often from "speed runs" where the aircraft is flown level through its speed range and the variation of recovery temperature with airspeed is used with (6), with the assumption that T_a remains constant, to determine the recovery factor. Data files and project summaries normally document what recovery factor was used for processing a particular project.

As can be seen in the above equation, the true airspeed U_a is used to calculate the ambient temperature T_a. However, the ambient temperature is also needed to calculate the true airspeed. Therefore the constraints imposed on ambient temperature and true airspeed by the measurements of recovery temperature, dynamic pressure (the pressure measured by a pitot tube pointed into the airstream and assumed to be that obtained when the incoming air is brought to rest relative to the aircraft), and ambient (or "static") pressure must be used to solve simultaneously for the two unknowns, temperature and airspeed.

The relationship is conveniently derived by first calculating the dimensionless Mach number (M), which is the ratio of the airspeed to the speed of sound ($U_s = \sqrt{\gamma R T_a}$ where γ is the ratio of specific heats of air, c_p/c_v), because the Mach number is a function of air temperature only. It can be determined as follows:
a). Express energy conservation, as in (5), in the form

$$d\left(\frac{U_a^2}{2}\right) + c_t dT = 0 \tag{7}$$

b). Use the perfect gas law to replace dT with $\frac{pV}{nR}(\frac{dV}{V} + \frac{dp}{p})$, and use the expression for adiabatic compression in the form $pV^\gamma = constant$ to replace the derivative dV with $-\frac{-1}{\gamma}\frac{dp}{p}$, leading to the equation:

$$\frac{U_a^2}{2} + c_p T_a = c_p T_a \left(\frac{p_s}{p_a}\right)^{\frac{R}{c_p}} \tag{8}$$

where p_s is the total pressure (i.e., PSXC+QCXC) and p_a is the ambient pressure (PSXC).
c). Use the above definition of the Mach number M ($M = U_a/U_s$) in the form $U_a^2 = \gamma M^2 R T_a$ to obtain:

$$M^2 = \left(\frac{2c_v}{R}\right)\left[\left(\frac{p_s}{p_a}\right)^{\frac{R}{c_p}} - 1\right] \tag{9}$$

d). Use the expression for ambient temperature in terms of recovery temperature and

[12] The recovery factor for the now retired NCAR fast-response (K-probe) temperature sensor was 0.8.

airspeed, (6), to obtain the temperature in terms of the Mach number and the recovery temperature:

$$
\begin{aligned}
T_a &= T_r - \alpha\frac{U_a^2}{2c_p} = T_r - \alpha\frac{M^2\gamma RT_a}{2c_p} \\
&= \frac{T_r}{1+\dfrac{\alpha M^2(\gamma-1)}{2}}
\end{aligned}
\tag{10}
$$

e). Express the true airspeed (U_a) as

$$U_a = M\sqrt{\gamma RT_a} \tag{11}$$

Then the temperature is found as described in the following box:

TTX = measured recovery temperature (T_r)
QCxC = measured difference between the dynamic and static pressures
PSXC = measured ambient pressure, after airflow/location correction (p_a)
MACHx = Mach number based on QCxC and PSXC
MACHX = Mach number based on QCXC and PSXC
α = recovery factor for the particular temperature sensor

From (9),

$$\text{MACHx} = \left\{\left(\frac{2c_v}{R}\right)\left[\left(\frac{\{\text{PSXC}\}+\{\text{QCxC}\}}{\{\text{PSXC}\}}\right)^{\frac{R}{c_p}} - 1\right]\right\}^{1/2} \tag{12}$$

From (10)

$$\text{ATx} = \frac{(\{\text{TTx}\}+\text{T}_0)}{\left(1+\dfrac{\alpha(\{\text{MACHX}\})^2(\gamma-1)}{2}\right)} - T_0 \tag{13}$$

Aircraft True Airspeed (m/s): <u>TASx</u>

This derived measurement of the flight speed of the aircraft relative to the atmosphere is based on the Mach number calculated from both the dynamic pressure at location x and the static pressure. See the derivation above for ATx. The different variables for TASx (TASF, TASR, etc) use different measurements of QCxC in the calculation of Mach number.

(see above box for ATx and MACHx)
Note dependence of M on choices for QCxC and PSXC
TASx depends on QCxC, PSXC, ATX
where PSXC and ATX are the preferred choices

$$\mathrm{TASx} = \{\mathrm{MACHx}\}\sqrt{\gamma R_d\left(\{\mathrm{ATX}\}+T_0\right)} \tag{14}$$

Aircraft True Airspeed (Humidity Corrected) (m/s): TASHC

This derived measurement of true airspeed takes into account the deviations the specific heats of moist air from those of air without water vapor. See List, 1971, pp 295, 331-339, and Khelif, et al., 1999. The present form of this equation, from Khelif et al. 1999), adds a moisture correction to a true airspeed derived for dry air:

SPHUM = specific humidity, g/kg

```
TASHC = TASX * (1.0 + 0.000304 * SPHUM)
```

Water Vapor Pressure (mb): EDPC

EDPC is the ambient vapor pressure of water, used in the calculation of several derived variables. It is usually obtained from a measurement of dew point, DPXC, which includes correction for the enhancement factor that influences dew point or frost point measurements.[13]) The formula for obtaining the equilibrium water vapor pressure as a function of dew point is given in the discussion of DPxC in Section 7.

Potential Temperature (K): THETA

The potential temperature in the output data files is the temperature reached if a dry parcel at the measured pressure and temperature would be compressed or expanded adiabatically to a pressure of 1000 mb. It does not take into account the difference in specific heats caused by the presence of water vapor.

ATX = ambient temperature, $^{\circ}C$
PSXC = ambient pressure (mb)
p_0 = reference pressure = 1000 mb

$$\mathrm{THETA} = \left(\{\mathrm{ATX}\}+T_0\right)\left(\frac{p_0}{\{\mathrm{PSXC}\}}\right)^{R/c_p} \tag{15}$$

[13] prior to 2011, this variable was calculated using the Goff-Gratch formula. See the discussion of DPXC for more information on previous calculations.

Equivalent Potential Temperature (K): THETAE

The equivalent potential temperature in the output data files is that obtained using the method of Bolton (1980), which uses an approximate fit to obtain the temperature at the lifted condensation level (T_{LCL}) and then uses that temperature to find the value of potential temperature that would result if the parcel were lifted from that point until all water vapor condensed and was removed from the air parcel.

T_{lcl}= temperature at the lifted condensation level, K
ATX = ambient temperature ($^\circ C$)
EDPX = water vapor pressure (mb)
MR = mixing ratio (g/kg)
THETA = potential temperature (K)

$$T_{lcl} = \frac{2840.}{3.5\ln(\{\text{ATX}\}+\text{T}_0) - \ln(\{\text{EDPX}\}) - 4.805} + 55.$$

$$\text{THETAE} = \{\text{THETA}\}\left(\frac{3.376}{\text{T}_{\text{lcl}}} - 0.00254\right)(\{\text{MR}\})(1+0.00081(\{\text{MR}\})) \tag{16}$$

Virtual Temperature (°C): TVIR

The virtual temperature is the temperature of dry air having the same pressure and density as the air being sampled, and so adjusts for the buoyancy added by water vapor. The calculation of virtual temperature in RAF output products is taken from page 295 of the Smithsonian Meteorological Tables (1958).

ATX = ambient temperature, $^\circ C$
MR = mixing ratio of water vapor, g/kg
q= specific humidity, g/g

$$q = \frac{\{\text{MR}\}/1000}{1+\{\text{MR}\}/1000}$$

$$\text{TVIR} = (\{\text{ATX}\}+T_0)\left(\frac{1+\frac{M_a}{M_w}q}{1+q}\right) - T_0 \tag{17}$$

Virtual Potential Temperature (K): THETAV

The virtual potential temperature is analogous to the potential temperature except that it is based on the virtual temperature (TVIR) instead of the ambient temperature (ATX).

TVIR = virtual temperature, $^{\circ}C$
PSXC = ambient pressure, mb

$$\text{THETAV} = (\{\text{TVIR}\} + T_0)\left(\frac{1000}{\{\text{PSXC}\}}\right)^{R/c_p} \tag{18}$$

Relative Humidity (per cent or Pa/hPa): RHUM

The relative humidity is the ratio of the water vapor pressure to the saturation water vapor pressure in equilibrium over a plane liquid-water surface, scaled to express the result in units of per cent.:
EDPX = atmospheric water vapor pressure (mb)
ATX = ambient air temperature ($^{\circ}C$)
$e_s(\text{ATX})$ = saturation water vapor pressure at *dewpoint* ATX (mb)
(see (**??**) for the equation used)
(see eq. **??**) for the formula used;
however, the branch for DPX$\geq$ 0 is used always)

$$\text{RHUM} = 100\% \times \frac{\{\text{EDPX}\}}{e_s(\{\text{ATX}\})} \tag{19}$$

Absolute Humidity (Vapor Density) (g/m^3): RHOx

The absolute humidity is the water vapor density computed from various measurements of humidity. The different sources of humidity information are indicated by the 'x' suffix, as usual. The calculation is based on the equation of state for a perfect gas.

ATX = ambient temperature ($^{\circ}C$)
EDPX = water vapor pressure, converted to consistent units
(e.g., multiplied by 100 Pa/mb if MKS units are used otherwise)

$$\text{RHOx} = \left(10^3 \frac{g}{kg}\right) \frac{(\{\text{EDPX}\})M_w}{R_0(\{\text{ATX}\} + T_0)} \tag{20}$$

Specific Humidity (g/kg): SPHUM

The specific humidity is the mass of water vapor per unit mass of (moist) air, onventionally measured in g/kg.

PSXC = ambient pressure
EDPX = ambient water vapor pressure

$$\text{SPHUM} = \left(10^3 \frac{g}{kg}\right) \frac{M_w}{M_a} \left(\frac{\{\text{EDPX}\}}{\{\text{PSXC}\} - (1 - \frac{\text{M}_\text{w}}{\text{M}_\text{d}})\{\text{EDPX}\}} \right) \tag{21}$$

Mixing Ratio (g/kg): MR, MRCR, MRLA, MRLA1, MRLH

the mixing ratio is the ratio of the mass of water to the mass of dry air, normally expressed in g/kg. It is related to specific humidity as follows: SPHUM=MR/(1+MR). Mixing ratios may be calculated for the various instruments measuring humidity on the aircraft, and the variable names reflect the source: MR from the dewpoint hygrometers, MRCR from the cryogenic hygrometer, MRLA from the Lyman-alpha snsor, MRLA1 if there is a second Lyman-alpha sensor, and MRLH from a laser hygrometer. The example in the box below is for the case of the dewpoint hygrometers; others are analogous.

EDPX = water vapor pressure (mb)
PSXC = ambient total pressure

$$\text{MR} = \left(10^3 \frac{\text{g}}{\text{kg}}\right) \frac{\text{M}_\text{w}}{\text{M}_\text{a}} \frac{\{\text{EDPX}\}}{(\{\text{PSXC}\} - \{\text{EDPX}\})} \tag{22}$$

Calculated Surface Pressure (mb): PSURF

The estimated surface pressure is calculated from HGM, TVIR, PSXC, and MR using the thickness equation. The average temperature for the layer is obtained by using HGM and assuming a dry-adiabatic lapse rate from the flight level to the surface. Because of this assumption, the result is only valid for flight in a well-mixed surface layer or in other conditions in which the temperature lapse rate matches the dry-adiabatic lapse rate.

PSXC = ambient pressure (mb)
HGM = altitude above the surface (m)
TVIR = virtual temperature ($^\circ C$)

$$T_m = (\{\text{TVIR}\} + T_0) + 0.5\{\text{HGM}\}\frac{g}{c_p}$$

$$\text{PSURF} = \{\text{PSXC}\}\, e^{\frac{g T_m}{R(\{\text{HGM}\})}}$$

9 WIND

Bulletin No. 23 documents the calculation of wind components, both with respect to the earth (UI, VI, WI, WS and WD) and with respect to the aircraft (UX and VY). In the data processing, a separate function (GUSTO in GENPRO, gust in NIMBUS) is used to derive these wind components. That function uses the Inertial Reference System measurements as well as aircraft true airspeed, aircraft angle of attack, and aircraft sideslip angle. The wind components calculated in GUSTO/gust are used to derive two additional components: wind direction (WD and wind speed (WS).

The details contained in Bulletin No. 23 will not be repeated here; please consult that bulletin for the processing algorithms. Instead, the output variables are only described briefly here, along with some additional detail in some cases where procedures are not documented in that bulletin.

Wind Vector East Component (m/s): UI
Wind Vector North Component (m/s): VI
Wind Vector Vertical Gust Component (m/s): WI

These measurements comprise the three-dimensional wind vector with respect to the earth. UI is the east-west component with positive values toward the east. VI is the north-south component with positive values toward the north. WI is the vertical component with positive values toward the zenith.

Wind Speed (m/s): WS

Wind Direction (°): WD

These variables are obtained in a straightforward manner from UI and VI. The resulting wind direction is relative to true north.

UI = easterly component of the horizontal wind
VI = northerly component of the horizontal wind
atan2 = 4-quadrant arc-tangent function producing output in radians from -π to π
C_{rd} = conversion factor, radians to degrees, = 180/π {units $^\circ/radian$

$$\begin{aligned} \text{WS} &= \sqrt{\{\text{UI}\}^2 + \{\text{VI}\}^2} \\ \text{WD} &= C_{rd}\,\text{atan2}(\{\text{UI}\},\{\text{VI}\}) + 180^\circ \end{aligned} \tag{23}$$

Wind Vector Longitudinal Component (m/s): UX
Wind Vector Lateral Component (m/s): VY

These measurements describe the horizontal wind vector relative to the frame of reference attached to the aircraft (and moving with the aircraft). UX is parallel to the longitudinal axis, and positive is toward the nose. The variable VY is the component normal to the longitudinal axis; positive is toward the port (or left) wing.

GPS-Corrected Wind Vector, East Component (m/s): **UIC**
GPS-Corrected Wind Vector, North Component (m/s): **VIC**

Horizontal wind components respectively toward the east and toward the north. The components combine measurements from an inertial reference system (IRS) and a Global Positioning System (GPS), as described in the discussion of VEW and VNS above. They are calculated just as for UX and VY except that the GPS-corrected values for the aircraft groundspeed are used in place of the IRS-based values. They are considered "corrected" from the original measurements from the INS or GPS.

GPS-Corrected Wind Vector, Vertical Component (m/s): **WIC**

This variable is actually misnamed. The GPS-correction algorithm does no vertical corrections, so this measurement does the same calculation as WI with the option of using a different vertical airplane velocity. Positive values are toward the zenith.

GPS-Corrected Wind Speed (m/s): **WSC**
GPS-Corrected Wind Direction (°)**:** **WDC**

These variables are obtained in a straightforward manner from UIC and VIC, using equations analogous to (23) but with UIC and VIC as input measurements.. They are expected to be the best measurements of wind because they combine the best features of the IRS and GPS measurements.

GPS-Corrected Wind Vector, Longitudinal Component (m/s): **UXC**
GPS-Corrected Wind Vector, Lateral Component (m/s): **VYC**

Longitudinal and lateral components of the three-dimensional wind, similar to UX and VY, but corrected by the complementary-filter algorithm that combines IRS and GPS measurements. The components UXC and VYC are toward the front of the aircraft and toward the port (left) wing, respectively.

10 RADIATION VARIABLES

10.1 Measurements of Irradiance and Radiometric Temperature

Radiometric (Surface or Sky/Cloud-Base) Temperature ($^\circ C$): RSTx

Radiomatric temperature is the equivalent black body temperature measured by one of two infrared radiometers. The x denotes either that the instrument is mounted on the bottom (B) or top (T) of the aircraft. Both of these instruments are calibrated using a black-body source manufactured by Eppley. The measurements may come from either of the following two instruments:
* a narrow bandwidth, narrow field-of-view (2°) Heimann Model KT-19.85 precision radiation thermometer. The wavelength range is 9.6 to 11.5 μm.
* a narrow bandwidth, narrow field-of-view (2°) Barnes Engineering Model PRT-5 precision radiation thermometer. This instrument is now retired.
The spectral bandwidth available was either 8 to 14 μm or 9.5 to 11.5 μm.
Its cavity temperature was monitored and recorded as either TCAVB or TCAVT.

Radiometer Sensor Head Temperature ($^\circ C$): TRSTB

This is the temperature of the Heimann radiometer's sensing head, usually from RSTB, the primary down-looking instrument.

Raw Pyrgeometer Output (W/m^2): IRx

The pyrgeometer, manufactured by Eppley Laboratory, Inc., measures long-wave irradiance using a calibrated thermopile. It has a coated glass hemisphere that transmits radiation in a bandwidth between 3.5 μm and 50 μm. It is calibrated at RAF according to procedures specified by Albrecht and Cox (1977). The pyrgeometers are usually flown in pairs, one up-looking and one down-looking. The x denotes either bottom (B) or top (T).

Corrected Infrared Irradiance (W/m^2): IRxC

Because the pyrgeometer measures net radiation, IRx must be corrected for emission from the dome covering the sensor and for emission from the thermopile itself. The corrected value
This is the output of , determined following procedures of Albrecht and Cox (1977), is the corrected infrared irradiance.

IRx = raw pyrgeometer output (W/m^2)
T_D = dome temperature
T_S = "sink" temperature (approx. the thermopile temperature)
ε = emissivity of the thermopile (dimensionless)
β = empirical constant dependent on the dome type

$$\mathrm{IRxC} = \mathrm{IRx} - \beta\sigma(T_D^4 - T_S^4) + \varepsilon\sigma T_S^4$$

Shortwave Irradiance (W/m^2): SWx

An Eppley Laboratory, Inc., pyranometer measures short-wave irradiance. The dome normally used is UG295 glass, which gives wide coverage of the solar spectrum (from 0.285 μm to 2.8 μm). Different bandwidths can be obtained by use of different glass domes, available from RAF upon request. (See Bulletin No. 25.) The pyranometers are usually flown in pairs, one up-looking and one down-looking. They are calibrated periodically at the NOAA Solar Radiation Facility in Boulder, Colorado. The x denotes either bottom (B) or top (T).

Corrected Incoming Shortwave Irradiance (W/m^2): SWTC

The down-welling shortwave irradiance measured by the difference between SWT and SWB) is corrected to take into account the sun angle and small variations in the aircraft attitude angles (pitch and roll). The correction is limited to $\pm 6°$ in either angle. This is the derived output of incoming (down-welling) shortwave irradiance, taking into account both solar position (sun angle) and modest variations in aircraft attitude (at present, restricted to less than 6° in pitch and/or roll). (For more information, refer to Bulletin No. 25.)

Ultraviolet Irradiance (W/m^2): UVx

A pair of UV radiometer/photometers measure either down-welling (x=T) or up-welling (x=B) irradiance in the ultraviolet, approximately from 0.295 μm to 0.385 μm. These units are periodically returned to the Eppley Laboratories for recalibration.

10.2 SOLAR ANGLES

The calculations described in this group are used primarily for deriving the Corrected Short Wave irradiance (SWTC) but can be used by themselves or in conjunction with other measurements that need them.

Solar Declination Angle (radians): SOLDE

This is a complex calculation of the astronomical measurement of solar declination angle, the angular distance of the sun north or south of the earth's equator. (Positive values are north.) It also makes a complex calculation of solar hour angle that takes leap year into account. The calculations were adapted by Ron Ruth from a FORTRAN program used by Lutz Bannehr.

time = day number (corrected for leap year) since 1 January 1980
theta = coarse solar time (radians)
g = equation-of-time term for calculating declination (radians)
el = equation-of-time term for calculating declination (radians)
eps = equation-of-time term for calculating declination (radians)

```
g = -0.031271 - (4.53963e-7 time) + theta
el = 4.900968 + (3.67474e-7 time) +
{[0.033434 - (2.3e-9 time)] sin(g)} +
[0.000349 sin(2 g) + theta]
sel = sin(el);
eps = 0.409140 - (6.2149e-9 time)
SOLDE = asin {sel sin(eps)}
```

Solar Zenith Angle (radians): SOLZE

This is the astronomical measurement of solar zenith angle, the angle from zenith to the sun, complementary to the sun's elevation angle:

lat = latitude (radians)
lha = local hour angle (radians)
SOLDE = solar declination angle (radians)

```
SOLZE = asin {sin(lat) sin(SOLDE)
      + cos(lat) cos(SOLDE) cos(lha)}
```

Solar Azimuth Angle (radians): SOLAZ

This is the astronomical measurement of solar azimuth angle, the angular distance between due south and the projection of the line of sight to the sun on the ground. A positive solar azimuth angle indicates a position east of south (i.e., morning).

lha = local hour angle (radians)
SOLDE = solar declination angle (radians)
SOLZE = solar zenith angle (radians)

```
SOLAZ = asin {cos(SOLDE) sin(lha) / cos(SOLZE)}
```

Solar Elevation Angle (radians): SOLEL

This is the astronomical measurement of solar elevation angle, describing how high the sun appears in the sky. The angle is measured between an imaginary line between the observer and the sun and the horizontal plane on which the observer is standing. The altitude angle is negative when the sun drops below the horizon.

SOLZE = solar zenith angle (radians)

```
SOLEL = Pi/2 - SOLZE
```

11 CLOUD PHYSICS VARIABLES

11.1 Measurements of Liquid Water Content

Raw Output PMS/CSIRO (KING) Liquid Water Content (W): PLWC, PLWC1
This is the output of a PMS/CSIRO (KING) liquid water probe (in Watts). It measures the power required to maintain a constant temperature through a heated element as that element is cooled by convection and evaporation of impinging liquid water. The convective heat losses are determined by calibration in dry air over a range of airspeeds and temperatures.

Corrected PMS/CSIRO (KING) Liquid Water Content (g/m^3): PLWCC, PLWCC1
This is the corrected liquid water content obtained from relating the power consumption (required to maintain a constant temperature) to liquid water content, taking into account the effect of convective heat losses.

PLWC = total power dissipated by the probe
P_D = power dissipated by the cooling effect of dry air alone
P_W = power needed to heat and vaporize the liquid water that hits the probe element
Nu = Nusselt Number (relating conduction heat loss to the total heat loss for dry air).
L = length of the probe sensitive element, m
d= diameter of the probe sensitive element, m
λ = thermal conductivity of dry air ()
T_s= sensor temperature (K)
T_a= ambient temperature (K) = ATX+273.15
L_v = latent heat of vaporization of water
C_w = specific heat of water
U_a = true airspeed (m/s) = TASX
χ = liquid water content (g/m^3) = PLWCC

$$\text{PLWC} = P_D + P_W$$

where

$$P_D = \pi \text{Nu}\, L\lambda (T_s - T_a)$$

$$P_W = Ld[L_v + c_w(T_s - T_a)]\, U_a \chi$$

Result:

$$\text{PLWCC} = \chi = \frac{\{\text{PLWC}\} - P_D}{Ld\, U_a[L_v + c_w(T_s - T_a)]}$$

Raw Output Rosemount Icing Detector (V): RICE
A Rosemount 871F ice-accretion probe consists of a rod set in vibration by a piezoelectric crystal. The oscillation frequency of the probe changes with ice loading, so

in supercooled cloud ice accumulates on the sensor, and the change in oscillation frequency is transmitted as a DC voltage.. When the probe loads to a trigger point, the probe heats the rod to remove the ice. Its output voltage is a measure of the mass of the accreted ice. The rate of voltage change is converted to an estimate of the supercooled liquid water content, as described in the next paragraph.

Derived Supercooled Liquid Water Content (g/m^3): SCLWC
This variable is the supercooled liquid water content obtained from the change in accreted mass on the Rosemount 871F ice-accretion probe over one second. Note that the output is not valid during the probe deicing cycle. This cycle is apparent in the RICE output (a peak followed by a decrease to near zero). Supercooled liquid water content is determined by first calculating a water drop impingement rate which is a function of the effective surface area, the collection efficiency, the true airspeed, and the supercooled liquid water content. The impingement rate obtained is equated to the accreted mass of ice collected by the probe in one second (empirical voltage/mass relationship). The resulting equation is solved for supercooled water content.

A = effective surface area of the probe (m^2)
Δt = time interval during which an increment of mass accretes (s)
Δm = mass of ice accreted on the probe in the time interval Δt (g)
U_a = true airspeed (m/s)

$$\mathrm{SCLWC} = AU_a \frac{\Delta m}{\Delta t}$$

SCLWC = A (Dm/Dt)/Ua.

11.2 Sensors of Individual Particles (1-D Probes)

The RAF operates a set of hydrometeor detectors that provide single-dimension measurements (i.e., not images) of individual particle sizes. RAF Bulletin No. 24 contains extensive information on the operating principles and characteristics of these instruments. Here the focus will be on the meanings of the variables in the archived data files.

Four- and five-character variable names shown in this section are generic. The actual names appearing in NIMBUS-generated production output data sets have appended to them an underscore (_) and three more characters which indicate a probe's specific aircraft mounting location. For example, AFSSP_RPI is the Total Accumulation from an FSSP-100 probe mounted on the inboard, right-side pod. The codes presently in use are given in the following table. For the GV, there are 12 locations available, characterized by three letters. The first is the wing ({L,R} for {port,starboard}), the second is the pylon ({I,M,O} for inboard, middle, outboard}), the third is which canister at the pylon is used ({I,O} for {inboard, outboard}).

Code	Location	Aircraft
OBL	Outboard Left	C-130Q
IBL	Inboard Left	C-130Q
OBR	Outboard Right	C-130Q
IBR	Inboard Right	C-130Q
LPO	Left Pod Outboard	C-130Q
LPI	Left Pod Inboard	C-130Q
LPC	Left Pod Center	C-130Q
RPO	Right Pod Outboard	C-130Q
RPI	Right Pod Inboard	C-130Q
RPC	Right Pod Center	C-130Q
OBL	Left Wing	Electra
IBL	Left Pylon	Electra
WDL	Window Left	Electra
OBR	Right Wing	Electra
IBR	Right Pylon	Electra
WDR	Window Right	Electra
{L,R}{I,M,O}{I,O}	see discussion above	GV

The probe type also is coded into each variable's name, sometimes using four characters, sometimes only one: FSSP-100 (FSSP or F), FSSP-300 (F300 or 3), PCAS (PCAS or P), OAP-200X (200X or X), OAP-260X (260X or 6) and OAP-200Y (200Y or Y). Prefix letters are used to identify the type of measurement (A=accumulated particle counts per time interval per channel, C = concentration per channel, CONC = Concentration from all channels, DBAR = Mean Diameter, DISP = Dispersion, PLWC =Liquid Water Content, DBZ = Radar Reflectivity Factor).

Generic Name		Probe	Channels	Usable	Diameter Range	Bin Width
FSSP	F	FSSP-100	0-15	1-16	(See FRNG below)	
F300	3	FSSP-300	0-31	1-31	0.3–20.0 μm	variable
PCAS	P	PCAS	0-15	1-15	0.1–3.0 μm	variable
200X	X	OAP-200X	0-15	1-15	40–280 μm	10 μm
260X	6	OAP-260X	0-63	3-62	40-620 μm	10 μm
200Y	Y	OAP-200Y	0-15	1-15	300–4500 μm	300 μm

Total Accumulation (counts per time interval):
AFSSP, AF300, APCAS, A200X, A260X, A200Y

This measurement is the total number of particles detected by a PMS-1D probe per unit time. These measurements have "vector" character in the NETCDF output files, with dimension equal to the number of usable channels in the table above and one entry per channel.

Concentration (per channel) (cm^{-3}): CFSSP, CF300, CPCAS
Concentration (per channel) ($liter^{-1}$): C200X, C260X, C200Y

These measurements give the particle concentrations in each usable bin of the probe. They have "vector" character is the NETCDF output files, with dimension equal to the number of usable channels in the table above and with one entry per channel. For the scattering spectrometer probes (FSSP-100, FSSP-300, PCAS) the concentration value is modified by the probe activity (FACT, PACT) as described below. The concentration is obtained from the total number of particles detected and a calculated, probe-dependent sample volume. For details, see RAF Bulletin No. 24.

Concentration, sum over all channels (cm^{-3}): CONCF, CONC3, CONCP
Concentration, sum over all channels ($liter^{-1}$): CONCX, CONC6, CONCY

These measurements are the particle concentrations summed over all channels to give the total particle concentration in the size range of the probe. For details, see RAF Bulletin No. 24.

Mean Diameter (μm): DBARF, DBAR3, DBARP, DBARX, DBAR6, DBARY
The mean diameter is the arithmetic average of all particle diameters. It is calculated as follows:

$\{Cy_i\}$ = concentration from probe y in channel i
(e.g., y=FSSP to calculate DBARx for x=F)
i1 = lowest usable channel for the probe
i2 = highest usable channel for the probe
d_i = mean diameter of particles in channel i for this probe (μm)

$$\mathrm{DBARx} = \frac{\sum_{i=i1}^{i2} \{\mathrm{Cy}_i\}\, d_i}{\sum_{i=i1}^{i2} \{\mathrm{Cy}_i\}}$$

Dispersion (dimensionless): DISPF, DISP3, DISPP, DISPX, DISP6, DISPY
The dispersion is the ratio of the standard deviation of particle diameters to the mean particle diameter.

$\{DBARx\}$ = mean particle diameter (μm)
$\{Cy_i\}$ = concentration from probe y in channel i
(e.g., y=FSSP to calculate DISPx for x=F)
d_i = diameter measured in channel i of probe y
i1 = lowest usable channel for the probe
i2 = highest usable channel for the probe

$$\mathrm{DISPx} == \frac{1}{\{\mathrm{DBARx}\}} \left\{ \frac{\sum_{i=i1}^{i2} \{\mathrm{Cy}_i\}\, d_i^2}{\sum_{i=i1}^{i2} \{\mathrm{Cy}_i\}} - \{\mathrm{DBARx}\}^2 \right\}^{1/2}$$

Liquid/Ice Water Content (g/m^3): PLWCF, PLWCX, PLWC6, PLWCY
This variable is a derived calculation of the liquid or ice water content obtained from

the measured concentration (CONCx) and the third moment of the equivalent droplet diameter. The equivalent droplet diameter is the diameter that represents the equivalent mass in the detected particle. For water, the equivalent droplet diameter is the normally the measured diameter, but some processing has used other assumptions and this is a choice that can be made differently based on project needs. Using this definition allows for the approximate estimation of ice water content in cases where it is known that all hydrometeors are ice.

:

$d_{e,i}$ = equivalent melted diameter for channel i of probe x
$\{Cy_i\}$ = concentration from probe y in channel i
(e.g., y=FSSP to calculate DISPx for x=F)
ρ_w = density of water ($10^3 kg/m^3$)
i1 = lowest usable channel for the probe
i2 = highest usable channel for the probe

$$\mathrm{PLWCx} = \frac{\pi\rho_w}{6}\sum_{i=i1}^{i2}\{\mathrm{Cy}_i\}\, d_{e,i}^3$$

(units and a scale factor are selected so that the output variable is in units of g/m^3)

Radar Reflectivity Factor (dbZ): <u>DBZF</u>, <u>DBZX</u>, <u>DBZ6</u>, <u>DBZY</u>
The radar reflectivity factor for water is a measure of the product of the concentration and the sixth moment of the dropleet diameter. An equivalent radar reflectivity factor can be calculated from the hydrometeor size distribution if an assumption about composition of the particles is made, but this variable is not part of normal data files. The radar reflectivity factor is a characteristic only of the hydrometeor size distribution; it is *not* a measure of radar reflectivity, because the latter also depends on wavelength, dielectric constant, and other characteristics of the hydrometeors. The radar reflectivity factor is measured on a logarithmic scale that depends on a particular choice of units, so (although it is not conventionally included) an appropriate scale factor Z_r is included in the following equation to satisfy the convention that arguments of logarithms should be dimensionless. /

d_i = diameter for channel i of probe x
$\{Cy_i\}$ = concentration from probe y in channel i
(e.g., y=FSSP to calculate DISPx for x=F)
i1 = lowest usable channel for the probe
i2 = highest usable channel for the probe
Z_r = reference factor for units = $1\, mm^6/m^3$

$$\mathrm{DBZx} = 10\log_{10}\left(\frac{1}{Z_r}\sum_{i=i1}^{i2}\{\mathrm{Cy}_i\}\, d_i^6\right)$$

FSSP-100 Range (dimensionless): FRNG, FRANGE
This variable records the size range in use for the FSSP-100 probe

Range	**Nominal Size Range**	**Nominal Bin Width**
0	2–47 μm	3 μm
1	2–32 μm	2 μm
2	1–15 μm	1 μm
3	0.5–7.5 μm	0.5 μm

In recent NETCDF data files, the actual bin boundaries used for processing are recorded in the header. That header should be consulted because processing often uses non-standard sizes selected to adjust for Mie scattering, which causes departures from the nominal linear bins.

FSSP-100 Fast Resets (number per sample interval): FRST, FRESET
The FSSP records events called "fast resets" that occur when a particle traverses the beam outside the depth-of-field and is therefore not accepted for sizing. To avoid the processing time associated with sizing, the probe resets quickly in this case, but there is still some dead time when the probe cannot record another event. Fast resets consume a time determined by circuit characteristics, so that time is determined in laboratory tests of the FSSP circuitry. This variable is needed in addition to the "Total Stobes" to determine what fraction of the time the probe is unable to accept another particle, and this "dead time" enters calculation of the concentration.

FSSP-100 Total Strobes (number per sample interval): FSTB, FSTROB
A "strobe" is generated in the FSSP whenever a particle is detected within its depth-of-field. Not all such particles are accepted for inclusion in the size distribution, however, because some pass through the outer regions of the illuminating laser beam and therefore produce shorter and smaller-amplitude pulses than those passing through the center of the beam. The probe maintains a running estimate of the average transit time and rejects particles with transit times shorter than this average. The total number of strobes recorded is therefore more than the number of sized particles, but the ratio of strobes to accepted particles can indicate quality of opeeration of the probe. Also, the strobes require processing and so contribute to the dead time of the probe, affecting the concentration unless a correction is made. See RAF Bulletin No. 24 for more discussion of the operation of the FSSP.

FSSP-100 Beam Fraction (dimensionless): FBMFR
This variable records the ratio of the number of velocity-accepted particles (particles that pass through the effective beam diameter) to the total number of particles detected in the depth-of-field of the beam (the total strobes). See the discussion of Total Strobes for more information.

AFSSP = valid particles sized per sample interval
FSTROB = strobes generated by particles in the depth-of-field, per sample interval

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$$\text{FBMFR} = \{\text{AFSSP}\}/\{\text{FSTROB}\}$$

FSSP-100 Calculated Activity Fraction (dimensionless): FACT

This variable represents the fraction of the time that the FSSP is unable to count and size particles (its "dead time"). The activity fraction is not measured directly but is estimated from fast resets and total strobes along with measurements of the dead times associated with each (as determined in laboratory tests). .

FSTROB = strobes generated by particles in the depth-of-field, per sample interval
FRESET = "fast resets" generated per sample interval
t_1 = slow reset time (for each strobe)
t_2 - fast reset time (for each fast reset)

$$\backslash\text{FACT} = \{\text{FSTROB}\}\, t_1 + \{\text{FRESET}\}\, t_2$$

PCAS Raw Activity (dimensionless); AACT, PACT

The PCAS probe provides this measure of dead time, the time that the probe is unable to sample particles because the electronics are occupied with processing particles. The manufacturer suggests that the actual dead time (f_{PCAS}) is given by the following formula, which is used in determining concentrations for the PCAS:

$$f_{PCAS} = 0.52\frac{\{\text{PACT}\}}{F_{PCAS}}$$

where $F_{PCAS} = 1024\,s^{-1}$. However, PACT (or AACT) is the variable archived in the data files.

PMS-2D Cloud Probe Particle Concentration (cm^{-3}): CON2C1

This concentration of all particles sensed by the PMS-2D Cloud Probe is based on the "shadow-or" count (SDWC1,SHDORC) from the probe. This counter is triggered each time a particle passes through the laser beam, so the rate at which these counts are produced can be used with the sample volume of the probe and the flight speed to determine this upper estimate of the particle concentration.

PMS-2D Precip Probe Particle Concentration (cm^{-3}): CON2P1

This measurement is based on SDWP1 or SHDORP and is analogous to CON2C1 but for the PMS-2D Precip Probe.

12 AEROSOL PARTICLE MEASUREMENTS

RAF uses a modified TSI, Inc. Model 3760 condensation nucleus counter to measure the concentration of particulates in the atmosphere larger than about 0.01 μm diameter. Individual inlets have been designed for each research aircraft that provide approximately isokinetic flow at research airspeeds. The CN counter is often used as a stand-alone instrument, but it also can be placed downstream of various instruments, such as a counterflow virtual impactor or differential mobility analyzer. It is useful at altitudes up to about 11km. It operates by condensing n-butyl alcohol on the particles as they pass through a cooling/condenser tube where supersaturation of a few hundred percent is produced. The particles grow large enough to be seen by a laser-diode optical detector, and the pulses from tat detector are counted to obtain an estimate of the total concentration of aerosol particles. The counter does not resolve particle concentration by size; the lower size limit of the TSI 3760 is about XXX μm, and all particles above that size enter the measurement of the total concentration.

If large concentrations are encountered, two or more particles may be present in the viewing volume at once and will produce only a single pulse from the photodetector. This "coincidence" error, which increases from about 0.6% at a total concentration of $10^3/cm^3$to about 6% at $10^4/cm^3$; a correction for these effects of coincidence is applied, but for concentrations above about $2 \times 10^4/cm^3$ effects of coincidence become large enough that the correction introduces significant uncertainty in the measurements.

The variables associated with these measurements of condensation-nucleus concentrations are discussed in the remainder of this section.

CN Counter Inlet Pressure (mbar): <u>PCN</u>
PCN is the absolute pressure inside the inlet tube of the instrument, as measured by a Heise Model 623 pressure sensor. The measurement is used to correct the sample flow rates (FCN and XICN) that are used to obtain measurements of concentration.

CN Counter Inlet Temperature ($°C$): <u>TEMP1</u>, <u>TEMP2</u>, <u>CNTEMP</u>
TEMP1, TEMP2 or CNTEMP is the output from a temperature sensor mounted on the outside of the sampling tube immediately ahead of the counter. The measurement, an approximation to the temperature of the air passing through the tube, is used to correct the sample flow rates (FCN and XICN).

Raw CN Counter Sample Flow Rate (slpm): <u>FCN</u>
Corrected CN Counter Sample Flow Rate (vlpm): <u>FCNC</u>
FCN is the raw sample flow rate in standard liters per minute (slpm) measured with a Sierra 830 Mass Flow meter. The flow meter measures the flow rate that would apply under "standard" conditions; i.e., pressure of 1013.25 and temperature of $0°C$. FCNC is the sample flow rate in vlpm (volumetric liters per minute) corrected for pressure and temperature.

PCN = pressure at the inlet to the CN counter (mb)
TEMP1 = temperature at the inlet of the sample tube ($^\circ C$)
P_{ref} = standard reference pressure, 1013.25 mb
T_{ref} = standard reference temperature, 293.26 K

$$\mathrm{FCNC} = \{\mathrm{FCN}\}\frac{P_{ref}}{\{\mathrm{PCN}\}}\frac{(\{\mathrm{TEMP1}\}+T_0)}{T_{ref}}$$

Raw CN Isokinetic Side Flow Rate (slpm): <u>XICN</u>
Corrected CN Isokinetic Side Flow Rate (vlpm): <u>XICNC</u>
XICN is the raw isokinetic side flow rate in standard liters per minute (slpm) measured with a Sierra 830 Mass Flow meter, and XICNC is that flow corrected for pressure and temperature to be the true volumetric flow. For isokinetic sampling, the flow rate at the inlet entrance needs to equal the true airspeed, and for proper operation the flow rate through the CN counter should be at least 1.2 vlpm. A side flow of filtered air is added so both of these conditions can be met.

PCN = pressure at the inlet to the CN counter (mb)
TEMP1 = temperature at the inlet of the sample tube ($^\circ C$)
P_{ref} = standard reference pressure, 1013.25 mb
T_{ref} = 293.26 K

$$\mathrm{XICNC} = \{\mathrm{XICN}\}\frac{P_{ref}}{\{\mathrm{PCN}\}}\frac{(\{\mathrm{TEMP1}\}+T_0)}{T_{ref}}$$

TSI CN Counter Output (counts per sample interval); <u>CNTS</u>
CNTS is the raw output count from the TSI, Inc. 3760 condensation cncleus counter. The project-dependent sample rate may be chosen in the range from 1–50 Hz. In some unusual cases the counts are divided by a selected power of two to keep the counter from overflowing; see the project documentation.

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Condensation Nucleus (CN) Concentration (cm^{-3}): <u>CONCN</u>
CONCN is the corrected concentration of condensation nuclei, calculated with consideration of the sample rate and corrected for losses caused by coincidence:

CNTS = counts per second from the CN counter
ΔT = interval between recorded samples
D = scale factor (normally 1)
FCNC = corrected sample flow rate (cm^3/s)
T_{vv} = time each particle is in the view volume = $4.167 \times 10 - 6$ s

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$$\mathrm{A} = \frac{\{\mathrm{CNTS}\}}{\{\mathrm{FCNC}\}\Delta\mathrm{T}}\mathrm{D}$$

$$\mathrm{CONCN} = \mathrm{A}\, e^{AT_{vv}\{\mathrm{FCNC}\}} \tag{24}$$

See the introduction to this section for comments regarding the range of validity of the coincidence correction in Eq. (24).

13 AIR CHEMISTRY MEASUREMENTS

Raw Carbon Monoxide Concentration (ppb): CO
CO is the uncorrected output of the TECO model 48 CO analyzer. This instrument measures the concentration of CO by gas filter correlation. The optics of the version operated by the RAF have been modified to increase the light through the absorption cell, and a zero trap has been added that periodically removes CO from the sample air stream to obtain an accurate zero. This permits correction for the significant temperature-dependent drift of the zero level of the meaasurement.

Carbon Monoxide Analyzer Status (V): CMODE,
Carbon Monoxide Baseline Zero Signal (V): COZRO
Raw Carbon Monoxide, Baseline Corrected (V): COCOR
CMODE records if the CO analyzer is supplied with air from which CO has been removed and so is recording its zero level. When CMODE is less than 0.2 V, the instrument is in the normal operational mode, and when CMODE is greater than 8.0 V the instrument is in the "zero" mode. When measurements are processed, the zero-mode signals are represented by a cubic spline to obtain a reference baseline for the signal (COZRO), and this baseline is subtracted from the measured value (CO) to obtain COCOR. This variable still jumps to zero periodically and does not include the calibration that enters the following variable, COCAL.

Corrected Carbon Monoxide Concentration (ppmv): COCAL
COCAL is the calibrated signal after correction for drift of the baseline and after application of the appropriate calibration coefficients to produce units of ppmv. The quality of the baseline fit can be judged by examining the offset at the zero points. If there are relatively small changes in the baseline, the zero offset will be only a few ppbv. If there have been rapid changes in the baseline, the zero offset can be up to 50 ppbv. The magnitude of the offset at the zero values gives a good measure of uncertainty in the data set.

The detection limit is 10 ppbv, with an uncertainty of $\pm 15\%$. At 1 Hz, data will have considerable variability, so 10-s averaging is often useful when the measurements are used for analysis.

Raw TECO Ozone Output (ppb): TEO3
TEO3 is the uncorrected output of the TECO 49 UV ozone analyzer. This commercial instrument has been modified to record the temperature and pressure inside the ozone absorption cell.

Internal TECO Ozone Sampling Pressure (mb): TEP, TEO3P TEP
Internal TECO Ozone Sampling Temperature ($^{\circ}C$): TET
(or TEO3P) is the pressure inside the detection cell of the TECO 49 UV ozone analyzer, and TET is the cell temperature. These are used to convert the measurements from the instrument to units of ppbv.

Corrected TECO Ozone Concentration (ppbv): TEO3C
TEO3C is the measurement from the TECO 49 UV ozone analyzer after correction for

the pressure and temperature in the cell. The instrument provides output only each ten seconds, and measurements are collected in the 3 s preceding the update. The measurements may be artificially high or low when rapid changes in humidity are present, as may occur when crossing the top of the boundary layer or when going through clouds. In operation on the ground prior to takeoff or immediately after landing, a high concentration of hydrocarbons can cause spuriously high measurements. The detection limit is 1 ppbv with an uncertainty of $\pm 5\%$.

NO Raw Counts (counts per sample interval): XNO
NOy Raw Counts (counts per sample interval): XNOY
NO Calibration Flow (slpm): XNOCF
NOy Calibration Flow (slpm): XNCLF
NO, NOy Measurement Status (dimensionless): XNST
NO Zero Air Flow (slpm): XNOZA
NOy Zero Air Flow (slpm): XNZAF
NO Sample Flow (slpm): XNOSF
NOy Sample Flow (slpm): XNSAF
NOy Reaction Chamber Pressure (mb): XNOYP
Gold NOy Converter Temperature (°C): XNMBT
XNO and XNOY are the raw data counts from the NO and NO_y instruments, respectively, and XNCLF and XNOCF are the respective calibration flows for these instruments. XNST records the status for both instruments: In measurement mode, XNST is 0, while XNST is 5 when the instruments are in zero mode and 10 when the instruments are in calibraation mode. the NOy and NO instruments. The instrument is in the measure mode for XNST of 0. For a XNST reading of 5 the instruments are in the zero mode. XNST value of 10 is the calibration mode. XNOZA and XNZAF are flow rates for zero air used to back flush inlets, typically at takeoff and landing, and for calibration using “zero” air. Even if the status, XNST, is 0, indicating the instrument is in the measurement mode, when XNOZA and XNZAF are approximately 1 slpm the instrument is measuring zero air and not ambient air. XNOSF and XNSAF are the sample flow rates through the NO and NO_y instruments respectively. These values are typically about 1 slpm. XNMBT is the temperature of the gold NO_y converter.

Corrected NO Concentration (ppbv): XNOCAL
Corrected NOy Concentration (ppbv): XNYCAL
XNOCAL and XNYCAL are the calibrated NO and NO_y concentrations, respectively, with units of ppbv. The NO and NOy data are represented by a cubic spline for baseline subtraction, and then the calibration coefficients are applied and the measurements are converted to units of ppbv. The quality of the data can be assessed by examining the accuracy of the zero correction. This instrument adds water vapor to the sample stream to reduce the effect of ambient water on the final signal. The water vapor addition is not sufficient to saturate the sample stream, but enough to remove much of the interference. The detection limits of the NO,NO_y instruments are 50 ppmv for a one-second averaging time. The uncertainty is $\pm$ 5%.

Raw Chemiluminescent Ozone Signal (V): O3FS
Raw output from the reverse chemiluminescence ozone instrument, which operates on the basis of reacting nitric oxide with ozone and detecting the resulting chemilumines-

cence.

Chemiluminescent Ozone Sample Flow Rate (sccm): <u>O3FF</u>
Chemiluminescent Ozone Nitric Oxide Flow Rate (sccm): <u>O3FN</u>
Chemiluminescent Ozone Sample Pressure (mb): <u>O3FP</u>
These variables characterize conditions within the chemiluminescence ozone sensor. The sample rate, in standard cm^3/s, is O3FF, while O3FN gives the NO flow rate in the same units and O3FP is the pressure in the ozone sample cell.

Chemiluminescent Ozone Concentration (ppbv): <u>O3FC</u>
This is the corrected ozone concentration, with units of ppbv. This instrument is calibrated both on the ground and in flight by comparison with the TECO 49 UV instrument. The final data are corrected for the influence of water vapor on the signal. The detection limit is 0.1 ppbv and the uncertainty is about 10% for a one-second sample.

14 EXPERIMENTAL VARIABLES

This bulletin does not document experimental variables, conventionally denoted by variable names starting with 'X'. Project documentation should be consulted for such variables. Many projects also include measurements from instruments provided by investigators outside NCAR/RAF. Identification of those variables, and processing algorithms, are contained in the project documentation and/or the NETCDF headers.

15 OBSOLETE VARIABLES

RAF retired the “GENPRO” processor, the software program previously used to produce data sets, in 1993, but data files produced by that processor are still retained and available for use. Also, there are some instruments that are now retired but provided measurements in some archived data files. Obsolete variable names that are associated only with GENPRO or a retired instrument are discussed below, for reference and to facilitate use of old data files.

Unaltered Tape Time (s): TPTIME
This variable is derived by converting the HOUR, MINUTE and SECOND to elapsed seconds after midnight of the current day. If time increments to the next day, its value is not reset to zero, but 86400 seconds are added to produce ever-increasing values for the data set.

Processor Time (s): PTIME
This is an internal time variable created by the GENPRO processor. It represents elapsed seconds after midnight. It differs from TPTIME in that, after it has been set at the beginning of the data set, it is incremented internally for each second of data processed. If duplicate or missing raw data records exist, it can differ from TPTIME. It is guaranteed to be a monotonically increasing and continuous series of values.

INS: Data System Time Lag (s): TMLAG
TMLAG is the amount of time between the reference time of a Litton LTN-5l Inertial Navigation System (INS) and the data system clock, in seconds. TMLAG will always be greater than zero and less than 2.

LORAN-C Latitude (°): <u>CLAT</u>
LORAN-C Longitude (°): <u>CLON</u>
LORAN-C Circular Error of Probability (n mi): <u>CCEP</u>
LORAN-C Ground Speed (m/s): <u>CGS</u>
LORAN-C Time (s): <u>CSEC</u>
LORAN-C Fractional Time (s): <u>CFSEC</u>
Before the advent of GPS, NCAR/RAF operated a LORAN-C receiver that provided information on the position and groundspeed of the aircraft. The measurements of latitude and longitude from this system are CLAT and CLON, measured at 1 Hz and with positive values of longitude to the east and positive values of latitude to the north. and CCEP provides an estimate of the uncertainty in those measurements (in units of nautical miles). A status word, CSTAT, was used to record a value of 15 when the system was operational. The ground speed and reference times were also recorded in the above corresponding variables. The sum of CSEC and CFSEC represented the time of the measurement, which was not always the time in the data file when the measurements were recorded,

INS Latitude (°): ALAT
INS Longitude (°): ALON
Raw INS Ground Speed X Component (m/s): XVI
Raw INS Ground Speed Y Component (m/s): YVI
Raw INS True Heading (°): THI
INS Wander Angle (°): ALPHA
INS Platform Heading (°): PHDG
These variables from the Litton LTN-51 Inertial Navigation System (INS) are analogous to the modern variables discussed in section 3. The measurements of latitude and longitude were provided with 1-Hz frequency and had a resolution of 0.0014°, while the ground speed components were provided at 10 Hz and had resolution equal to 0.012 m/s. The X component of the ground speed was along the longitudinal axis of the aircraft *at the time of alignment,* and the Y axis was in the starboard direction at the time of alignment. PHDG recorded the orientation of the platform relative to true north, with resolution 0.0028°. THI was the true heading of the aircraft, produced at 5 Hz with resolution of 0.0014°. The "wander angle" is an INS-only variable that recorded the angle of the INS platform x-axis relative to its original orientation; it "wandered" in response to east-west motion of the aircraft on a spherical Earth.

Raw Aircraft Vertical Velocity (m/s): VZI
This is an integrated output from an up/down binary counter connected to the INS vertical accelerometer. Resolution is 0.012 m/s. Due to changes in local gravity and accumulated errors, this often develops a significant offset during flight.

Aircraft True Heading (°): THF
This measurement of aircraft heading was derived from the angle between the horizontal projection of the aircraft center and true north: THF = PHDG + ALPHA. Resolution is 0.0028°.

Aircraft Ground Speed (m/s): GSF
Aircraft Ground Speed East Component (m/s): VEW
Aircraft Ground Speed North Component (m/s): VNS
These variables have the same names as the modern variables for ground speed. (Cf. section 3.) GSF is the magnitude of the ground speed determined by the INS, as derived from XVI and YVI:

$$\mathrm{GSF} = \sqrt{\{\mathrm{XVI}\}^2 + \{\mathrm{YVI}\}^2}$$

VEW and VNS are the east and north projections of this ground speed, derived using THF for the aircraft heading.

Wind Speed (m/s): WSPD
Wind Direction (°): WDRCTN
These variables are calculated from UI and VI, the east and north components of the wind determined as described in RAF Bulletin No. 23 and summarized in section 9:

$$
\begin{aligned}
\mathrm{WS} &= \sqrt{\{\mathrm{UI}\}^2+\{\mathrm{VI}\}^2} \\
\mathrm{WD} &= \frac{180^\circ}{\pi}\mathrm{atan2}(-\{\mathrm{UI}\},-\{VI\})+180^\circ
\end{aligned}
$$

Raw Attack Force (Fixed Vane) (g): AFIXx
AFIXx is an amplified output from a strain-gage, fixed-vane sensor mounted in the horizontal plane of the aircraft at the end of a gust boom. The "force" on the vane (calibrated in "equivalent grams" at Jefferson County Airport gravity) varies as a function of the aircraft attack angle and dynamic pressure. Here x refers to left or right.

Raw Sideslip Force(Fixed Vane) (g): BFIXx
BFIXx is an amplified output from a strain-gage, fixed-vane sensor mounted in the vertical plane of the aircraft at the end of a gust boom. The "force" on the vane (calibrated in "equivalent grams" at Jefferson County Airport gravity) varies as a function of the aircraft sideslip angle and dynamic pressure. Here x refers to top or bottom.

Attack Angle (Fixed Vane) (°): AKFXx
AKFXx is the angle of attack, computed from AFIXx and QCx (either boom or gust dynamic pressure). An empirically derived function, HSSATK, is used to determine the attack angle based upon wind tunnel test data.

Sideslip Angle (Fixed Vane) (°): SSFXx
SSFXx is the sideslip angle, computed from BFIXx, and QCx (either boom or gust dynamic pressure). An empirically derived function, HSSATK, is used to determine the sideslip angle based upon wind tunnel test data.

Dynamic Pressure (Boom) (mb): QCB, QCBC
Dynamic Pressure (Gust Probe) (mb): QCG, QCGC
These variables, measured by a differential pressure gauge, record the difference between a pitot (total) pressure and a static pressure. The QCBC and QCGC values are corrected for local flow-field distortion. The boom and gust probe measurements referred to the same aircraft structure. The different designations used for those measurements specified the transducer used and its location. In the gust probe dynamic pressure measurement (QCG), a Rosemount Model 1332 differential pressure transducer was located closer to the sensor in the gust probe itself, whereas in the boom measurement (QCB), a Rosemount Model 1221 pressure transducer was typically located in the aircraft nose.

Total Temperature, Reverse Flow ($^\circ C$): TTRF
TTRF is the recovery temperature from a calibrated NCAR reverse-flow temperature sensor, for which the housing was designed to separate water droplets and protect the element from wetting in cloud.

Total Temperature (Fast Response) ($^\circ C$): TTKP
This is the output of recovery temperature from the NCAR fast-response temperature

probe, originally designed by Karl Danninger. (See discussion of total temperature in section 8 above.)

Ambient Temperature ($^{\circ}C$): ATRF
The ambient temperature computed using the NCAR reverse-flow temperature sensor. (See discussion in Section 8 above.)

Ambient Temperature (Fast Response) ($^{\circ}C$): ATKP
The ambient temperature computed using the fast-response temperature probe. (See discussion of ambient temperature in section 8.)

Raw Cloud Technology (Johnson-Williams)
Liquid Water Content (g/m^3): LWC
This is the raw output of a Johnson-Williams liquid water content sensor converted to units of grams per cubic meter. The Johnson-Williams indicator measures the evaporative cooling caused by the latent heat of vaporization of droplets contacting the heated sensing element by sensing changes in its resistance as it cools. Through calibration this resistance is converted to a liquid water content. A "compensation" wire is also mounted in the J-W sensor, parallel to the droplet stream, to compensate for cooling effects of the airstream. Typically the instrument is set for a true airspeed of 200 knots. The instrument must be zeroed in "cloud-free air." The Johnson-Williams liquid water content sensor is designed for the cloud droplet spectrum. There is some evidence to indicate that droplets larger than 30 μm are shed before completely vaporizing on the sensor element. This tends to underestimate the liquid water content.

Corrected Cloud Technology (Johnson-Williams)
Liquid Water Content (g/M3): LWCC
This is the corrected liquid water content obtained by using the aircraft's true airspeed after removing the zero offset: LWCC=LWCU_a/U_{ref} where U_a is the true airspeed of the aircraft and U_{ref} is the true airspeed set on the dial of the instrument. U_{ref} was normally 200 kts = 102.88889 m/s.

Water Vapor Pressure (mb): EDPC
This is a derived intermediate variable used in the calculation of several derived thermodynamic variables. The vapor pressure over a plane water surface is obtained by the method of Paul R. Lowe (1977), a derived, sixth-order, Chebyshev polynomial fit to the Goff-Gratch Formulation (1946) as a function of temperature expressed in $^{\circ}C$. The error is much less than 1% over the range -50°C to +50°C. EDPC was calculated using this method for most RAF research projects between 1993 and 1996. This variable does not have the enhancement factor applied that is discussed in Appendix C.

A. T < -50 C:

$$
\begin{aligned}
\text{EDPC} &= 4.4685 + T(0.27347 + T\{6.83811 \times 10^{-3} \\
&+ T[8.7094x10^{-5} + T(5.63513x10^{-7} + T\,1.47796 \times 10^{-9})]\})
\end{aligned}
$$

B. T >= -50°C:

$$
\begin{aligned}
\text{EDPC} &= 6.107799961 + T\,[0.4436518521 + T(0.01428945805 \\
&+ T\{2.650648471 \times 10^{-4} + T\,[3.031240396 \times 10^{-6} \\
&+ T(2.034080948 \times 10^{-8} + T\,6.136820929 \times 10^{-11})]\})]
\end{aligned}
$$

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