RAF Technical Note: Processing Algorithms

Variables and Algorithms Used to Produce Data Products from Research Aircraft

revision of 2012

Contents

1 INTRODUCTION

1.1 Background Information

This technical report defines the variables used in data sets that are collected by the research aircraft operated by the Research Aviation Facility (RAF) of the National Center for Atmospheric Research. Where appropriate, it also documents the equations that are used by the processing software (currently "nimbus") to calculate the derived measurements that result from the use of one or more other basic measurements (e.g., potential temperature). Since 1993, data from research flights have been archived in NetCDF format (cf. http://www.unidata.ucar.edu/software/netcdf/docs/), and the NetCDF header for recent projects includes detailed information on the measurements present in the file, how they depend on other measurements, units, etc. The conventions that the RAF uses for NetCDF data files are documented at http://www.eol.ucar.edu/raf/Software/netCDF.html.

Currently, the data acquisition process on the research aircraft of the Research Aviation Facility, Earth Observing Laboratory, proceeds as follows:

1. Analog or digital outputs from instruments are sampled at regular intervals, typically 50 Hz when possible. Analog outputs are converted to digital values via analog-to-digital converters. The investigator's handbooks for each aircraft describe this process in detail, including resolution of the sampling and handling of the results. Often, signals from user-supplied instruments are also included in the measured values that are handled by the data system.

2. The digital outputs are then recorded by the data system on the aircraft. Currently, this is a task of the "NIDAS" system described below. That system also controls the sampling, time stamps, and other aspects of data recording.

3. In flight, the data are processed by the *"nimbus"* data processing program, which makes them available for display via "aeros" for real-time monitoring of measurements.

4. Following the flight, *nimbus* again processes the data. At this stage, measurements can be re-sampled with averaging and/or interpolation to produce various data rates, usually 1 Hz or 25 Hz, and known lags in measurements can be introduced to adjust measurements to a common time basis. As part of this processing, *nimbus* applies calibration coefficients where appropriate to convert recorded values (e.g., voltage) to engineering units (e.g., °C). Determining or checking these calibration coefficients is part of the pre-flight and post-flight procedures for each project.

5. The output from *nimbus* is the data file that is the permanent archive from the experiment, often after merging in additional data sets from users that are not recorded in the original data file produced by *NIDAS*. These files, in NetCDF format, have headers that contain metadata on each measurement (such as the calibration coefficients, the instrument that produced the measurement, etc.). Many of the variables in these files are discussed in this technical note, but the files may also include additional project-specific measurements for which the NetCDF header and the project reports will be the only documentation.

The data system has changed several times over the history of RAF. For a discussion of the history of the data systems, see ADShistory.pdf, written by Richard Friesen. The versions of data systems that produced most of the data still available were, approximately, as given in the following table:

Data System	start	end	Aircraft
ADS I	1984	1992	King Air 200T, Sabreliner (1987), Electra (1991)
ADS II	1992	2007	C-130
ADS III (NIDAS)[a]	2005		GV, C-130 (2007)

[a] ADS III is the name given to the full data system, which includes these components: NIDAS (for data acquisition and recording); NIMBUS (for data processing, both in flight and after the flight); AEROS (for data display in flight); and the Mission Coordinator Station and satellite communications system (for transmission of data to and from the aircraft, display of such data for mission decisions, and support for written "chat" communications among project participants both on the aircraft and on the ground).

Before 1993, data were processed by a different program, "GENPRO," and a different output format (also named GENPRO) was used for archived datasets. Appendix E in RAF Bulletin 9, the previous description of RAF data products that is now superseded by this technical note, describes that format. Some variable names in this document, esp. in section 10, 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 report can be a reference for older archived data as well as for current data files.

1.2 Alphabetical List of Variables

At the end of this document, on page 88, there is a list of all the variable names that appear in standard data files along with links to the primary discussion of those variables. The index to this technical report (on page 81) also includes all variables described here, and also some variables not discussed in detail in this document. Where possible, reference to those variables and information on the project(s) where they were used have been included also. In cases with multiple references, the bold entry is the primary discussion of the variable.

In some cases 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 usually made regarding which measurement is considered most reliable for a particular project or flight, and a single derived variable is calculated on the basis of the chosen input variable(s). To record which measurements were so designated, a reference measurement chosen from a group of redundant measurements usually has a variable name ending with the letter(s) X or XC. [1]

[1] Some that do not follow this convention are ATTACK and SSLIP; see the individual descriptions that follow.

1.3 Constants Used in Data Processing, with List of Symbols

The following table contains values used for some constants in this document. For reference, the symbols used here and elsewhere in this document are defined in the List of Symbols that follows the table, and links are provided to where they are used. Where references are to the "NIST Chemistry WebBook", the associated URL is http://webbook.nist.gov. References to the CODATA Internationally recommended values of the Fundamental Physical Constants are available at http://physics.nist.gov/.cuu/.Constants. The optimization involved in adjustment of these coefficients is documented in Mohr et al., 2008a and 2008b, referenced at that URL. [2] In this technical note, references to these symbols will often have these symbols or definitions marked by the symbol † to indicate that the values used are those in the following table.

[2] P. J. Mohr, B. N. Taylor, and D. B. Newell, Rev. Mod. Phys 80(2), 633-730(2008); P. J. Mohr, B. N. Taylor, and D. B. Newell, J. Phys. Chem. Ref. Data 37(3), 1187-1284(2008).

Table of Constants

g = acceleration of gravity[a] at latitude λ and altitude z above the WRS-80 geoid,[b]

$$g = g_e \left(\frac{1 + g_1 \sin^2(\lambda)}{(1 - g_2 \sin^2 \lambda)^{1/2}} \right) - a_z z \tag{1}$$

where $g_e = 9.780327\,\mathrm{m\,s^{-2}}$ is the reference value at the surface and equator, $g_1 = 0.001931851$ $g_2 = 0.006694380$, and $a_z = 3.086 \times 10^{-6}\,\mathrm{m^{-1}}$.

T_0 = temperature in kelvin corresponding to $0°C$ = 273.15 K

T_3 = temperature corresponding to the triple point of water = 273.16 K

M_d= molecular weight of dry air[a], 28.9637 $\mathrm{kg\,kmol^{-1}}$ [c]

M_w = molecular weight of water, 18.0153 $\mathrm{kg\,kmol^{-1}}$ [d]

R_0 = universal gas constant[a] = $8.314472 \times 10^3\ \mathrm{J\,kmol^{-1}K^{-1}}$ [e]

$R_d = (R_0/M_d)$ = gas constant for dry air

$R_w = (R_0/M_w)$ = gas constant for water vapor

R_E = radius of the Earth = 6.371229×10^6 m [f]

c_p = specific heat of dry air at constant pressure = $\frac{7}{2}R_d = 1.00473 \times 10^3\ \mathrm{J\,kg^{-1}K^{-1}}$ [g]
(value at $0°C$; small variations with temperature are not included here)

c_v = specific heat at constant volume = $\frac{5}{2}R_d = 0.71766 \times 10^3\ \mathrm{J\,kg^{-1}K^{-1}}$
(value at $0°C$; 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 = 7.292115×10^{-5} radians/s

Ω_{Sch} = angular frequency of the Schuler oscillation = $\sqrt{\frac{g}{R_E}}$

σ = Stephan-Boltzmann Constant = $5.6704 \times 10^{-8}\mathrm{W\,m^{-2}K^{-4}}$ [h]

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[a] In the International Standard Atmosphere g is specified as 9.80665 $\mathrm{m\,s^{-2}}$, M_w = 28.9644 , and R_0=8.31432×103 J kmol−1 K−1

[b] cf., e.g., Moritz, H., 1988: Geodetic Reference System 1980, Bulletin Geodesique, Vol. 62 , no. 3.

[c] Jones, F. E., 1978: J. Res. Natl. Bur. Stand., 83(5), 419, as quoted by Lemmon, E. W., R. T. Jacobsen, S. G. Penoncello, and D. G., Friend, J. Phys. Chem. Ref. Data, Vol. 29, No. 3, 2000, pp. 331-385. The quoted values of mole fraction from Jones (1978) and the calculation of mean molecular weight are tabulated below using values of molecular weights taken from the NIST Standard Reference Database 69: NIST Chemistry WebBook as of March 2011. With CO_2 increased to about 0.00039 and others decreased proportionately, the mean is 28.9637.

Gas	mole fraction x	molecular weight M	$x * M$
N_2	0.78102	28.01340	21.87903
O_2	0.20946	31.99880	6.70247
Ar	0.00916	39.94800	0.36592
CO_2	0.00033	44.00950	0.01452
Mean:			28.96194

[d] NIST Standard Reference Database 69: NIST Chemistry WebBook as of March 2011

[e] 2006 CODATA

[f] matching the value used by the inertial reference systems discussed in Section 3

[g] The specific heat of dry air at 1013 hPa and 250–280 K as given by Lemmon et al. (2000) is 29.13 J/(mol-K), which translates to 1005.8±0.3 J/(kg-K). However, the uncertainty limit associated with values of specific heat is quoted as 1%, and the experimental data cited in that paper show scatter that is at least comparable to several tenths percent, so the ideal-gas value cited here is well within the range of uncertainty. For this reason, and because this value is in widespread use, the ideal-gas value is used throughout the algorithms described here.

[h] 2006 CODATA

List of Symbols

α= recovery factor, temperature probe, 35
α_T= $\tanh(e_s(T-T_x)$, Murphy/Koop equations, 39

χ= liquid water content, 57
C_{kg2g}= conversion factor, g to kg, 57
c_p= specific heat of dry air at constant pressure, 8
c'_p= specific heat at constant pressure for moist air, 36
c_v= specific heat of dry air at constant volume, 8
c'_v =specific heat at constant volume for moist air, 36
c_w= specific heat of liquid water, 57
Cy_i= concentration from hydrometeor probe y in channel i, 60

$d_{e,i}$= equivalent melted diameter for channel i of a hydrometeor spectrometer, 61
d_i= diameter of hydrometeor in channel i, 60

e= water vapor pressure, 39
e_a= ambient water vapor pressure, 39
e_h= water vapor pressure in an instrument housing, 40
$\varepsilon = M_W/M_d$, 37
$e_{s,i}$= equilibrium vapor pressure over a plane ice surface, 39
$e_{s,l}$= equilibrium vapor pressure over a plane water surface, 39
η =update constant for exponential updating, 27

f_c= cutoff frequency for the filter F_L, 26
F_d= interpolation formula, dew point temperature from water vapor pressure, 40
F_L= digital low-pass filter, 26
$f(p,T_p)$= enhancement factor for equilibrium water vapor pressure, 39

g= acceleration of gravity, 8
γ' $=c'_p/c'_v$, 36

γ= ratio of specific heats of air, c_p/c_v, 8

λ= latitude, 8
λ_a= tropospheric lapse rate, standard atmosphere, 24
λ_c= thermal conductivity, dry air, 57
L_v= latent heat of vaporization of water, 57
L_v =latent heat of vaporization of water, 49

M= Mach number, ratio of airspeed to the speed of sound, 35
M_d= molecular weight of dry air, 8
μ_a= dynamic viscosity of air, 57
M_w= molecular weight of water, 8

Nu= Nusselt number, 57

Ω= angular rotation rate of the Earth, 8
Ω_{Sch}= angular frequency of the Schuler oscillation, 8

p= pressure, 36
p_0= reference pressure equal to 1000 hPa, 46
$p_0^{\ddagger}$= reference pressure for zero altitude, ISA, 24
p_a= ambient air pressure, 36
p_d= partial pressure of dry air, 47
p_h= pressure in a sensor housing, 40
p_T= pressure at the ISA tropopause, 24
p_t =total pressure (ambient + dynamic), 36

q= dynamic pressure, 32

R' =gas constant for moist air, 36
R_0= universal gas constant, 8
r= mixing ratio of water vapor, 47
r =water-vapor mixing ratio, dimensionless, 49
R_d =gas constant for dry air, 8
R_E= radius of the Earth, 8
Re= Reynolds number, 57
ρ_a= density of air, 57
ρ_w= density of liquid water, 61
R_W= gas constant for water vapor, 8

σ= Stephan-Boltzmann constant, 8

T_0=temperature in kelvin corresponding to $0°C$
= 273.15 K, 8
T_3= triple point temperature of water, 8
T_a= ambient air temperature in absolute units;
sometimes, T_K, 35
T_b= boiling temperature of water, 57
T_{DP}= temperature at the dew point, 39
T_L= temperature
lifted condensation level, 47
Θ_q =temperature
wet-equivalent potential, 49
T_{FP}= temperature at the frost point, 39
T_K= absolute temperature (in kelvin), 41
T_p =dew point temperature if above $0°C$, frost
point temperature otherwise, 39
T_{ref}= absolute reference temperature, STP, 69
T_r= recovery temperature, 35
T_T= temperature at the ISA tropopause, 24
T_t= total air temperature, 35
T_x= 218.8 k, Murphy/Koop equations, 39

U_a= true airspeed (sometimes U), 35
U_s= speed of sound, 35

V= volume, 36

z = height, 8

2 GENERAL INFORMATION ABOUT DATA FILES

2.1 System of Units

This report uses the SI system of units, but with many exceptions. Among them are the following:

1. The millibar (mb), equal to one hectopascal (hPa), was used for pressure with some older variables.

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 [$\mathrm{g\,m^{-3}}$] for liquid water content or [$\mathrm{cm^{-3}}$] 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 $10^{-3}\,\mathrm{m}^3$. 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 when this term is used.

4. The International Bureau of Weights and Measures recommends against use of units like percent or parts per million, but these are in common use in atmospheric chemistry and elsewhere so data files 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 as follows:

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

   When concentrations are recorded with units of "ppmv", "ppbv" or "pptv", these units refer respectively to $10^6 r_v$, $10^9 r_v$, or $10^{12} r_v$ with r_v 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 "samples per second." This usage is 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).

There is a list of symbols used in this report, on page 9.[3]. The next table defines some abbreviations and additional symbols used for units in this report, in addition to the standard abbreviations for the mks system of units:

abbreviation/symbol	definition[a]
°	degree, angle measurement ≡ (π/180) radian
ft	foot ≡ 0.3048 m
mb	millibar ≡ 100 Pa ≡ 1 hPa
ppmv	parts per million by volume (see subsection 2.1 item 4)
ppbv	parts per billion (10^9) by volume (see subsection 2.1 item4)
pptv	parts per trillion (10^{12}) by volume (see subsection 2.1 item4)
n mi	nautical mile ≡1852 m
kt	knot (n mi/hour) ≡ (1852/3600) m/s = 0.514444... m/s

[a]where the symbol ≡ is used, the relationship is exact by definition

2.2 Variables Used To Denote Time

Although there are some exceptions in old archived data files, the data in all modern output files are referenced to Coordinated Universal Time (UTC). The time and date of the data acquisition system are synchronized to time from 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 vary 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): Time

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 to obtain the UTC time.

[3] Some symbols used only once and defined where they are used are omitted from this list

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): base_time (*Obsolete; versions before ADS-3 only*)
The reference time for the NETCDF output data files for 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). Add time_offset (below) 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): time_offset (*Obsolete*)
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): HOUR, MINUTE, SECOND (*Obsolete*)
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): MONTH, DAY, YEAR (*Obsolete*)
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.

2.3 Other Comments On Terminology

2.3.1 Variable Names In Equations

This report often uses variable names in equations, and sometimes there is potential for confusion because the variable names consist of multiple characters. In most cases, to denote that the variable name is 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 are displayed with upright Roman character sets, while other symbols in equations are shown using 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 could be 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.

2.3.2 Distinction Between Original Measurements and Derived Measurements

Many of the variables in the data files and in this report are derived from combinations of measurements. The terms "raw" or "original" measurement are sometimes used for a minimally processed output received directly from a sensor or instrument. Such measurements may be converted to engineering units via calibration coefficients, but otherwise they are a direct representation of the output from a sensor.[4] In contrast, derived 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 in this report to document the processing algorithm. The box has a line dividing top from bottom; in the top are definitions used and explanations regarding variables that enter the calculation, while the bottom portion contains the equation, algorithm, or code segment that documents how the variable is calculated.

2.3.3 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 logarithmic or exponential functions), and some effort was made to isolate dimensions to defined constants rather than requiring that variables in equations be used with specific units. However, some exceptions remain to be consistent with historical usage.

[4]Calibration coefficients, e.g. those used to convert from voltage output from an analog sensor to a measured quantity with physical units like ºC), are not included or discussed in this report. They are normally included in project reports and, in recent years, many are included in the header of the NETCDF file.

3 THE STATE OF THE AIRCRAFT

The primary sources of information on the location and motion of the aircraft are from inertial reference systems and from global positioning systems. Both are described in this section, and combined results that merge the best features of each into composite variables for location and motion are also discussed. Useful references for material in this section are Lenschow (1972) and RAF Bulletin 23.

3.1 Inertial Reference Systems

An Inertial Reference System (IRS) or Inertial Reference Unit (IRU) provides measurements of aircraft position, velocity relative to the Earth, acceleration and attitude or orientation. For the GV, the system is a Honeywell Laseref III/IV SM Inertial Reference System; for the C-130, it is a Honeywell Model HG1095-AC03 Laseref SM 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 and section XXX [needed new section re time interpolation/adjustment, see 13]. 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 subsection. See also Section XXX for information on results from inertial systems that were used prior to installation of the present Honeywell systems.

needs review; rbf?

cjw will provide

this section XXX is still needed; rbf? Perhaps in obsolete var section at end?

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 3.4 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

The aircraft latitude or angular distance north of the equator in an Earth reference frame. 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. Values are provided by the IRU at a frequency of 10 Hz.

Longitude (°): LON

The aircraft longitude or angular distance east of the prime meridian in an Earth reference frame. 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. Values are provided by the IRU at a frequency of 10 Hz.

Aircraft True Heading (°): THDG

The azimuthal angle between the centerline of the aircraft (pointing ahead, toward the nose) and a line of meridian. This azimuthal angle is measured in a polar coordinate system oriented relative to the Earth with polar axis upward and azimuthal angle measured relative to true north. The heading thus indicates the orientation of the aircraft, not necessarily the direction in which the aircraft is traveling. The resolution is 0.00017º and the accuracy is quoted by the manufacturer as 0.2º after 6 h of flight. Values are provided by the IRU at a frequency of 50 Hz. “True” distinguishes the heading from the magnetic heading, the heading that would be measured by a magnetic compass. For more information on the coordinate system used, see RAF Bulletin 23.

Aircraft Pitch Attitude Angle (º): PITCH
The angle between the centerline of the aircraft (pointing ahead, toward the nose) and the horizontal plane in a reference frame relative to the Earth with polar axis upward. Positive values correspond to the nose of the aircraft pointing above the horizon. The resolution is 0.00017º and the accuracy is quoted by the manufacturer as 0.05º after 6 h of flight. Values are provided by the IRU at a frequency of 50 Hz.

Aircraft Roll Attitude Angle (º): ROLL
The angle of rotation about the longitudinal axis of the aircraft required to bring the lateral axis (along the wings) to the horizontal plane. Positive angles indicate that the starboard (right) wing is down ((i.e., a clockwise rotation has occurred from level when facing forward in the aircraft). The resolution is 0.00017º and the accuracy is quoted by the manufacturer as 0.05º after 6 h of flight. Values are provided by the IRU at a frequency of 50 Hz.

Aircraft Vertical Acceleration ($\mathrm{m\,s^{-2}}$): ACINS
The acceleration upward (relative to the Earth) as measured by an inertial reference unit. With IRUs now in use, the internal drift is removed by the IRU via pressure damping through reference to the pressure altitude.[5] Positive values are upward. The sample rate is 50 Hz and the resolution is 0.0024 $\mathrm{m\,s^{-2}}$.

Computed Aircraft Vertical Velocity (m/s): VSPD
The upward velocity of the aircraft as measured by the IRU, relative to the Earth. VSPD is determined within the IRU 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. This variable 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)
XXX This was a derived variable 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 that ACINS already incorporates pressure damping). Documentation is included

[5] 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.

here because many old data files include this variable. Note that "pressure altitude" is not a true altitude but an altitude equivalent to the ambient pressure in a standard atmosphere, so updating a variable integrated from inertial measurements to this value can introduce errors vs. the true altitude.. WP3 was calculated by the data-processing software as follows (with coefficients in historical use and not updated to the recommendations elsewhere in this technical note):[6]

[See next page]

[6] Regarding signs, note that ACINS is a number near zero, not near g, and so already has the estimated acceleration of gravity removed. 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 reference value for ACINS being the gravity measured at alignment (G_L) when it should actually be the sensed gravity (g_f) at the measurement point, so to obtain (sensed acceleration - g_f) it is necessary to add $(G_L - g_f)$ to ACINS, *increasing* "acz" in this case. However, the situation with "vcorac" is 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 it 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 conceptual extreme that the aircraft flies 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 = 0.31391116×10^{-6} m^{-1}
a_2 = .0052885 (dimensionless)
VEW (VNS) = eastward (northward) groundspeed of the aircraft (see below)
LAT = latitude measured by the IRS [º]
$C_{dr} = \pi/180°$ = conversion factor, degrees to radians
PALT = pressure altitude of the aircraft
Ω = angular rotation of the earth = 7.292116×10^6 radians/s
R_E = radius of the Earth = 6.371229×10^6 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 IRU alignment, corrected to zero altitude
$\{C[0], C[1], C[2]\}$ = feedback coefficients, {0.15, 0.0075, 0.000125} for 125-s response

---

1. From the pressure altitude PALT (in m) and the latitude LAT, 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:

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

   Estimate the acceleration a_z (code variable 'acz') experienced by the aircraft as follows:

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

   Use a feedback loop to update the integrated value of the acceleration. 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];
```

3. 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];
```

4. Set WP3 to the average of the last wp3 result and the current wp3 result.

Inertial Altitude (m): ALT

The altitude of the aircraft as provided by an IRU, with pressure damping applied within the IRU to the integrated aircraft vertical velocity to avoid the accumulation of errors. The value therefore is updated to the pressure altitude, not the geometric altitude, and should be regarded as a measurement of pressure altitude that has short-term variations as provided by the IRU. The sample rate is 25 Hz with a resolution of 0.038 m.

Aircraft Ground Speed (m/s): GSF

The ground speed of the aircraft as provided by an IRU. The resolution is 0.0020 m/s, and the IRU provides this measurement at a frequency of 10 Hz.

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

The east-directed component of ground speed as provided by an IRU. The resolution is 0.0020 m/s, and the IRU provides this measurement at a frequency of 10 Hz..

Aircraft Ground Speed North Component (m/s) VNS

The north-directed component of ground speed as provided by an IRU. The resolution is 0.0020 m/s, and the IRU provides this measurement at a frequency of 10 Hz..

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

Distance east or north of a project-dependent reference point. These are derived outputs obtained by subtracting a fixed reference position from the current position. The values are 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 of latitude and longitude measurements (see LAT and LON), 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 (º)
LAT_{ref} = reference latitude (º)
C_{deg2km} = conversion factor, degrees latitude to km $\equiv$ 111.12 km /º

$$\mathrm{DEI} = (\{\mathrm{LON}\} - \{\mathrm{LON}_{ref}\})\mathrm{C}_{\mathrm{deg2km}}\cos(\{\mathrm{LAT}\})$$

$$\mathrm{DNI} = (\{\mathrm{LAT}\} = \{\mathrm{LAT}_{\mathrm{ref}}\})\mathrm{C}_{\mathrm{deg2km}}$$

Radial Azimuth/Distance from Fixed Reference: FXAZIM, FXDIST

Azimuth and distance from a project-dependent reference point. The units of the azimuthal angle are degrees (relative to true north) and the distance is in kilometers. These are calculated by rectangular-to-polar conversion of DEI and DNI, described in the preceding paragraph.

–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
The raw output from the IRU lateral accelerometer. Positive values are toward the starboard, normal to the aircraft center line. The sample rate is 50 Hz with a resolution of 0.0024 m s^{-2}.

Raw Longitudinal Body Acceleration (m/s^2): BLONA
The raw output from the IRU longitudinal accelerometer. Positive values are in the direction of the nose of the aircraft and parallel to the aircraft center line. The sample rate is 50 Hz with a resolution of 0.0024 m s^{-2}.

Raw Normal Body Acceleration (m/s^2): BNORMA
The raw output from the IRU vertical accelerometer. Positive values are upward in the reference frame of the aircraft, normal to the aircraft center line and lateral axis. The sample rate is 50 Hz with a resolution of 0.0024 m s^{-2}.

Raw Body Pitch Rate (°/s): BPITCHR
The raw output of the IRU pitch rate gyro. Positive values indicate the nose moving upward and refer to rotation about the aircraft's lateral axis. The sample rate is 50 Hz with a resolution of 0.0039°/s.

Raw Body Roll Rate (°/s): BROLLR
The raw output of the IRU roll rate gyro. Positive values indicate starboard wing moving down and refer to rotation about the aircraft center line. The sample rate is 50 Hz with a resolution of 0.0039°/s.

Raw Body Yaw Rate (°/s): BYAWR
The raw output of the IRU yaw rate. Positive values represent the nose turning to the starboard and refer to rotation about the aircraft's vertical axis. The sample rate is 50 Hz with a resolution of 0.0039°/s.

3.2 Global Positioning Systems

Primary GPS variables specifying the position and velocity of the aircraft are provided by GPS receivers, currently a NovAtel Model OEM 5 unit on the GV and a NovAtel Model OEM-4 receiver on the C-130 (to be replaced by an OEM-6 after January 2014). The coordinate system used for all GPS measurements is the World Geodetic System WGS-84; for details, see this link. The uncertainty of the position measurements is specified by the manufacturer to be 1.5 m CEP horizontal (3.3 m 95% CEP).[7] The accuracy of velocity measurements is 0.03 m/s RMS for all axes. All variables are provided by the GPS receivers at 5 Hz. Latitude and longitude are recorded in a special log file (called the GPGGA log) with a resolution of 0.0001 degree,

thanks to Stuart for this info

[7] CEP is the Circular Error Probability, the radius of a circle that contains 50% of the measurements; 95% CEP contains 95% of the measurements. When OnmiSTAR corrections are available (involving extra cost and not available in all areas of the globe, so not available for all projects) the uncertainty decreases to 0.15 m 95% CEP. The vertical uncertainty is about twice as great as the horizontal uncertainty. Because variables are stored as 4-byte single-precision floating point numbers, the inherent storage precision can limit the precision of the recorded position to about 1 m.

while Earth-relative velocity is recorded in the GPRMC log with resolution of 0.1 m/s. Starting in January 2014 new logs (named BESTPOS and BESTVEL) will also be recorded to preserve more significant digits in the measurements. The BESTPOS log will have a position resolution of 10^{-11} deg, while the BESTVEL log will be recorded with 0.0001 m/s resolution.

Some of the following variables are also available from alternate Garmin GPS16 receivers, for which the variable name is qualified by the name of that unit; e.g., GGLAT_GMN for GGLAT as measured by a Garmin GPS unit. In addition, some of the measurements from the GPS units that are part of the aircraft avionics systems are recorded; these are denoted by a suffix "_G" or "_A". Measurements from before about 2000 used Trimble TANS-III receivers, with the ability to track up to 6 satellites at a time but needing only 4 to provide 3-dimensional position and velocity data (3 satellites for 2-dimensions). The accuracy of the position measurements for that unit was stated to be 25 meters (horizontal) and 35 meters (vertical) under "steady-state conditions."[8] 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 were provided by the Trimble receivers at 1 Hz.

GPS Latitude (°): GGLAT, LAT_G; also formerly **GLAT**
: *The aircraft latitude measured by a global positioning system.* Positive values are north of the equator; negative values are south. Because these variables are recorded in netCDF files as single-precision 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 that requires special processing.

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

GPS Ground Speed (m/s): GGSPD, GSF_G
: *The aircraft ground speed measured by a global positioning system.* GGSPD originates from a data-system GPS; GSF_G originates from an avionics-system GPS.

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

GPS Ground Speed Vector North Component (m/s): GGVNS, VNS_G
: *The northward component of ground speed as measured by a global positioning system.* GGVNS originates from a data-system GPS; VNS_G originates from an avionics-system GPS.

[8]Note: The GPS signals at one time suffered from "selective availability," a US DOD term for a perturbed signal that degraded 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 on selective availability and GPS measurements prior to 2000.

GPS-Computed Aircraft Vertical Velocity (m/s): VSPD_G, GVZI (obsolete)
The aircraft vertical velocity provided by an avionics GPS unit. Positive values are upward.

GPS Altitude (m): GGALT, ALT_G
The aircraft altitude measured by a global positioning system. The measurement is with respect to a geopotential surface (MSL) defined by the GPS's built-in earth model, WGS84. Positive values are above the reference surface. GGALT originates from a data-system GPS; ALT_G originates from an avionics-system GPS.

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

GPS Height of the Geoid (m): GGEOIDHT
Height of geoid, approximating mean sea level, above the WGS84 ellipsoid.

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

GPS Mode: GGQUAL
GPS quality flag:

0	Invalid
1	Valid measurement but without quality enhancement
2	Measurement enhanced by the Satellite-Based Augmentation System, a means of improving GPS accuracy and integrity by broadcasting from geostationary satellites wide area corrections for GPS satellite orbits and ionospheric delays. In the US, this uses the Wide-Area Augmentation System or WAAS. This is described in some data files as a differential-GPS measurement.
5	Fully locked-in OmniSTAR XP, usually starting after about 20 minutes of tracking the GPS satellites and receiving the OmniSTAR data feed. This mode tracks the carrier phases of the L1 and L2 GPS carrier frequencies and provides about 15 cm accuracy in position.

GPS Mode: GMODE (obsolete)
This is the former output from the Trimble GPS indicating the 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: 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.

3.3 Other Measurements of Aircraft Altitude

Geometric Radio Altitude (m): HGM - *(obsolete)*

The distance to the surface below the aircraft, measured by a radar 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

The distance to the surface below the aircraft, measured by a radar altimeter. 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 the ground as measured by an APN-232 radar altimeter.

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

The aircraft altitude obtained from the twice-integrated IRU 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 inertial system changes 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 IRU for vertical wind. See the discussion of WP3 on page 16. This variable is now obsolete.

ISA Pressure Altitude (m): PALT

The altitude in the International Standard Atmosphere where the pressure is equal to the reference barometric (ambient) pressure (PSXC). ([9] 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 such as those given in the table in section 1.3 (e.g., $R_0^{\ddagger}$).[10] A note at this URL describes the pressure altitude in more detail and documents the change that was made in November 2010. Revised Nov 2010

[9] See "U.S. Standard Atmosphere, 1976", NASA-TM-A-74335, available for download at this URL.

[10] 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 .)

$T_0^{\ddagger}$= 288.15 K, reference temperature†
$\lambda_a^{\ddagger}$ = -0.0065 K/m = the lapse rate for the troposphere‡
p = measured static (ambient) pressure, hPa, usually from PSXC
$p_0^{\ddagger}$ = 1013.25 hPa, reference pressure for PALT=0 ‡
$M_d^{\ddagger}$ = 28.9644 $kg/kmol$= molecular weight of dry air, ISA definition ‡
$g^{\ddagger}$ = 9.80665 m s^{-2}, acceleration of gravity ‡
$R_0^{\ddagger}$ = universal gas constant, defined‡ as 8.31432×10^3 $J\,\mathrm{kmol}^{-1}\,\mathrm{K}^{-1}$
$z_T^{\ddagger}$ = altitude of the ISA tropopause = 11,000 m ‡
$x = R_0^{\ddagger}\lambda_a^{\ddagger}/(M_d^{\ddagger}g^{\ddagger}) \approx 0.1902632$ (dimensionless)[a]

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

$$\mathrm{PALT} = -\left(\frac{T_0^{\ddagger}}{\lambda^{\ddagger}}\right)\left(1-\left(\frac{p}{p_0^{\ddagger}}\right)^x\right)$$

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

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

$$p_T = p_0^{\ddagger}\left(\frac{T_0^{\ddagger}}{T_T}\right)^{\frac{g^{\ddagger}M_d^{\ddagger}}{\lambda^{\ddagger}R_0^{\ddagger}}} = 226.3206\,\mathrm{hPa}$$

$$\mathrm{PALT} = z_T^{\ddagger} + \frac{R_0^{\ddagger}T_T}{g^{\ddagger}M_d^{\ddagger}}\ln\left(\frac{p_T}{p}\right)$$

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.

Altitude, Reference (MSL): ALTX *(Obsolete)*, **GGALTC** *(Obsolete)*

Derived altitude above the geopotential surface, obtained by combining information from a GPS receiver and an inertial reference system. This variable was intended to compensate for times when GPS reception was lost by incorporating information from the IRS measurement of altitude. GPS status measurements were used to detect signal loss, although sometimes this signal was delayed for a few seconds after the signal was lost. A 10-second running average was calculated of the difference between the GPS altitude and the reference altitude. When the sample-to-sample altitude difference changed more than 50 meters or when the GPS status detected a degraded signal, the derived variable (ALTX or GGALTC) became the alternate reference altitude adjusted by the latest running-average difference between that reference altitude and GGALT. When reception was recovered, to avoid a sudden discontinuity in altitude, the derived variable was adjusted back to the GPS altitude gradually over the next 10 seconds.

note rec to treat as obsolete, and see ALTC below

This obsolete variable should be used with caution because the reference altitude used in past calculations was the IRS altitude updated to the pressure altitude of the aircraft. To account for the difference between pressure and geometric altitude, a regression equation was used, normally $z = a_0 + a_1{*}\mathrm{PALT}$ where $a_0 = -46.3\,\mathrm{m}$ and $a_1 = 0.97866$ but often adjusted dependent on project conditions. This introduced problems in early applications with the GV because it did not account for the pressure-altitude transition at the ISA tropopause. Use of a pressure altitude as reference introduces additional errors in altitude in regions that are not barotropic.

3.4 Combining IRS and GPS Measurements

Measurements from the global positioning and inertial reference systems are combined to produce new variables that take advantage of the strengths of each, so that the resulting variables have the long-term stability of the GPS and the short-term resolution of the IRU. 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.

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 degrading toward those of the IRU. 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 1.5 m. Due to the nature of the algorithm, the error will increase from about 1.5 meters to the IRU specification in about one-half hour after GPS information is lost.

GPS-Corrected Inertial Ground Speed Vector, (m/s): VEWC, VNSC

These variables result from combining GPS and IRU output of the east and north components of ground speed from a 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 measurements from the GPS, {GVNS, GVEW}, which have good long-term stability, 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 IRU measurements are almost the same, then the detailed characteristics of the filter (e.g., phase shift) in the transition region 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
GGVEW = GPS-measured east component of the aircraft ground speed
GGVNS = GPS-measured north component of the aircraft ground speed
$F_L()$ = three-pole Butterworth lowpass recursive digital filter

---

$$\{\mathrm{VNSC}\} = F_L(\{\mathrm{GGVNS}\}) + (1-F_L)(\{\mathrm{VNS}\})$$
$$\{\mathrm{VEWC}\} = F_L(\{\mathrm{GGVEW}\}) + (1-F_L)(\{\mathrm{VEW}\})$$

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:

this differs slightly from current practice

1. If GPS reception has never been valid earlier in the flight, use the IRU values 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, use the correction factors from the complementary filter 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 IRU 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 separate 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 a discontinuous transition would. 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 (°): LATC, LONC

Combined GPS and IRS output of latitude and longitude. 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
GGLAT = latitude measured by the GPS
GGLON = 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 (>5º) 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 accumulated and used to extrapolate through periods when the GPS is invalid.

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

proposed new 2014

ALTC

Derived altitude above the WGS84 surface, obtained by combining information from a GPS receiver and an IRU. When OmniSTAR corrections are available and satellite reception is good, the GPS altitude variable GGALT has very low associated uncertainty and the change represented by this variable is not useful so in those cases ALTC is set equal to GGALT. However, sometimes reception is lost (esp. in turns), and OmniSTAR is not available in some locations and for some projects. Therefore, a variable that combines information from the GPS receiver and an inertial reference unit can be useful. As provided by the current Honeywell IRUs, the vertical motion and position of the aircraft is adjusted via a baro-inertial feedback loop to match the pressure altitude. To obtain a variable that is based on the WGS84 coordinate system, the longer-term fluctuations in the GPS measurement of altitude are combined with the shorter-term fluctuations from the IRU measurement of altitude to obtain the new derived variable ALTC. The approach resembles that described above for LATC and LONC, except that a fit to the Schuler oscillation is not used and integration of the hydrostatic equation is used for updating of the IRU altitude in the absence of GPS reception. The steps are as follows:

1. Initialize by setting the components of the filters below and the PID feedback loop, and by setting the two integration heights used below and the new variable ALTC to the first valid measurement of GPS altitude.
2. Increment a variable h, representing the IRU altitude, by integrating the IRU-provided vertical velocity VSPD one time step. Also increment the value of the new variable ALTC in the same way. For both increments, subtract the value V_b from VSPD; V_b is determined as the bias term in a PID feedback loop described below.
3. Increment the height h_h obtained from integration of the hydrostatic equation, using the measured pressure change and temperature.
4. Use the difference between h and h_h as an error term in a PID feedback loop, to obtain an estimate of the bias V_b in the vertical velocity measurement. There is already updating of the IRU-provided vertical velocity, to pressure altitude, but this updating is instead to geometric altitude as represented by integration of the hydrostatic equation so it helps remove some of the false effects on altitude that arise from using pressure altitude.
5. If the GPS-measured vertical altitucde GGALT is valid:

    - Determine an updated filtered value of Δh, the difference between GGALT and h, as for LATC or LONC but with a time constant of 200 s.
    - Apply exponential updates with 60 s time constants to h and h_h, updating both to GGALT.

    Otherwise:

    - Update Δh instead to the difference between h_h and h.
6. Adjust ALTV via exponential filtering to add the difference Δh.

VSPDC proposed new 2014

Derived variable representing the vertical velocity of the aircraft, obtained by combining measurements from a GPS receiver and an IRU. The calculation applies the bias term V_b calculated above to the IRU-provided measurement of vertical velocity, and uses a complementary filter to combine the GPS and IRU measurements as for VNSC or VEWC. If GPS OmniSTAR reception is available (i.e., GGQUAL is 5), the GPS measurement of vertical velocity is used without change.

4 THE STATE OF THE ATMOSPHERE

4.1 General Information On Variable Names

Measurements of some meteorological state variables like pressure, temperature, and water vapor pressure may originate from multiple sensors mounted 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 be one of 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 among similar measurements and is therefore used to calculate derived variables that depend on the measured quantity. Other suffixes sometimes used to distinguish among measurements are these: 'D' for a digital sensor; 'H' for a heated (usually, anti-iced) sensor, 'L' for port side, and 'R' for starboard side.

4.2 Pressure

Static Pressure (hPa): PSx, PSxC, PS_A, PSXC. PSFD, PSFRD

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 or ambient pressure before correction, and it may be affected by local flow-field distortion. PS_A is the pressure measurement taken from the avionics system on the aircraft, processed via unknown algorithms in the avionics system that may smooth, correct, and perhaps delay the result. PSxC is PSx corrected for local flow-field distortion. (See RAF Bulletin #21 and the discussion in this memo), and PSXC is the preferred corrected measurement used for derived calculations. These measurements have been made using various sensors, so it is best to consult the project documentation for the transducer used. Recent measurements from both the C-130 and the GV have been made using a Paroscientific Model 1000 Digiquartz Transducer.

Corrections to the pressures have been determined by reference to some standard, including a "trailing cone" sensor, PS_A, or (since 2012) the Laser Air Motion Sensing System

(LAMS). The latter correction is discussed in the memo referenced above, where corrections used prior to 2011 are also discussed. The deduced correction Δp to the measured pressure as a function of dynamic pressure q, the pressure difference Δp_α between the top and bottom ports on the radome, and the Mach number M (all described later in this section), is described by the following equation and coefficients:

changed 2012

For the C-130 and for the pressure measurement PSFD, [11]

$$\frac{\Delta p}{p} = b_0 + b_1 \frac{\Delta p_\alpha}{\Delta q_r} + b_2 M \tag{2}$$

where, for p = PSFD, Δp_α = ADIFR, and Δq_r = QCR, $\{b_0, b_1, b_2\}$={0.001858, 0.02019, 0.01349}. For PSFRD, the coefficients are $\{b'_0, b'_1, b'_2\}$ = {-0.004433, 0.006133, 0.03594}. These coefficients are significantly different from the coefficients for PSFD, but the static ports where PSFRD is measured are at a different location on the fuselage so different flow-distortion effects are expected.

For the GV, [12]

$$\frac{\Delta p}{p} = a_0 + a_1 \frac{q}{p} + a_2 M + a_3 \frac{\Delta p_\alpha}{\Delta q_r} \tag{3}$$

where, for p = PSF and q = QCF, $\{a_0, a_1, a_2, a_3\}$ = {-0.00071, 0.073, -0.0861, 0.0460}. In equations (2– 3), the Mach number is calculated from the uncorrected measurements of p and q, via

$$M = \left\{ \left(\frac{2c_v}{R_a} \right) \left[\left(\frac{p+q}{p} \right)^{R_1/c_p} - 1 \right] \right\}^{1/2}$$

Dynamic Pressure (hPa): QCx, QCxC, QCXC

The pressure excess caused by bringing the airflow to rest relative to the aircraft. These quantities represent the difference between the total pressure as measured at the inlet of a pitot tube or other forward-pointing port and the ambient pressure that would be present in the absence of motion through the air. The variables ending in "C" have been corrected for flow-distortion effects, mostly arising from errors in the measurement of static pressure. Since 2012, the corrections are based on measurements from the LAMS system as described for PSxC, and they have the same functional form as in (2) and (3) except that the correction applied to q is $-\Delta p$ with reversed sign because $q = p_t - p_a$ and the error arises primarily from the error in p_a. The same correction is applied to QCR because it is also measured relative to the static pressure ports so errors in the pressure sensed at

[11] For measurements prior to 2012 but after September 2003, the correction applied to PSF was $\Delta p = p + \max((3.29 + \{QCX\} * 0.0273), 4.7915)$ using units of hPa. Prior to Sept 2003, the correction was $\Delta p = \max((4.66 + 11.4405 \Delta p_\alpha / \Delta q_r),\ 1.113)$. For both PSFD and PSFRD, the correction prior to (2012?) was $\Delta p = p + \max((3.29 + \{QCX\} * 0.0273), 4.7915)$.

[12] Aug 2006 to 2012, Δp = (-1.02 + 0.1565*q) + q1*(0.008 + q1*(7.1979e-09*q1 - 1.4072e-05))
Before Aug 2006: Δp =(3.08 - 0.0894*{PSF}) + {QCF}*(-0.007474 + {QCF}*4.0161e-06)

those ports affect QCR in the same way that QCF is affected. See the notes referenced in the preceding section, and also RAF Bulletin 21 for the corrections applied to earlier data files.[13] A Rosemount Model 1221 differential pressure transducer is used for current measurements of dynamic pressure on the C-130, and a Honeywell PPT transducer is used on the GV. This measurement enters the calculation of true airspeed and Mach number and so is needed to calculate many derived variables.

Special Pressure Measurements: PSDPx, CAVP_x, PCAB, PSURF

PSDPx and CAVP_x are measurements of the pressure in the housing of the dew-point sensors, as discussed in connection with DPxC. PCAB is a measurement of the pressure in the cabin of the aircraft. PSURF is the estimated surface pressure calculated from HGME (a radar-altimeter measurement of height), TVIR, PSXC, and MR using the thickness equation. The units for all these pressure measurements are hPa. TVIR and MR are described later in this section, and HGME was described in the previous section. The average temperature for the layer is obtained by using HGME 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.[14]

PSXC = ambient pressure (hPa)
HGME = (radar) altitude above the surface (m)
TVIR = virtual temperature (°C)
PSURF = estimated surface pressure (hPa)
g = acceleration of gravity†
R_d = gas constant for dry air†
c_{pd} = specific heat of dry air at constant pressure†

$$T_m = (\{\mathrm{TVIR}\} + T_0) + 0.5\{\mathrm{HGM}\}\frac{g}{c_{pd}}$$

$$\mathrm{PSURF} = \{\mathrm{PSXC}\}\exp\left\{\frac{g\,\{\mathrm{HGM}\}}{R_d T_m}\right\} \tag{4}$$

4.3 Temperature

Recovery Temperature (ºC): RTx, RTxH, RTHRx

The recovery temperature is the temperature sensed by a temperature probe that is exposed

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[13] * C-130:
Prior to 2012,
For QCFC: subtract max$((4.66 + 11.4405 * \mathrm{ADIFR}\}/\{\mathrm{QCR}), 1.113$
For QCFRC prior to Sept 2003: same as for QCFC
after/including Sept 2003, subtract max$((3.29 + \{\mathrm{QCX}\} * 0.0273)$,4.7915)
For QCRC: subtract max$((3.29 + \{\mathrm{QCX}\} * 0.0273)$,4.7915)
* GV:
Aug 2006 to 2012,
For QCF, subtract (1.02+{PSF}*(0.215 - 0.04*{QCF}/1000.) + {QCF}*(-0.003266 + {QCF}*1.613e-06))

[14] The symbol † indicates that values are included in the table of constants, p. 8.

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. [15]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 variable name also conveys the sensor type: RTx is a measurement from a Rosemount Model 102 non-deiced temperature sensor, RTxH is the measurement from a Rosemount Model 102 anti-iced (heated) temperature sensor, and RTHRx is the measurement from a HARCO heated sensor. Some past experiments also used a reverse-flow temperature housing and a fast-response "K" housing; the associated variable names for these probes were TTRF and TTKP.

Ambient Temperature (ºC): ATx, ATxH, ATxD

The temperature of the atmosphere at the location of the aircraft, as it would be measured by a sensor at rest relative to the air. The 'x' in 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 above regarding RTx. 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 RTx as well as the dynamic and ambient pressure, usually respectively QCXC and PSXC. The ambient and dynamic pressures are first corrected from the raw measurements QCX and PSX to obtain variables that account for deviations caused by airflow around the aircraft and/or position-dependent systematic errors, as discussed in the section describing PSxC. 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. To provide accuracy in the equations, this discussion considers effects of the humidity of the air on characteristics like the gas constant and the specific heats. Most archived data before 2012 used values for dry air, although a special variable TASHC has been used in cases where the correction was significant to represent the true airspeed. That variable is based on a good approximation to the results from the following equations; see the discussion of TASHC later in this section. TASHC is now considered an obsolete variable. New variables ATxD and TASxD have been introduced that neglect the humidity corrections and perform all calculations as if the humidity is negligible.

As discussed above, temperature sensors on aircraft that are exposed to the airflow do not measure the total temperature but rather the temperature of the air immediately in con-

[15]Prior to 2012, these variables were called "total temperature" and symbols starting with 'TT' instead of 'RT' were used. That name ws misleading because these values are not true total-temperature measurements, for which the air would be at the same speed as the aircraft, but instead recovery-temperature measurements. The name has been changed to correct this mis-labeling, although this was a long-standing convention in past datasets.

tact with the sensing element. This air will not have undergone an adiabatic deceleration completely to zero velocity and hence will have a temperature T_r somewhat less than T_t which would require the air to reach zero velocity. 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 :

$$\alpha = \frac{T_r - T_a}{T_t - T_a} \tag{5}$$

From conservation of energy:

$$\frac{U_a^2}{2} + c_p T_a = \frac{U_r^2}{2} + c_p T_r = \frac{U_t^2}{2} + c_p T_t \tag{6}$$

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 (6),

$$T_a = T_r - \alpha \frac{U_a^2}{2c_p} \tag{7}$$

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).[16] 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 (7), 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 calculating the true airspeed and ambient temperature for 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, total 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 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'

[16] The recovery factor determined for the now-obsolete NCAR reverse-flow sensor was 0.6. The recovery factor for the now retired NCAR fast-response (K-probe) temperature sensor was 0.8.

is the ratio of specific heats of (moist) air, c'_p/c'_v). The Mach number is a function of air temperature only and can be determined as follows:
a). Express energy conservation, as in (6), in the form

$$d\left(\frac{U^2}{2}\right) + c'_p dT = 0 \ . \tag{8}$$

where the total derivatives apply along a streamline as U changes from U_a to $U_t = 0$ and T changes from T_a to T_t.
b). Use the perfect gas law to replace dT with $\frac{pV}{nR}(\frac{dV}{V} + \frac{dp}{p})$ where V and p are the volume and pressure of a parcel of air. Then use the expression for adiabatic compression in the form $pV^\gamma = constant$ to replace the derivative $\frac{dV}{V}$ with $-\frac{1}{\gamma}\frac{dp}{p}$, leading to $dT = \frac{RT}{c_p}\frac{dp}{p}$ or, after integration, $T(p) = T_a\left(\frac{p}{p_a}\right)^{R/c_p}$. Using this expression for T in the formula for dT and then integrating both total derivatives in (8) along the streamline leads to

$$\frac{U_a^2}{2} + c'_p T_a = c_p T_a \left(\frac{p_t}{p_a}\right)^{\frac{R'}{c'_p}} \tag{9}$$

where p_t is the total pressure (i.e., PSXC+QCXC) and p_a 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:

$$M^2 = \left(\frac{2c'_v}{R'}\right)\left[\left(\frac{p_t}{p_a}\right)^{\frac{R'}{c'_p}} - 1\right] \ . \tag{10}$$

this shows that M can be found from p_t and p_a alone, except for the moist-air corrections.

d). Use the expression for ambient temperature in terms of recovery temperature and airspeed, (7), to obtain the temperature in terms of the Mach number and the recovery temperature:

$$\begin{aligned} T_a &= T_r - \alpha\frac{U_a^2}{2c'_p} = T_r - \alpha\frac{M^2\gamma' R' T_a}{2c'_p} \\ &= \frac{T_r}{1 + \dfrac{\alpha M^2 R'}{2c'_v}} \end{aligned} \tag{11}$$

e). Express the true airspeed (U_a) as

$$U_a = M\sqrt{\gamma' R' T_a} \tag{12}$$

Then the temperature is found as described in the following box:[17][18]

[17]Primes on the symbols denote that corresponding units are needed and that these values should be moist-air values, appropriately weighted averages of the dry-air and water-vapor contributions. The practice prior to 2012 was to use the dry-air values for specific heats and the gas constant, except as described in connection with TASHC below. Since 2012, calculations use the appropriate values for moist air, except that to avoid errors introduced by unrealistically high measurements of humidity the humidity correction was limited to be less than or equal to the equilibrium value at the measured temperature. Because temperature is determined using measured values for humidity, this is an iterative process in which the temperature is first calculated and then, if the corresponding dew point is higher than this temperature, the humidity is lowered and the calculation repeated. The formulas used for the specific heats and gas constant of moist air in terms of the water vapor pressure e and the specific heats for dry air ($c_{pd} = \frac{7}{2}R_0$, $c_{vd} = \frac{5}{2}R_0$) and water vapor ($c_{pw} = 4R_0$, $c_{vw} = 3R_0$) are these:

$$R' = R_d/[1+(\varepsilon-1)\frac{e}{p}] \tag{13}$$

$$c'_v = \frac{(p-e)R'}{pR_d}\frac{5R_0}{2M_d} + \frac{eR'}{pR_w}\frac{3R_0}{M_w} = c_{vd}\frac{R'}{R_d}\left(1+(\frac{6}{5\varepsilon}-1)\frac{e}{p}\right) = c_{vd}\frac{R'}{R_d}(1+0.92926\,\frac{e}{p}) \tag{14}$$

$$c'_p = c_{pd}\frac{R'}{R_d}\left(1+(\frac{8}{7\varepsilon}-1)\frac{e}{p}\right) = c_{pd}\frac{R'}{R_d}(1+0.83739\,\frac{e}{p}) \tag{15}$$

$$\gamma' = \gamma_d\frac{1+(\frac{8}{7\varepsilon}-1)\frac{e}{p}}{1+(\frac{6}{5\varepsilon}-1)\frac{e}{p}} = \gamma_d\frac{1+0.83739\frac{e}{p}}{1+0.92926\frac{e}{p}} \tag{16}$$

See also the discussion of TASHC in section 4.6.

[18]A problem sometimes arises from use of the measured humidity, because that measurement might be obviously in error. For example, following descents the dew point determined from chilled-mirror hygrometers sometimes overshoots the correct value significantly, producing dew-point measurements well above the measured temperature. If such measurements are used, the result can produce a significant error in derived variables based on the humidity-corrected gas constant and specific heats. If the measurements are flagged as bad, there will be gaps in derived variables . To avoid these two errors, the corrections applied to the gas constant and specific heats are treated as follows:

- If the humidity corresponds to a dew point that exceeds the measured temperature, the calculation of temperature is repeated without the humidity correction. Then the dew point corresponding to that temperature is used to recalculate the corrections for humidity. Those adjusted values for R', c'_v, and c'_p are then used to recalculate the Mach number.

- If the humidity from the primary sensor is flagged as a missing measurement (e.g., from a dew-point sensor), a secondary measurement is used (e.g., the VCSEL) in cases when the secondary sensor is almost always present in an experiment.

- As a backup, the variables TASxD and ATxD are always calculated omitting the humidity correction to the gas constant and the specific heats. These variables usually provide continuous measurements, although they will be offset from the humidity-corrected values. The offset indicates the magnitude of the correction when both are present, and one of the variables TASxD (ATxD) may be selected as TASX (ATX) in cases where missing values might cause a problem for derived variables.

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

From (10),

$$\text{MACHx} = \left\{ \left(\frac{2c_v'}{R'} \right) \left[\left(\frac{\{\text{PSXC}\} + \{\text{QCxC}\}}{\{\text{PSXC}\}} \right)^{\frac{R'}{c_p'}} - 1 \right] \right\}^{1/2} \tag{17}$$

From (11)

$$\text{ATx} = \frac{(\{\text{RTx}\} + \text{T}_0)}{\left(1 + \frac{\alpha (\{\text{MACHX}\})^2 R'}{2c_v'} \right)} - T_0 \tag{18}$$

4.4 Humidity

Dew/Frost Point (ºC): DPx, DP_x, MIRRTMP_DPx

The mirror temperature measured directly by a dew-point sensor, without correction. The dew point or frost point is measured by either an EG&G Model 137, a General Eastern Model 1011B or a Buck Model 1011C dew-point hygrometer. Below 0º**C** the instrument is assumed to be responding to 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 and that can introduce a measurement error. The measurements are usually made within a housing where the pressure (p_h) may differ from the ambient pressure, so the pressure in the housing affects the measured dew point or frost point. The housing pressure is often adjusted to be near the ambient pressure by appropriate orientation of inlets, and recently the pressure in the housing is measured and a correction is applied, as discussed in the next paragraph.

Corrected Dew Point (C): DPxC

The dew point obtained from the original measurement after correction for the housing pressure, the enhancement arising from the total pressure, and conversion from frost point if appropriate, The result is that temperature at which the equilibrium vapor pressure over a plane water surface in the absence of other gases would match the actual water-vapor pressure. Dew/frost-point hygrometers measure the equilibrium point in the presence of air, and the presence of air as well as water vapor affects the measurement in a minor way that is represented by a small correction here named the "enhancement factor." Calculation of DPxC removes this dependence, so the vapor pressure obtained from the DPxC will be that vapor pressure corresponding to equilibrium in the absence of air. In addition, if the measurement is below 0ºC, it is assumed to be a measurement of frost point and a cor-

changed 2011

responding dew point is calculated from the measurement (also with correction for the influence of the total pressure on the measurement).

An additional correction is needed in those cases where the pressure in the housing of the instrument (measured as PSDPx or CAVP_x) differs from the ambient pressure, because the changed pressure affects the partial pressure of water vapor in proportion to the change in total pressure and so changes the measured dew point from the desired quantity (that in the ambient air) to that in the housing. This is especially important in the case of the GV because the potential effect increases with airspeed. If the pressure in the housing is measured or otherwise known (e.g., from correlations with other measurements), then this correction can be introduced into the processing algorithm at the same time that the correction for the presence of dry air is introduced.

The relationship between water-vapor pressure and dew- or frost-point temperature is based on the Murphy and Koop[19] (2005) equations.[20] They express the equilibrium vapor pressure as a function of frost point or dew point *and at a total air pressure p* via equations that are equivalent to the following:

$$e_{s,i}(T_{FP}) = \quad b_0' \exp(b_1 \tfrac{(T_0 - T_{FP})}{T_0 T_{FP}} + b_2 \ln(\tfrac{T_{FP}}{T_0}) + b_3 (T_{FP} - T_0)) \tag{19}$$

$$e_{s,w}(T_{DP}) = c_0 \exp\left((\alpha - 1) c_6 + d_2 (\frac{T_0 - T_{DP}}{T_{DP} T_0}) \right) + d_3 \ln(\frac{T_{DP}}{T_0}) + d_4 (T_{DP} - T_0) \tag{20}$$

$$f(p, T_P) = 1 + p(f_1 + f_2 T_p + f_3 T_P^2) \tag{21}$$

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 T_0), and $f(p, T_P)$is the enhancement factor at total air pressure p and temperature T_p, with T_P equal to $T_{DP} - T_0$ when above T_0 and $T_{FP} - T_0$ when below 0ºC . The enhancement factor is defined so that the ambient vapor pressure e_a is related to the *measured* dew or frost point (not the dew or frost point equivalent to the saturation vapor pressure at the dew or frost point) by $e_a = f(p, T_P) e$ where e is the ambient water vapor pressure. If the effect of the enhancement factor is to be removed in order to report a dew point in correspondence with the saturation vapor pressure, then the effect of the enhancement factor as represented by $f(p, T_P)$ must be removed from the measurement. The coefficients used in the above formulas are given in the following tables, with the additional definitions that $\alpha_T = \tanh(c_5(T - T_x))$, T_X = 218.8 K, and $d_i = c_i + \alpha_T c_{i+5}$ for i = {2,3,4}:

[19] Q. J. R. Meteorol. Soc. (2005), 131, pp. 1539–1565

[20] Prior to 2010, the vapor pressure relationship used was the Goff-Gratch formula as given in the Smithsonian Tables (List, 1980).

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	$-3.25\times10^{-7}\mathrm{hPa}^{-1}\mathrm{K}^{-1}$
f_3	$5.84\times10^{-10}\mathrm{hPa}^{-1}\mathrm{K}^{-2}$

coefficient	value
c_0	6.091886 hPa
c_1	6.564725
c_2	-6763.22 K
c_3	-4.210
c_4	0.000367 K^{-1}
c_5	0.0415 K^{-1}
c_6	-0.1525967
c_7	-1331.22 K
c_8	-9.44523
c_9	0.014025 K^{-1}

The vapor pressure in the instrument housing, e_h, is related to the sensed dew or frost point according to equation (19) or (20), but further corrections must also be made for the enhancement factor and to account for possible difference between the pressure in the sensor housing p_h and the ambient pressure p_a:

$$e_a = f(p_a, T_p)e_h\frac{p_a}{p_h} \tag{22}$$

Because processing to obtain the corrected dew point DPxC from the ambient vapor pressure e_a would require difficult inversion of the above formulas, interpolation is used instead. A table constructed from (19) and another constructed from (20), giving vapor pressure as a function of frost point or dew point temperature in 1°C increments from -100 to +50ºC, is then used with three-point Lagrange interpolation (via a function described below as $F_D(e)$) to find the dew point temperature from the vapor pressure.[21] Tests of these interpolation formulas against high-accuracy numerical inversion of formulas (19) and (20) showed that the maximum error introduced by the interpolation formula was about 0.004°C and the standard error about 0.001°C. This inversion then provides a corrected dew point that incorporates the effects of the enhancement factor as well as differences between the ambient pressure and that in the housing.

For other instruments that measure vapor density, such as a Lyman-alpha or tunable diode laser hygrometers (including the Vertical Cavity Surface Emitting Laser (VCSEL) hygrometer), a similar conversion is made from vapor density to dew point, as documented below:

[21] 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 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 $Z = \ln((\mathrm{ATX} + 273.15)\mathrm{RHO}/1322.3)$.

DPx = uncorrected mirror-temperature measurement directly from instrument x, $^\circ C$
RHO = water vapor density measurement directly from the instrument, $\mathrm{g\,m^{-3}}$
ATX = reference ambient temperature, $^\circ C$
T_K = temperature in kelvin = ATX+T_0 †
PSXC = reference ambient pressure, hPa = p
e_t = intermediate vapor pressure used for calculation only
e =EWx = water vapor pressure from source x, hPa
M_w= molecular weight of water†
R_0 = universal gas constant†

---

for dew/frost point hygrometers, producing the measurement DPx: if DPx < 0ºC:
obtain e_t from (19) using T_{FP}=DPx + T_0
else (i.e., DPx $\geq$ 0ºC):
obtain e_t from (20) using $T_{DP} = \mathrm{DPx} + T_0$
correct e_t for enhancement factor to get actual vapor pressure e:
$e = f(p, T_P)\, e_t$
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} $R_0 T_K/M_w$)$\times 10^{-5}$
find the equivalent dew point:
DPxC=$F_{DP}(e)$

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

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

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

Water Vapor Pressure (hPa): EDPC, EWx, EWX

The ambient vapor pressure of water, also used in the calculation of several derived variables. It is often obtained from an instrument measuring dew point or water vapor density. In the case of DPx, a correction is applied for the enhancement factor that influences dew point or frost point measurements.[22] The formula for obtaining the ambient water vapor pressure as a function of dew point is given in the discussion of DPxC above, Eqs. (20) and (21), where the calculation of the variables EWx and EWX are also discussed. EWX (or previously EDPC) is the preferred variable from among the possibilities {EWx} that is selected for subsequent calculation of derived variables (including DPXC).

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

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

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 or Pa/hPa:*

EDPC = atmospheric water vapor pressure (hPa)
ATX = ambient air temperature ($^\circ C$)
T_0 =273.15 K
$e_s(\mathrm{ATX}+\mathrm{T}_0)$ = saturation water vapor pressure at *dewpoint* ATX (hPa)
(see eq. 20) for the formula used.)

$$\mathrm{RHUM} = 100\% \times \frac{\{\mathrm{EDPX}\}}{e_s(\{\mathrm{ATX}\}+\mathrm{T}_0)} \tag{23}$$

To follow normal conventions, the change in saturation vapor pressure that arises from the enhancement factor is not included in the calculated relative humidity, even though the true relative humidity should include the enhancement factor as specified in (21) in the denominator of (23).

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

The water vapor density computed from various measurements of humidity as indicated by the 'x' suffix, and conventionally expressed in units of g kg or per mille. The calculation proceeds in different ways for different sensors. For sensors that measure a chilled-mirror temperature, the calculation is based on the equation of state for a perfect gas and uses the water vapor pressure determined by the instrument, as in the following box.

ATX = ambient temperature ($^\circ C$)
EDPC = water vapor pressure, hPa
C_{mb2Pa} = 100 Pa hPa^{-1} (conversion factor to MKS units)
C_{kg2g} =10^3 g kg^{-1} (conversion factor to give final units of g m^{-3})
T_0 = 273.15 K

$$\mathrm{RHOx} \quad = \quad C_{kg2g}\frac{C_{mb2Pa}\{\mathrm{EDPC}\}}{R_w(\{\mathrm{ATX}\}+T_0)} \tag{24}$$

For instruments measuring the vapor pressure density (including the Lyman-alpha probes and the newer version called the UV hygrometer), the basic measurement from the instrument is the water vapor density, **RHOUV** or **RHOLA**, determined by applying calibration coefficients to the measured signals (XUVI or VLA). In addition, a slow update to a dewpoint measurement is used to compensate for drift in the calibration. The algorithm for the UV Hygrometer is as described in the following box; the processing used for early projects with the Lyman-alpha instruments is similar but more involved and won't be documented here because the instruments are obsolete. See RAF Bulletin 9 for the processing previously used for archived measurements from the Lyman-alpha hygrometers.

Specific Humidity (g/kg): SPHUM

The mass of water vapor per unit mass of (moist) air, conventionally measured in units of g/kg or per mille.

PSXC = ambient pressure. hPa
EDPC = ambient water vapor pressure, hPa
C_{kg2g} =10^3 g kg^{-1} (conversion factor to give final units of g kg^{-1})
M_w =molecular weight of water†
M_d =molecular weight of dry air†

$$\mathrm{SPHUM} = C_{kg2g}\frac{M_w}{M_d}\left(\frac{\{\mathrm{EDPC}\}}{\{\mathrm{PSXC}\}-(1-\frac{\mathrm{M_w}}{\mathrm{M_d}})\{\mathrm{EDPC}\}}\right) \tag{25}$$

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

The ratio of the mass of water to the mass of dry air in the same volume of air, conventionally expressed in units of g/kg or per mille. 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 sensor, MRLA1 if there is a second Lyman-alpha sensor, MRLH from a laser hygrometer, and MRVXL is from the VCSEL hygrometer (also a laser hygrometer). The example in the box below is for the case of the dewpoint hygrometers; others are analogous.

EDPC = water vapor pressure, hPa
PSXC = ambient total pressure, hPa
C_{2kg2g} =10^3 g kg^{-1} (conversion factor to give final units of g kg^{-1})
M_w =molecular weight of water†
M_d =molecular weight of dry air†

$$\mathrm{MR} = \mathrm{C_{kg2g}}\frac{\mathrm{M_w}}{\mathrm{M_d}}\frac{\{\mathrm{EDPC}\}}{(\{\mathrm{PSXC}\}-\{\mathrm{EDPC}\})} \tag{26}$$

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

These are measurements made directly in the chamber of the cryogenic hygrometer, a now obsolete cabin-mounted instrument connected to outside air by an inlet line. CRHP is the pressure and VCRH is the frost-point temperature measured 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 (ºC): FPCRC and DPCRC (obsolete)

The frost point or dew point determined after corrections are applied to the direct measurements from a cryogenic hygrometer. This is an obsolete instrument but its description is included here because these variables appear in some old data files. 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[23] 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, and this is converted to an equivalent dew-point in the same manner as for the standard variables DPxC. The instrument was only used for measurements of frost point less than -15°C because it did not function well above that frost point. The steps are documented below:

[23]Goff, J. A., and S. Gratch (1946) Low-pressure properties of water from −160 to 212 °F, referenced and used in the Smithsonian Tables (List, 1980).

VCRH = frost point inside the cryogenic hygrometer (°C)
CRHP = pressure inside the chamber of the cryogenic hygrometer (hPa)
PSXC = reference ambient pressure (hPa)
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} (hPa):

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

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

ambient vapor pressure e_a (hPa):

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

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

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

Voltage Output From the Lyman-alpha Sensor (V): VLA, VLA1 (obsolete)

The voltage output from the Lyman-alpha absorption hygrometer. This instrument provided fast-response, high-resolution measurements of water vapor density. (If a second sensor is used, a 1 is added to the variable name associated with the second sensor.) The sensors are now obsolete.

Voltage Output from the UV Hygrometer (V): XUVI

The voltage from a modern (as of 2009) version of the Lyman-alpha hygrometer, which provides a signal that represents water vapor density. The instrument also provides measurements of pressure and temperature inside the sensing cavity; they are, respectively, **XUVP** and **XUVT**.

XUVI = output from the UV Hygrometer, after application of calibration coefficients
DPXC = corrected dewpoint from some preferred source, °C
ATX = preferred temperature, °C
RHODT =water vapor density determined by a chilled-mirror sensor
Tau = time constant for the exponential update (typically 300 s)

```
For valid measurements:[a]
    Offset += (RHODT-XUVI-Offset)/Tau
RHOUV = XUVI + Offset
```

[a]defined by DPXC<ATX and valid numbers for XUVI and RHODT

4.5 Derived Thermodynamic Variables

Potential Temperature (K): THETA

The absolute temperature reached if a dry parcel at the measured pressure and temperature were to be compressed or expanded adiabatically to a pressure of 1000 hPa. It does not take into account the difference in specific heats caused by the presence of water vapor, and water vapor can change the exponent in the formula below enough to produce errors of 1 K or more.

ATX = ambient temperature, °C
PSXC = ambient pressure (hPa)
p_0 = reference pressure = 1000 hPa
R_d = gas constant for dry air[†]
c_{pd} = specific heat at constant pressure for dry air[†]

$$\mathrm{THETA} = (\{\mathrm{ATX}\} + T_0)\left(\frac{p_0}{\{\mathrm{PSXC}\}}\right)^{R_d/c_{pd}} \tag{27}$$

changed 2011

Pseudo-Adiabatic Equivalent Potential Temperature (K): THETAP

The absolute temperature reached if a parcel of air were to be expanded pseudo-adiabatically (i.e., with immediate removal of all condensate) to a level where no water vapor remains, after which the dry parcel would be compressed to 1000 hPa. Beginning in 2011, pesudo-adiabatic equivalent potential temperature is calculated using the method developed by Davies-Jones (2009).[24] His formula is

$$\Theta_P = \Theta_{DL} \exp\{\frac{r(L_0^* - L_1^*(T_L - T_0) + K_2 r)}{c_{pd} T_L}\} \tag{28}$$

[24]Davies-Jones, R., 2009: On formulas for equivalent potential temperature. *Mon. Wea. Review,* **137,** 3137–3148.

and

$$\Theta_{DL} = T_K(\frac{p_0}{p_d})^{0.2854}(\frac{T_k}{T_L})^{0.28\times10^{-3}r} \tag{29}$$

where T_K is the absolute temperature (in kelvin) at the measurement level, p_d is the partial pressure of dry air at that level, p_0 is the reference pressure (conventionally 1000 hPa), r is the (dimensionless) water vapor mixing ratio, c_{pd} the specific heat of dry air, T_L the temperature at the lifted condensation level (in kelvin), and $T_0 = 273.15\,\mathrm{K}$. The coefficients in this formula are: $L_0 = 2.56313\times10^6\mathrm{J\,kg^{-1}}$, $L_1 = 1754\ \mathrm{J\,kg^{-1}\,K^{-1}}$, and $K_2 = 1.137\times10^6\ \mathrm{J\,kg^{-1}}$. The asterisks on L_0^* and L_1^* indicate that these coefficients depart from the best estimate of the coefficients that give the latent heat of vaporization of water, but they have been adjusted to optimize the fit to values obtained by exact integration. Note that, unlike the formula discussed below that was used prior to 2011, the mixing ratio must be used in dimensionless form (i.e., kg/kg), *not* with units of g/kg. The following empirical formula, developed by Bolton (1980),[25] is used to determine T_L:

$$T_L = \frac{\beta_1}{3.5\ln(T_K/\beta_3)-\ln(\mathrm{e}/\beta_4)+\beta_5}+\beta_2 \tag{30}$$

where e is the water vapor pressure, $\beta_1 = 2840K$, $\beta_2 = 55\,\mathrm{K}$, $\beta_3 = 1\,\mathrm{K}$, $\beta_4 = 1\,\mathrm{hPa}$, $\beta_5 = -4.805$. (Coefficients β_3 and β_4 have been introduced into (30) only to ensure that arguments to logarithms are dimensionless and to specify the units that must be used to achieve that.)

Prior to 2011, the variable called the equivalent potential temperature[26] and named THETAE in the output data files was that obtained using the method of Bolton (1980), which used the same formula to obtain the temperature at the lifted condensation level (T_L) and then used that temperature to find the value of potential temperature of dry air that would result if the parcel were lifted from that point until all water vapor condensed and was removed from the air parcel. The formulas used were as follows:

[25]Bolton, D., 1980: The computation of equivalent potential temperature. *Mon. Wea. Rev.,* **108,** 1046–1053.

[26]The AMS glossary defines equivalent potential temperature as applying to the adiabatic process, not the pseudo-adiabatic process; the name of this variable has therefore been changed.

T_L= temperature at the lifted condensation level, K
ATX = ambient temperature ($^\circ C$)
EDPC = water vapor pressure (hPa)
MR = mixing ratio (g/kg)
THETA = potential temperature (K)

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

$$\text{THETAE} = \{\text{THETA}\}\left(\frac{3.376}{\text{T}_\text{L}} - 0.00254\right)(\{\text{MR}\})(1+0.00081(\{\text{MR}\})) \qquad (31)$$

Differences vs the new formula are usually minor but can be of order 0.5 K.

Virtual Temperature (ºC): TVIR

The temperature of dry air having the same pressure and density as the air being sampled.
change 2011 The virtual temperature thus adjusts for the buoyancy added by water vapor.

ATX = ambient temperature, $^\circ C$
r = mixing ratio, dimensionless [kg/kg] = {MR}/(1000 g/kg)
$T_0 = 273.15\,\text{K}$

$$\text{TVIR} = (\{\text{ATX}\}+T_0)\left(\frac{1+\frac{M_d}{M_w}r}{1+r}\right) - T_0 \qquad (32)$$

Virtual Potential Temperature (K): THETAV

A potential temperature analogous to the conventional potential temperature except that it is based on virtual temperature instead of ambient temperature. Dry-adiabatic expansion or compression to the reference level (1000 hPa) is assumed. As for THETA, use of dry-air values for the gas constant and specific heat at constant pressure can lead to significant errors in humid conditions. For further information, see this note.

change 2011

TVIR = virtual temperature, $^\circ C$
PSXC = ambient pressure, hPa
R_d =gas constant for dry air†
c_{pd} =specific heat at constant pressure for dry air†
$T_0 = 273.15\,\text{K}$
p_0 = reference pressure, conventionally 1000 hPa

$$\text{THETAV} = (\{\text{TVIR}\}+T_0)\left(\frac{p_o}{\{\text{PSXC}\}}\right)^{R_d/c_{pd}} \qquad (33)$$

Wet-Equivalent Potential Temperature (K): THETAQ

new 2012

The absolute temperature reached if a parcel of air were to be expanded adiabatically (i.e., retaining the condensed water in the liquid phase and accounting for the specific heat of that condensate) to a level where no water vapor remains, after which the condensate would be removed and the resulting dry parcel compressed to 1000 hPa. Emanuel (1994) gives the following formula (his Eq. 4.5.11):

$$\Theta_q = T(\frac{p_0}{p_d})^{\frac{R_d}{c_{pt}}} \exp\left\{\frac{L_v r}{c_{pt} T}\right\} \left(\frac{e}{e_{s,w}(T)}\right)^{-rR_w/c_{pt}} \tag{34}$$

where Θ_q is the wet-equivalent potential temperature, L_v the latent heat of vaporization, r the (dimensionless) water-vapor mixing ratio,$c_{pt} = c_{pd} + r_t c_w$ where r_t is the total-water mixing ratio including vapor and condensate, $c_w$is the specific heat of liquid water, and other symbols are as used previously. See thisnote for additional discussion of this variable, for values to use for the latent heat and specific heat, and in particular for analysis indicating that Θ_q evaluated with this formula can be expected to vary from the true adiabatic value by a few tenths kelvin (in a worst case, by about 1 K) because of variation in (and uncertainty in) the specific heat of supercooled water at low temperature. The details of the calculation are described in the following box. Note that this algorithm only uses the liquid water content as measured by a King probe, PLWCC; other similar calculations could be based on other measures of liquid water such as that from a cloud-droplet spectrometer.

e ={EDPC}*100 = water vapor pressure (Pa)
ATX = ambient temperature ($^\circ C$)
r ={MR}/1000. = mixing ratio (dimensionless)
p_d =({PSXC}-{EDPC})*100 = ambient dry-air pressure (Pa)
p_0 =reference pressure for potential temperature, 10^5Pa
χ ={PLWCC}/1000.=cloud liquid water content ($\mathrm{kg\,m^{-3}}$)
R_d =gas constant for dry air†
ρ_d =density of dry air = $\frac{p_d}{R_d(\{ATX\}+T_0)}$
c_{pd} =specific heat of dry air†
c_w =specific heat of liquid water†
$L_V = L_0 + L_1\{\mathrm{ATX}\}$ where $L_0 = 2.501 \times 10^6 \mathrm{J\,kg^{-1}}$ and $L_1 = -2370\,\mathrm{J\,kg^{-1}\,K^{-1}}$

$$r_t = r + (\chi/\rho_d)$$

$$c_{pt} = c_{pd} + r_t c_w$$

If outside cloud or below saturation, define

$$F_1 = \left(\frac{e}{e_{s,w}(T)}\right)^{\frac{rR_w}{c_{pt}}} \quad ,$$

otherwise set $F_1 = 1$.

$$T_1 = (\{\mathrm{ATX}\} + T_0)\left\{\frac{p_0}{(\{\mathrm{PSXC}\} - \{\mathrm{EDPC}\})}\right\}^{\frac{R_d}{c_{pt}}}$$

$$\mathrm{THETAQ} = T_1 F_1 \exp\left\{\frac{L_v r}{c_{pt}(\{\mathrm{ATX}\} + T_0)}\right\}$$

4.6 Wind

RAF Bulletin 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 data processing, a separate function (GUSTO in GENPRO, gust in NIMBUS) is used to derive these wind components. That function uses the measurements from an Inertial Reference Unit (IRU) 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 the wind direction (WD) and wind speed (WS). Additional variables UIC, VIC, WSC, WDC, UXC, and VYC are also calculated based on the variables VNSC, VEWC discussed in section 3.4, which combine IRU and GPS information to obtain improved measurements of the aircraft motion. Those are usually the highest-quality measurements of wind because the merged IRU/GPS variables combine the high-frequency response of the IRU with the long-term accuracy of the GPS.

The details contained in Bulletin 23 will not be repeated here; the description there still describes the wind calculations in use, so please consult that bulletin for the processing algorithms. The variables pertaining to the relative wind are described in the next subsection, and the variables characterizing the wind are then described briefly in the last subsection. Some additional detail is included in cases where procedures are not documented in that earlier bulletin.

4.6.1 Relative Wind

Wind is measured by adding two vectors: (1) the measured air motion relative to the aircraft (called the relative wind), and (2) the motion of the aircraft relative to the Earth. The following are the measurements used to determine the relative wind. The motion of the aircraft relative to the ground was discussed in Section 3, and the combination of these two vectors to measure the wind is described in RAF Bulletin 23.

RAF uses the radome gust-sensing technique[27] to measure incidence angles of the relative wind (i.e., 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. The sideslip angle is determined similarly using the pressure ports on the starboard and port sides of the radome. A Rosemount Model 858AJ gust probe has occasionally been 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.

Mach Number (dimensionless): MACHx

The Mach Number that characterizes the flight speed. The Mach number is defined as the ratio of the flight speed (or the magnitude of the relative wind) to the speed of sound. See Eq. (17) in Section 4 for the algorithm used.

Aircraft True Airspeed (m/s): TASx, TASxD

The flight speed of the aircraft relative to the atmosphere. This derived measurement of

[27] Brown, E. N, C. A. Friehe, and D. H. Lenschow, 1983: *Journal of Climate and Applied Meteorology,* **22,** 171–180

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 for ATx on page 34. The different variables for TASx (TASF, TASR, etc) use different measurements of QCxC in the calculation of Mach number. The variable TASxD is the result of calculations for which the Mach number, air temperature, and true airspeed are determined for dry instead of humid air. See the discussion of ATX on page 4.3 for an explanation of how humidity is handled in the calculation of true airspeed.

(see box for ATx and MACHx)
Note dependence of MACHx on choices for QCxC and PSXC
TASx depends on QCxC, PSXC, ATX
where PSXC and ATX are the preferred choices
γ', R', and T_0: See the List of Symbols on p. **??**.

$$\mathrm{TASx} = \{\mathrm{MACHx}\}\sqrt{\gamma' R' (\{\mathrm{ATX}\} + T_0)} \qquad (35)$$

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

This derived measurement of true airspeed accounted for deviations of specific heats of moist air from those of dry air. See List, 1971, pp 295, 331-339, and Khelif, et al., 1999. The equation used for this variable, given by Khelif et al. 1999,[28] added a moisture correction to the true airspeed derived for dry air, as follows:

q = specific humidity (dimensionless) = SPHUM/1000. for SPHUM expressed in g/kg
$c = 0.000304\,\mathrm{kg\,g^{-1}} = 0.304$ (dimensionless)

```
TASHC = TASX * (1.0 + c * q)
```

Attack Angle Differential Pressure (mb): ADIFR

The pressure difference between the top and bottom pressure ports of a radome gust-sensing system. This measurement is used to determine the angle of attack. Obsolete variable ADIF is a similar variable used for old gust-boom systems or for Rosemount Model 858AJ flow-angle sensors.

Sideslip Angle Differential Pressure (mb): BDIFR

The pressure difference between starboard and port pressure inlets of a radome gust-sensing system. This measurement is used to determine the sideslip angle. Obsolete variable BDIF is a similar variable used for old gust-boom systems or for Rosemount Model 858AJ flow-angle sensors.

Attack Angle, Radome (°): AKRD

The angle of attack of the aircraft. This derived measurement represents the angle between

[28] Khelif, D., S.P. Burns, and C.A. Friehe, 1999: Improved wind measurements on research aircraft. *Journal of Atmospheric and Oceanic Technology,* **16,** 860–875.

the relative wind vector and the plane determined by the longitudinal and lateral axes of the aircraft. Positive values indicate flow moving upward relative to that plane. The calculation is based on ADIFR and a measurement of dynamic pressure, and so is the measurement produced by a radome gust-sensing system. Empirical sensitivity coefficients for each aircraft, determined from special flight maneuvers, are used; see RAF Bulletin 23 for more information.

ADIFR = attack differential pressure, radome (hPa)
QCXC = reference dynamic pressure (hPa)
MACHX = reference Mach number
c_0, c_1 = sensitivity coefficients determined empirically
= {0.3843, (1/0.06653) º} for the C-130
= {0.2571, (1/0.04724) º} for the GV
c_3, c_4 = additional coefficients for the GV
= {0.6195º, -1.02758 º} for MACHX**2 > 0.194
= {0.42 º, 0} for MACHX**2 $\leq$ 0.194

For the C-130:

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

For the GV:

$$\text{AKRD} = c_1 \left(\frac{\{\text{ADIFR}\}}{\{\text{QCXC}\}} + c_0 \right) + c_3 + c_4 \{\text{MACHX}\}^2$$

Reference Attack Angle (º): ATTACK

The reference angle of attack used to calculate derived variables. 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) (º): SSRD

The angle of sideslip of the aircraft. This derived measurement represents the angle between the longitudinal axis of the aircraft and the projection of the relative wind onto the plane determined by the longitudinal and lateral axes. Positive values indicate airflow from the starboard side. This variable is derived from BDIFR and a dynamic pressure using a sensitivity function that has been determined empirically for each aircraft.

BDIFR = differential pressure between sideslip pressure ports, radome (mb)
QCXC = dynamic pressure (mb)
b_0, b_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

$$\text{SSRD} = b_1\left(\frac{\{BDIFR\}}{\{\text{QCXC}\}} - b_0\right)$$

Reference Sideslip Angle (°): SSLIP

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

4.6.2 Wind Components and the Wind Vector

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

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, and WI is the vertical component with positive values toward the zenith.

Wind Speed (m/s): WS
Wind Direction (°): WD

The magnitude and direction of the horizontal wind. These variables are obtained in a straightforward manner from UI and VI. The resulting wind direction is relative to true north and represents the direction from which the wind blows; that is the reason that 180° appears in the following algorithm.

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: $^\circ/radian$]

$$\begin{aligned}\text{WS} &= \sqrt{\{\text{UI}\}^2 + \{\text{VI}\}^2} \\ \text{WD} &= C_{rd}\,\text{atan2}(\{\text{UI}\}, \{\text{VI}\}) + 180^\circ \end{aligned} \tag{36}$$

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

The horizontal wind vector relative to the frame of reference attached to the aircraft. UX is parallel to the longitudinal axis and positive toward the nose. VY is along the lateral axis and 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

The horizontal wind components respectively toward the east and toward the north. They are derived from measurements from an inertial reference unit (IRU) 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 IRU-based values. They are considered "corrected" from the original measurements from the IRU or GPS, as described in section 3.4.

Wind Vector, Vertical Component (m/s): WIC

The component of the wind in the vertical direction. This is the standard calculation of vertical wind, obtained from the difference between the measured vertical component of the relative wind and the vertical motion of the aircraft (VSPD) as determined from an IRU.[29] This should be used in preference to WI if the latter is present; see the discussion of WP3 in section 3. Positive values are toward the zenith. change 2011

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

The direction and magnitude of the wind vector, obtained by combining measurements from GPS and IRU units. These variables are obtained in a straightforward manner from UIC and VIC, using equations analogous to (36) but with UIC and VIC as input measurements. They are expected to be the preferred measurements of wind because they combine the best features of the IRU and GPS measurements.

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

The longitudinal and lateral components of the three-dimensional wind, similar to UX and VY, but corrected by the complementary-filter algorithm that combines IRU and GPS measurements. See the discussion in Section 3.4. The components UXC and VYC are toward the front of the aircraft and toward the port (left) wing, respectively.

[29] This variable is named "GPS-Corrected Wind Vector" in some output prior to 2011, but that name was incorrect because the algorithm does not involve measurements from a GPS.

5 CLOUD PHYSICS VARIABLES

5.1 Measurements of Liquid Water Content

Raw Output PMS/CSIRO (KING) Liquid Water Content (W): PLWC, PLWC1

This variable is the output of a PMS/CSIRO (King) liquid water probe (in watts). PLWC is the power required to maintain constant temperature in 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, so that the remaining power can be related to the liquid water content. The instrument is described in RAF Bulletin 24. See PLWCC (which follows) for processing.

Corrected PMS/CSIRO (KING) Liquid Water Content (g/m^3): PLWCC, PLWCC1

change 2011

This is the corrected liquid water content obtained from relating the power consumption required to maintain a constant temperature to the liquid water content, taking into account the effect of convective heat losses. The instrument and processing are described by King et al. (1978)[30] and in a note available at this URL: on the RAF Science Wiki. Because the temperature of the sensing wire is typically well above the boiling point of water, the assumption made in processing is that the water collected on the sensing wire is vaporized at the boiling point T_b. The boiling point is represented as a function of pressure as described below.

[30] King, W. D., D. A. Parkin and R. J. Handsworth, 1978 A hot-wire liquid water device having fully calculable response characteristics. J. Appl. Meteorol., 17, 1809–1813. See also Bradley, S. G., and W. D. King, 1979 Frequency response of the CSIRO Liquid Water Probe. J. Appl. Meteorol., 18, 361–366.

PLWC = total power dissipated by the probe (W)
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
L = length of the probe sensitive element, typically 0.021 m
d= diameter of the probe sensitive element, typically 1.805×10^{-3}m
T_s= sensor temperature (K)
T_a= ambient temperature (K) = ATX+273.15
T_b = boiling temperature of water (dependent on pressure):
with $x = \log_{10}(p/(1\text{hPa}))$, $B = 1°C$, and $\{b_0, b_1, b_2\}$ = {0.03366503, 1.34236135, -0.33479451, 0.0351934}: $T_b = B\times10^{(b_0+b_1x+b_2x^2+b_3x^3)}$
$T_m = (T_a+T_s)/2$ = mean temperature for air properties
$L_v(T_b)$ = latent heat of vaporization of water = $(2.501+0.00237(T_a-T_0))\times10^6\,\text{J kg}^{-1}$
c_w = specific heat of water=1875 $\text{J kg}^{-1}\text{K}^{-1}$
U_a = true airspeed (m/s) = TASX
λ_c = thermal conductivity of dry air $(2.38+0.0071(T_m-T_0))\times10^{-2}\,\text{J m}^{-1}\text{s}^{-1}\text{K}^{-1}$
μ =viscosity of air = $(1.718+0.0049(T_m-T_0))\times10^{-5}$ kg m^{-1}s^{-1}
ρ_a = density of air = $p/(R_dT_a)$
Re = Reynolds number = ρ_aU_ad/μ_a
Nu = Nusselt Number relating conduction heat loss to the total heat loss for dry air:
typically Nu=$a_0\text{Re}^{a_1}$
C_{kg2g} = 1000 = grams per kilogram
(unit conversion to conventional units for liquid water content)
χ = liquid water content (g/m^3) = PLWCC

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

where

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

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

Result:

$$\text{PLWCC} = \chi = \frac{C_{kg2g}(\{\text{PLWC}\}-P_D)}{Ld\,U_a[L_v(T_b)+c_w(T_b-T_a)]}$$

PVM-100 Liquid Water Content (g/m^{-3}): PLWCG

Cloud liquid water content for cloud droplets in the approximate size range from 3–50 μm. The PVM produces a measure of the liquid water content directly, but a baseline value is sometimes subtracted by reference to another cloud droplet instrument such as an FSSP or CDP, such that when the other instrument measures a very low droplet concentration the baseline value for the PVM-100 is updated at the corresponding time and that average is then subtracted from the measurements directly produced by the PVM-100. Typical values are

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 {obsolete? Couldn't find code}

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)

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

5.2 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 24 contains extensive information on the operating principles and characteristics of some of the older 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 of the two possible canister locations 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), CDP (CDP or D), UHSAS (UHSAS or U), 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)	
UHSAS	U	UHSAS	0-63	??		
CDP	D	CDP				
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, ACDP, AUHSAS

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, CCDP, CUHSAS**
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, CDP, UHSAS) 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 24.

Concentration, sum over all channels (cm^{-3})**: CONCF, CONC3, CONCP, CONCD, CONCU**
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 24.

Mean Diameter (μm)**: DBARF, DBAR3, DBARP, DBARX, DBAR6, DBARY, DBARD, DBARU**

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 DBARF)
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, DISPD, DISPU

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 DISPF)
d_i = diameter measured in channel i of probe y
i1 = lowest usable channel for the probe
i2 = highest usable channel for the probe

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

Liquid/Ice Water Content (g/m^3):
PLWCF, PLWCX, PLWC6, PLWCY, PLWCD
These variables are derived from the measured concentration (CONCx) and the third moment of the equivalent droplet diameter. The equivalent droplet diameter is the diameter that represents the mass in the detected particle. The equivalent droplet diameter is normally the measured diameter for liquid hydrometeors, but some processing has used other assumptions and this is a choice that can be made 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

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

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

Radar Reflectivity Factor (dbZ): DBZF, DBZX, DBZ6, DBZY, DBZD
The radar reflectivity factor for water is a measure of the product of the concentration and the sixth moment of the droplet 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 normally used 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 sometimes 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 therefore is 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, and the ratio of strobes to accepted particles can indicate quality of operation 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 24 for more discussion on 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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$$\mathrm{FBMFR} = \{\mathrm{AFSSP}\}/\{\mathrm{FSTROB}\}$$

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). The characteristic times are in the NetCDF header (for recent projects). .

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)

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

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 (L^{-1}): 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 (L^{-1}): CON2P1

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

5.3 Hydrometeor Imaging Probes

– NEEDED: 2DC, 2DP, CPI, etc

6 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
Internal TECO Ozone Sampling Temperature ($^{\circ}C$): TET

TEP (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 ±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 (ºC): 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 ppbv for a one-second averaging time. The uncertainty is ± 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 chemiluminescence.

Chemiluminescent Ozone Sample Flow Rate (sccm): O3FF
Chemiluminescent Ozone Nitric Oxide Flow Rate (sccm): O3FN
Chemiluminescent Ozone Sample Pressure (mb): O3FP

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): O3FC

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.

7 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 $10^4\mathrm{cm}^{-3}$; a correction for these effects of coincidence is applied, but for concentrations above about 2×10^4 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): PCN

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 ($^\circ C$): TEMP1, TEMP2, CNTEMP

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): FCN
Corrected CN Counter Sample Flow Rate (vlpm): FCNC

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 $0^\circ C$. 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): XICN
Corrected CN Isokinetic Side Flow Rate (vlpm): XICNC
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

$$\mathrm{XICNC} = \{\mathrm{XICN}\}\frac{P_r}{\{\mathrm{PCN}\}}\frac{(\{\mathrm{TEMP1}\}+T_0)}{T_r}$$

TSI CN Counter Output (counts per sample interval); CNTS
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}): CONCN
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

---

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

$$\mathrm{CONCN} = \mathrm{A}\, e^{AT_{vv}\{\mathrm{FCNC}\}} \tag{37}$$

See the introduction to this section for comments regarding the range of validity of the coincidence correction in Eq. (37).

8 RADIATION VARIABLES

8.1 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 (2º) 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 (2º) 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 sensing head of the Heimann radiometer, usually from RSTB, the primary down-looking instrument.

Raw Pyrgeometer Output ($\mathrm{W\,m^{-2}}$): IRx

A 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 letter 'x' denotes either bottom (B) or top (T).

Corrected Infrared Irradiance ($\mathrm{W\,m^{-2}}$): 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. IRxC is the corrected infrared irradiance, determined following procedures of Albrecht and Cox (1977). .

change 2011

IRx = raw pyrgeometer output [$\mathrm{W\,m^{-2}}$]
T_D = dome temperature [K]
T_S = "sink" temperature (approx. the thermopile temperature) [K]
ε = emissivity of the thermopile (dimensionless) = 0.986
β = empirical constant dependent on the dome type = 5.5
σ = Stephan-Boltzmann constant = $5.6704\times10^{-8}\ \mathrm{W\,m^{-2}K^{-4}}$

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

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 letter '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 $\pm 6^\circ$ in either angle, so these measurements should be considered invalid beyond these limits. 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 6º 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.

8.2 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 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.) To obtain this, the solar hour angle is calculated (taking leap years into account). The calculations were adapted by Ron Ruth from an algorithm developed by Lutz Bannehr.

time = day number (corrected for leap year) since 1 January 1980
theta = coarse solar time (radians)
gg = 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)

```
gg = -0.031271 - (4.53963e-7 time) + theta
el = 4.900968 + (3.67474e-7 time)
     + {[0.033434 - (2.3e-9 time)] sin(gg)}
     + [0.000349 sin(2 gg) + 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
```

9 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.

10 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 (°): CLAT
LORAN-C Longitude (°): CLON
LORAN-C Circular Error of Probability (n mi): CCEP
LORAN-C Ground Speed (m/s): CGS
LORAN-C Time (s): CSEC
LORAN-C Fractional Time (s): CFSEC

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 0.0014º, 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 0.0028º. THI was the true heading of the aircraft, produced at 5 Hz with resolution of 0.0014º. 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 0.0028º.

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 4.6:

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

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) (º): 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) (º): 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 4.2.)

Ambient Temperature ($^{\circ}C$): ATRF

The ambient temperature computed using the NCAR reverse-flow temperature sensor. (See discussion in Section 4.2 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 4.2.)

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 -50ºC to +50ºC. EDPC was calculated using this method for most RAF research projects between 1993 and 1996. This variable did not have the enhancement factor applied that was discussed in Appendix C of Bulletin 9.

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 >= -50ºC:

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

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Appendix A: List of Variables

Variable Names