U.S. DEPARTMENT OF ENERGY | Office of Science

DOE/SC-ARM-TR-255

Navigation and Meteorological Data from Multiple Sensors on Airborne Platform (NAVMET-AIR) Value-Added Product Report

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Work supported by the U.S. Department of Energy,
Office of Science, Office of Biological and Environmental Research

Acronyms and Abbreviations

AAF	ARM Aerial Facility
ACAPEX	ARM Cloud Aerosol Precipitation Experiment
ACE-ENA	Aerosol and Cloud Experiments in the Eastern North Atlantic
ACME V	Airborne Carbon Measurements V
ADC	ARM Data Center
AIMMS	Aircraft-Integrated Meteorological Measurement System
ARM	Atmospheric Radiation Measurement
BBOP	Biomass Burning Observation Project
CACTI	Cloud, Aerosol, and Complex Terrain Interactions
CARES	Carbonaceous Aerosol and Radiative Effects Study
CMH	chilled-mirror hygrometer
CVI	counterflow virtual impactor
DGPS	Differential Global Positioning System
DSM	Differential Survey Module
G-1	Gulfstream-159
GNSS	Global Navigation Satellite System
GoAmazon	Green Ocean Amazon 2014/15
GPS	Global Positioning System
HI-SCALE	Holistic Interactions of Shallow Clouds, Aerosols, and Land-Ecosystems
ICARTT	International Consortium for Atmospheric Research on Transport and Transformation
INS	inertial navigation system
IOP	intensive operational period
ISO	isokinetic
IWGADTS	Inter-Agency Working Group for Airborne Data and Telemetry Systems
NAVMET-AIR	Navigation and Meteorological Data from Multiple Sensors on Airborne Platform
NGA	National Geospatial-Intelligence Agency
NREL	National Renewable Energy Laboratory
QC	quality control
SPLATT	single-particle laser ablation time-of-flight mass spectrometer
TANS	Trimble Advanced Navigation Sensor
TAS	true airspeed
TCAP	Two-Column Aerosol Project
VAP	value-added product
WGS	World Geodetic System

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1.0 Introduction

The Navigation and Meteorological Data from Multiple Sensors on Airborne Platform (NAVMET-AIR) value-added product encompasses the aafnaviwg data set in the ARM Data Center (ADC), known as the IWG file, named for the Inter-Agency Working Group for Airborne Data and Telemetry Systems (IWGADTS). Its purpose is to produce a suite of tools to promote standardization of instrument interface, data format, and data processing. This data set's contents are navigational and meteorological state variables at 1 Hz. It also contains higher-order data flags created by ARM Aerial Facility (AAF) scientists to aid analysis such as periods when the aircraft is flying level, operating in maneuvers, or flying through cloud.

Due to the nature of research flights, the payload of the aircraft consists of many duplicate and overlapping instruments to ensure, in case of instrument failure, there is a backup to record the data. Measurements from multiple instruments are consolidated into a single file. Each variable of this data set is carefully chosen from the onboard instrumentation and quality checked by AAF scientists to create this wholistic and most accurate data set for airborne research.

This document is intended to be a hub towards the individual "read me" files produced for each campaign. For reference about what instrument was used for calculations on specific days, the read me files are located in the ARM IOP archive at the addresses listed below. Or access the IOP (intensive operational period) database at https://www.archive.arm.gov/.

- CACTI (2018) arm-iop/2018/cor/cacti/mei-iwg/
- ACE-ENA (2017-2018) arm-iop/2017/ena/aceena/mei-iwg1/
- Hi-SCALE (2016) arm-iop/2016/sgp/hiscale/mei-iwg1/
- ACME V (2015) arm-iop/2015/nsa/acmev/mei-iwg1/
- ACAPEX (2015) arm-iop/2015/acx/acapexaaf/mei-iwg1/
- GoAmazon (2014) arm-iop/2014/mao/goamazon/mei-iwg1/
- BBOP (2013) arm-iop/2013/osc/bbop/mei-iwg1/
- TCAP (2012) arm-iop/2012/pvc/tcap/G1_aircraft/hubbe-iwg1/
- Calwater (2011) arm-iop/2011/osc/calwater/hubbe-iwg1/

There is no IWG1 file for the Carbonaceous Aerosol and Radiative Effects Study (CARES; 2010) campaign. Navigational and meteorological data available from individual instruments.

2.0 Algorithm and Methodology

The script that develops the IWG merged data set based on the aircraft's integrated measurements is coded in Matlab. As the aircraft carries a dynamic (changing) payload with primary and secondary measurements of the same variable, the script is updated for each campaign. The methodology remains the same, but the instruments referred to may be updated.

1. Select research flight of interest
    a. The naming convention is the date as YYYYMMDD and the flight indicator (a for 1st, b for 2nd flight of the day)
2. Open instrument data files associated with meteorological and navigational variables
    a. Navigational
        i. GPS: The Global Positioning System (GPS), is a satellite-based radionavigation system owned by the United States. Based on the time and position of GPS satellites, GPS receivers' locations can be triangulated down to 15 m in best-case scenarios.
        ii. GNSS: Refers to the global navigation satellite system (GNSS), which encompasses the U.S. GPS satellites

1. INS: An inertial navigation system (INS) is a navigation device that uses a computer, motion sensors (accelerometers), and rotation sensors (gyroscopes) to continuously calculate by dead reckoning the position, orientation, and velocity (direction and speed of movement) of a moving object without the need for external references. GPS/INS is the use of GPS satellite signals to correct or calibrate a solution from an INS. The method is applicable for any GNSS/INS system. The benefits of using GPS with an INS are that the INS may be calibrated by the GPS signals and that the INS can provide position and angle updates at a quicker rate than GPS.
    a. DGPS: A Differential Global Positioning System (DGPS) is an enhancement to the GPS that provides improved location accuracy to about 1–3 cm in case of the best implementations. It does this by including a fixed ground-based site as an additional reference to the GPS satellite system.
    b. Meteorological
        iii. Temperature
        iv. Pressure
        v. Relative humidity
        vi. Wind speed
        vii. Wind direction

3. Verify the file time aligns with the take-off time recorded by the flight scientist
    a. Find the start time for the file based on the aircraft reaching 40 m/s or ~80 knots rotation (take-off) and checking platform vertical velocity greater than -2 m/s
    b. Verify time with take-off time recorded by flight scientist
4. Verify there is no time offset or shift for the DGPS and GPS data
    a. Often the aircraft must be moving and/or aloft for these instruments to get a good signal with the GPS satellites
5. Select between the primary and secondary instrument for which data set to use for each variable assigned in the IWG file
    a. Assign pitch and roll offset from the selected data sources

   b. All QC flags set to zero until changed

6. Calculate extra parameters

   a. Mean Sea Level Altitude

      i. Calculated from GPS altitude using the geoid model EGM96 (Earth Gravitational Model 1996) provided open source via the Office of Geomatics. The Matlab script EGM96GEOID imports global geoid height in meters from the EGM96 geoid model. The data set is gridded at 15-minute intervals, but may be down-sampled if specified. The result is returned in the regular data grid N along with a referencing vector.

   b. WGS Altitude

      i. Calculates altitude above the ellipsoid based on the World Geodetic System 1984 (WGS-84). WGS-84 is an Earth-centered and Earth-fixed terrestrial reference system and geodetic datum, based on a consistent set of constants and model parameters that describe the Earth's size, shape, and gravity and geomagnetic fields (https://earth-info.nga.mil/).

   c. Pressure Altitude

      i. Calculated from US standard atmospheric tables, originally developed and adopted in 1976 by the United States Committee on Extension to the Standard Atmosphere. The tables can now be accessed online and implemented into software.

   d. Radar Altitude

      i. Calculated using GPS altitude and position with the digital terrain elevation data sets from the National Geospatial-Intelligence Agency (NGA). Resolution of terrain is 30 arc sec spacing

   e. Solar_Zenith

      i. Angle calculated using National Renewable Energy Laboratory's (NREL) solar position calculator

   f. Sun_Elev_AC

      i. Angle between sun and aircraft calculated using NREL's solar position calculator

   g. Sun_Az_Grd

      i. Azimuth angle to ground calculated using NREL's solar position calculator

   h. Sun_Az_AC

      i. Azimuth angle to aircraft calculated using NREL's solar position calculator

   i. Potential temperature

      i. The temperature of a parcel of air at pressure P_s if that parcel of air were adiabatically brought to a standard reference pressure P_0.

$$\theta = T\left(\frac{P_0}{P_s}\right)^{R/c_p} \quad (1)$$

1. T, absolute temperature [K]
2. R, gas constant of air [8.314 $JK^{-1}mol^{-1}$]
3. c_p, specific heat capacity of air at constant pressure [1.00 $kJkg^{-1}$]
4. P_0, reference pressure [1000 mb or 1000 hPa]

7. Create data flags
   a. Level Flight
      i. Condition met when the pressure derivative dP/dt halfwidth = 30
   b. Maneuvers
      i. Condition met when a threshold of unusual attitude is met

Table 1. Definitions and conditions of maneuvers flags.

Flag		Conditions
+ 4	Climb right turn	
+ 3	Climb straight	
+ 2	Climb left turn	
+ 1	Level flight right turn	Roll angle > 4 °
0	Straight and level flight	-0.15 < dP/dt < 0.15
- 1	Level flight left turn	Roll angle < - 4 °
- 2	Descent right turn	
- 3	Descent straight	
- 4	Descent left turn	

   c. Inlet Position
      i. Condition true when in-cabin aerosol instrumentation sample from the counterflow virtual impactor (CVI) inlet, false when sampling from the isokinetic (ISO) inlet
   d. Cloud Presence
      i. Condition true when a threshold of liquid water content is met
8. Write the file with IWG1 formatting
   a. Each data string is terminated by a carriage-return and line feed: \r\n
   b. Fields not supplied are assigned -9999, which means the measurements are not available.
   c. Custom parameters are added at the end of each string, campaign dependent. For example, flags were developed to mark aircraft attitude, inlet position (ISO or CVI), and cloud types

9. Quality Check IWG text file. See section 4.
10. ICARTT format the file via Matlab script ICARTT_main.m
    a. ICARTT is a specifically formatted text file uniform for all airborne atmospheric data sets
11. Manually check ICARTT IWG file

3.0 The Input Data

Multiple instrument-based data sets are collected to create the IWG file, but not all make it into the final product. The Instrument Class Names that identify these instruments at arm.gov, where you can find the entirety of these data sets, are in square brackets.

- Navigational Instrumentation
  - Trimble Differential Survey Module (DSM) 232 (DGPS) [NAV-AIR]
  - Systron Donner Inertial C-MIGITS III global positioning system (GPS) & Inertial Navigational System (INS) Tactical System [NAV-AIR]
  - Vector Nav VN-200 (GNSS/INS) [NAV-AIR]
  - TANS, Trimble Advanced Navigation Sensor (GPS) [NAV-AIR]
    - Retired 2015
  - AIMMS20 Aircraft-Integrated Meteorological Measurement System [MET-AIR]
  - Trimble BX992 (GPS/INS) [NAV-AIR]
    - New 2020
- Meteorological Instrumentation
  - AIMMS20 [MET-AIR]
  - General Eastern Chilled Mirror Hygrometer [CMH-AIR]
  - Rosemount 3144P and 3051 temperature and pressure measurements [GUSTPROBE-AIR]
  - MET file (meteorological data recorded from the data acquisition system on the aircraft, the M300 built by SEA)

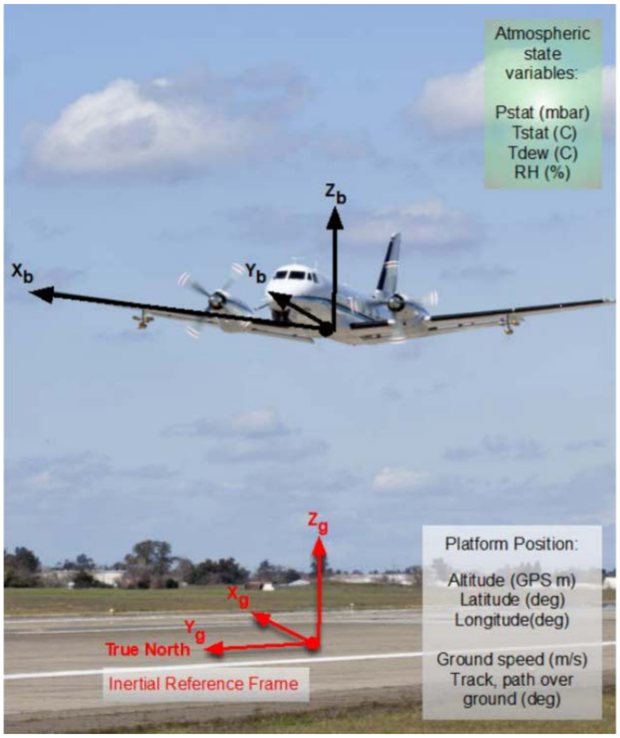

Figure 1. IWG1 definitions, aircraft frame of reference versus inertial (Earth).

Table 2. Primary and secondary instrumentation for each variable. *When flag selected, the Rosemount static temperature and AIMMS true airspeed are recalculated via an iterative process.

Variable	Primary Instrument	Secondary Instrument	Flag
Position and velocity	AIMMS	DGPS	
Altitude	AIMMS	GPS	
Static pressure	Rosemount	AIMMS	
Temperature	Rosemount	AIMMS	Flag*
Dewpoint temperature	CMH	AIMMS	
True airspeed	AIMMS		Flag
Wind speed	AIMMS		Flag
Wind direction	AIMMS		Flag
Vertical velocity	AIMMS		Flag

3.1 Flow Chart

The flow chart represents the process taken from data collection to publication. Boxes with the same color represent processes that happen simultaneously.

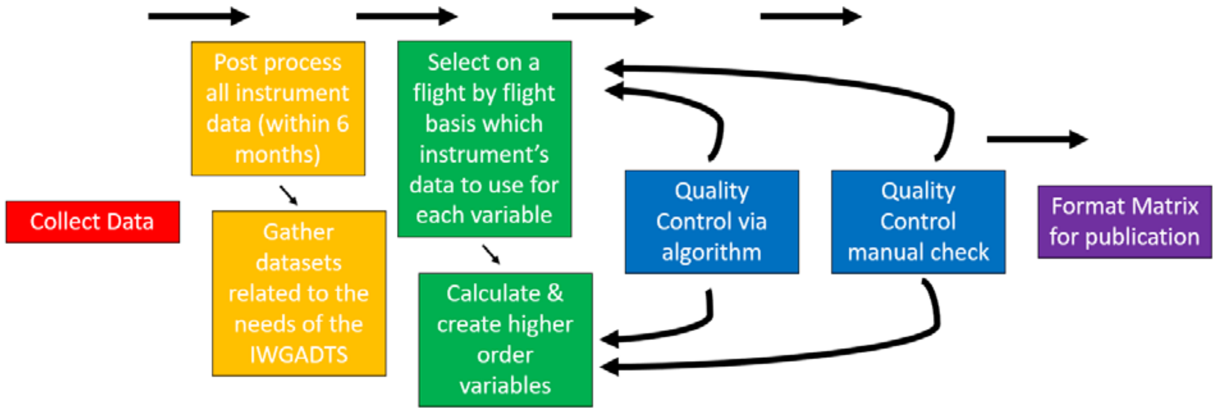

Figure 2. High-level data processing flow chart.

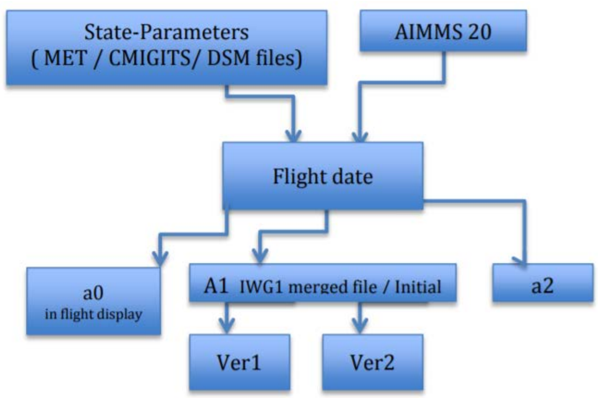

Figure 3. Detailed data processing flow chart.

- Level "a0" data consist of the output data from SEA M300 data acquisition. The file is only used in flight to disseminated information to instruments and provides visual display of aircraft location.
- Level "a1", Version1, data consist of aircraft state and meteorological parameters from different instruments consolidated into one file. The version 1 is typically used for testing flights. Level a1 data is available in 2 formats:
  - ascii file under the name: "YYYYMMDDs.IWG1.a1.ver1.txt". The file is comma delimited. It contains 2 lines of headers: IWGADTS variable short name and corresponding units.
  - IWGATS formatted files under the name: "aaf.iwg1001s.g1.camp_name.YYYYMMDDs.hhmmss.a1.txt". The name of the file reflects the version.
- Level "a1", Version 2, is produced during the campaign to include dilution corrections and may also reproduce after campaign to include other corrections. (i.e., instruments post-campaign calibrations.) The ascii file name will be "YYYYMMDDs.IWG1.a1.ver2.txt".
- Level a2 data set is the final version of IWG1 file. The name of the file reflects the version: "aaf.iwg1001s.g1.camp_name.YYYYMMDDs.a2.txt"

4.0 Output Data

4.1 Definitions and Diagrams

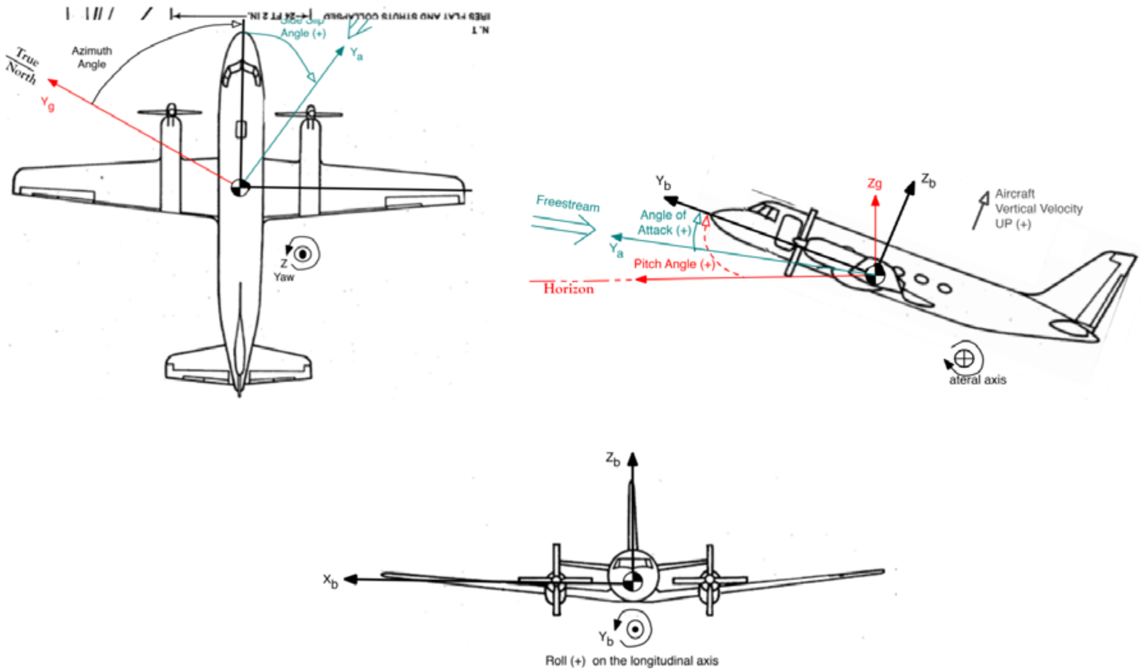

Figure 4. Aircraft reference frame and angles definitions: top, side, and front views.

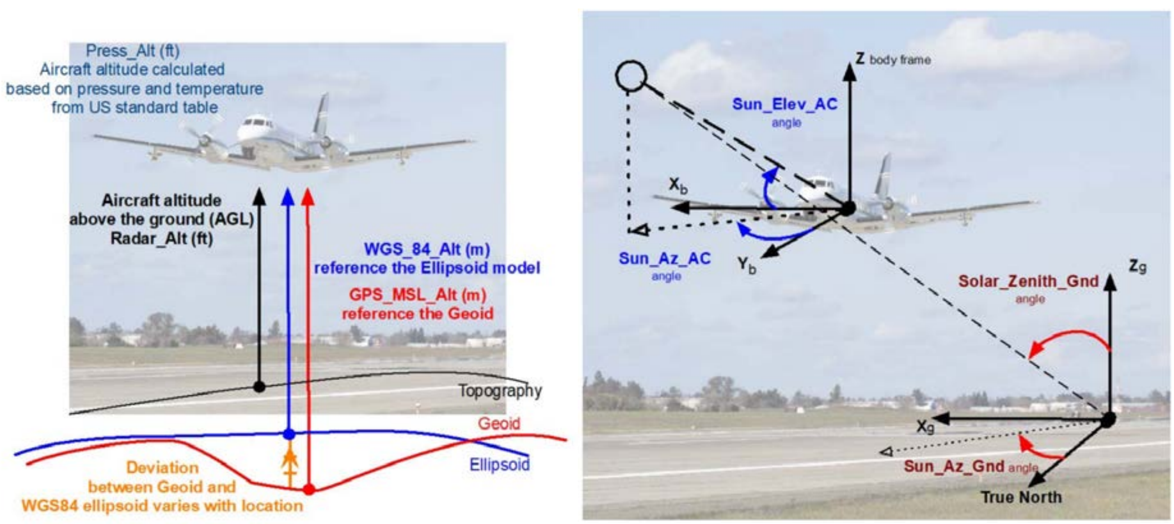

Figure 5. Altitude and sun angle definitions.

4.2 Quality Control Definitions

Table 3. Quality control definitions.

MSB index	*Variable short name*	*IWG1 list index*	*Issue*
1	Lat, Lon, WGS_84_Alt, Vert_Velocity	3, 4 6 13	Platform position and velocity from DSM (default instrument)
2	Radar_Alt	8	Calculated altitudes to be used with caution due to inaccuracy (precision is around 100m due to grid size of the DTED input files)
3	True_Airspeed	10	TAS flagged due to problem with AIMMS-20
4	True_Hdg, Pitch, Roll	14 17 18	Platform attitude from TANS (default instrument) or corrected with TANS offset due to known bias in pitch and roll of Aimms20 probe.
5	Side_Slip, Angle_of_Attack	19 20	Freestream direction to be used with caution due to sensor error or correction applied
6	Ambient_Temp, Total_Temp	21 23	Temperature from AIMMS-20 sensors or corrected due to known error
7	Dew_Point_Temp	22	Dew point temperature flagged due to problem with GE sensor
8	Static_Press	24	Static pressure from AIMMS-20 sensors instead of usual static source
9	Dynamic_Press	25	Dynamic Pressure to be used with Caution, problem with sensor
10	Cabin_Press	26	Known problem with cabin pressure sensor
11	Wind_Speed, Wind_Dir	27 28	AIMMS20 winds speed and direction to be used with caution
12	Vert_Wind_Spd	29	AIMMS20 Wind Vertical Velocity to be used with caution
13	Solar__Zenith_gnd, Sun_Az_Gnd	30 32	Solar angles to be used with caution
14	Sun__Elev_AC, Sun_Az_AC	31 33	Sun angles from the platform to be used with caution

4.3 Data Variables and Descriptions

Table 4. Data variables and descriptions.

Index	Variable Name	Units	Range or Frequency	From Instrument:	Accuracy	Description Definition
1	IWG1		1Hz			String identifier
2	Date / Time	UTC	YYYY-MM-DD hh:mm:ss	SEA M300 DAQ		Date and Time stamp in Iso8601 format. Synchronized daily with GPS external antenna or available zulu time.
3	Lat	Degrees	-90 to 90	Aimms-20 *(DSM)*	± 1 m *(±1 m)*	Platform latitude
4	Lon	Degrees	-180 to 179.99999	Aimms-20 *(DSM)*	± 1 m *(±1 m)*	Platform longitude
5	GPS_MSL_Alt	m	0 to 15 km	Calculated		Mean Sea Level altitude calculated from GPS altitude using the geoid model EGM96 worldwide 15-minute binary geoid height data from National Geospatial Intelligence Agency.
6	WGS_84_Alt	m	0 to 15 km	Aimms-20	*±5 m*	Altitude above the ellipsoid based on WSG-84.
7	Press_Alt	ft	0 to 11 km	Calculated		Calculated from US standard atmospheric tables.
8	Radar_Alt	ft	0 to 36,000 ft	Calculated		Calculated using GPS altitude and position with the Digital Terrain Elevation Data sets from NGA. Resolution of

						terrain is 30 arc sec spacing.
9	Gnd_Spd	ms^{-1}	0 to 150 ms^{-1}	Calculated		Platform speed over the ground. Calculated from Aimms20 measurements.
10	True_Airspeed	ms^{-1}	0 to 150 ms^{-1}	Aimms-20		Platform airspeed through the air (TAS). Compensated for non-standard pressure and temperature.
11	Indicated_ Airspeed	ms^{-1}	0 to 150 ms^{-1}	Aimms-20		Calculated based on the TAS and static temperature measured by Aimms-20.
12	Mach_Number	Dimension -less	0 to 1	Calculated		Aircraft Mach number Ma = TAS/speed of sound
13	Vert_Velocity	ms^{-1}		Aimms-20 *(DSM)*		Platform vertical velocity defined in the body frame. Positive is up.
14	True_Hdg	Degrees	0 to 359	Aimms-20 *(CMIGITS)*	*(0.3°)*	Platform direction with respect to **true north**. Angle between aircraft longitudinal axis and true north. Defined in the body frame.
15	Track	Degrees	0 to 359	Calculated		Platform path angle from the True North. Defined in the earth reference frame. Calculated from Aimms20 measurements.
16	Drift angle	Degrees	-45 to 45	Calculated		The angle between the heading of aircraft and the track
17	Pitch	Degrees	-90 to 90	Aimms-20 *(CMIGITS)*	*(0.25°)*	Angle between the aircraft longitudinal axis and the horizon. Defined in the body
18	Roll	Degrees	-90 to 90	Aimms-20 *(CMIGITS)*	*(0.5°)*	Angle between the aircraft vertical and lateral axis. Defined in the body frame. Positive is right wing down.

19	Side_Slip	Degrees	-90 to 90	Calculated		Derived from Aimms-20 differential pressures. Angle between the longitudinal axis and relative wind or flight path.
20	Angle_of_Attack	Degrees	-90 to 90	Calculated		Derived from Aimms-20 differential pressures. Angle between the aircraft longitudinal axis and relative wind or flight path.
21	Ambient_Temp	Celsius	-50 to 50 *(-20 to 50)*	G-1 Rosemount 102E *(Aimms-20)*	± 0.5C *(± 0.1C)*	Air temperature also called static temperature or OAT.
22	Dew_Point_Temp	Celsius	-75 to 50	G-1 General Eastern 1011-B	± 0.5C	Dew point temperature
23	Total_Temp	Celsius	-50 to 50 *(-20 to 50)*	G-1 Rosemount 102E *(Aimms-20)*	± 0.5C *(± 0.1C)*	Total temperature
24	Static_Press	mbar	400 to 1060 *(0 to 1100)*	G-1 Rosemount 1201F1 *(Aimms-20)*	3mb *(1mb)*	Static pressure
25	Dynamic_Press	mbar	0 to 140	Gust Probe (Aimms-20)	0.2mb	Dynamic pressure
26	Cabin_Press	mbar		G-1 Setra		Cabin pressure
27	Wind_Speed	ms^{-1}		Aimms-20		Wind speed. Defined in the earth frame at altitude Zg.
28	Wind_Dir	Degrees	0 to 359	Aimms-20		Wind direction (from). Angle is with respect to True North in the earth frame at altitude Zg.
29	Vert_Wind_Spd	ms^{-1}		Aimms-20		Vertical Wind speed in the earth frame at altitude Zg. Up is positive.
30	Solar_Zenith_Gnd	Degrees	0 to 90	Calculated		Calculated using Matlab script running equations derived from NREL technical report TP560-34302. Defined in the earth reference frame with respect to vertical.
31	Sun_Elev_AC	Degrees	0 to 90	Calculated		Calculated NREL/TP560-34302 Defined in the body frame.

32	Sun_Az_Gnd	Degrees	0 to 359	Calculated		Calculated NREL/TP560-34302 Defined in the earth reference frame with respect to True North.
33	Sun_Az_AC	Degrees	0 to 359	Calculated		Calculated NREL/TP560-34302 Defined in the body frame.
34	Flag_qc	Dimension less	Integer value 0 to 127	Binary flag		Quality check flag. When positive indicates secondary instrument was used or some data must be used with caution. See table below.
35	Flag_ac	Dimension less	- 4 to + 4	Integer flag		Maneuver flag (level, climb, etc...) See table below.
36	Flag_cloud	Dimension less	0 or 1	Integer flag		See table below 0 = Clear (no cloud) 1 = Cloud
37	RH_water	Percent	0 to 100	Calculated		Calculation is based on Goff–Gratch (1946) equation
38	RH_ice	Percent	0 to 100	Calculated		Calculation is based on Goff–Gratch (1946) equation over ice
39	Theta	Celsius		Calculated		Calculated from ambient temperature and pressure.
40	Cabin_Temp	Celsius		G-1 Setra		Temperature sensor located on the first rack in G1.
41	Leg_num	Dimension less	1-20	Integer		Calculated based on altitudes

Table 5. Flags present in TCAP IWg1 file.

34	Flag_qc	Dimension less	Integer value 0 to 127	Binary flag		Quality check flag. When positive indicates secondary instrument was used or some data must be used with caution. See table below.
35	Flag_ac	Dimension less	- 4 to + 4	Integer flag		Maneuver flag (level, climb, etc...) See table below.
36	Flag_inlet	Volts	0 or 3	Integer flag		Inlet selection flag for SPLATT 0 = IsoK inlet 3 = PCVI output
37	Flag_in_cloud	Dimension less	0 or 1	Integer flag		See table below 1 = in cloud 0 = no cloud
38	Flag_cloud_phase	Dimension less				1 = Ice cloud 2 = Liquid cloud 3 = Mixed cloud

5.0 Summary

The IWG1 file is useful for any investigation using aircraft data. It provides the highest-quality navigational and meteorological data collected from each campaign, ensures proper time alignment, and includes extra calculated parameters and data flags to aid analysis.

6.0 References

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