Background: *Cloud Absorption Radiometer (CAR)*

The NASA/ Goddard Space Flight Center (GSFC) Cloud Absorption Radiometer (CAR) instrument is an airborne multi-wavelength scanning radiometer that measures scattered light in fourteen spectral bands between 0.34 and 2.30 µm, located in the atmospheric window regions of the UV, visible, and near-infrared. One of the strengths of this instrument is its unique ability to measure, almost simultaneously, both downwelling and upwelling radiance at 14 narrow spectral bands (see Table 1).

As the CAR scan mirror rotates 360° in a plane perpendicular to the direction of flight, data (60 MB/hr) are collected through a 190° aperture that allows observations of the earth-atmosphere scene around the starboard horizon from local zenith to nadir. This unique viewing geometry, makes it most suitable for measuring surface bidirectional reflectance-distribution function (BRDF) even under low sun conditions with a better accuracy than any other known airborne sensor. Data are acquired at a high angular (1°) and spatial (better than 10 m at nadir, assuming 600 m altitude) resolution, coupled with a high signal-to-noise ratio.

During operations, CAR is stabilized by an independent system (CAR Autonomous Navigation System, CANS) that corrects the sensor with respect to aircraft roll in real time based upon inputs from a precision navigation sensor. This stabilization ensures that the resulting data and imagery are clear and require little to no post-processing for correction due to aircraft motion. Radiometric calibration of the CAR is performed at GSFC.

The CAR instrument has made important contributions to multi-angle remote sensing. To complement the DISCOVER-AQ instrument suite, CAR will provide surface BRDF and spectral albedo. This instrument will enable various types of studies that will reveal surface properties at unprecedented scales, but more importantly, these data will help resolve the effect of land surface reflectance directional effects on aerosol optical depth (AOD) retrieval from satellite (e.g. MODIS, MISR, VIIRS and the newly operational Geostationary Trace gas and Aerosol Sensor Optimization (GEO-TASO)) and ground-based sensors such as AErosol RObotic NETwork (AERONET). AOD retrieval is very sensitive to surface BRDF, especially over dark surfaces (e.g. forested areas in Colorado). Some studies have shown that an uncertainty in the surface albedo of 1% can translate in some cases to an AOD error of 0.2. Trace gas retrievals from satellite measurements are also very sensitive to surface BRDF.

More information on the CAR project: http://car.gsfc.nasa.gov/ or contact Charles Gatebe, Email: Charles.k.gatebe@nasa.gov, Tel: +1-301-614-6228

Table 1: CAR Band Configurations/30-year Period

Band Index	Central Wavelength[bandpass] nm			
	1984-1993	1994-1998	1999-2011	2014
1	502 [16]	472 [21]	472 [21]	480[21]
2	673 [20]	675 [20]	682 [22]	687 [26]
3	754 [19]	300 []	340 [9]	340[9]
			381 [6]	381[6]
4	866 [20]	868 [20]	870 [20]	870 [10]
5	1031 [20]	1038 [20]	1036 [22]	1028 [4]
6	1220 [22]	1271 [22]	1219 [22]	609 [9]
7	1270 [21]	1219 [21]	1273 [23]	1275[24]
8	1547 [30]	1552 [30]	1556 [32]	1554 [33]
9	1640 [41]	1643 [41]	1656 [45]	1644 [46]
10	1722 [38]	1725 [38]	1737 [40]	1713 [46]
11	2100 [39]	2100 [39]	2103 [44]	2116[43]
12	2200 [40]	2207 [40]	2205 [42]	2203[43]
13	2289 [23]	2302 [23]	2302 [43]	2324 [48]]

Data:

CAR data are stored and distributed as Hierarchical Data Format (HDF), which is the standard data storage format selected by the NASA Earth Observing System Data and Information System (EOSDIS). HDF is developed and maintained by the National Center for Supercomputing Applications (NCSA) at the University of Illinois at Urbana-Champaign (http://ncsa.uiuc.edu).

The advantage of using HDF allows sharing of self-describing files across different platforms (portable) such that a DEC ALPHA machine can read an HDF file generated on a Silicon Graphics machine — where ordinarily the byte ordering of binary files would need to be considered. The HDF library functions take care of such details. It also implies that a data set, such as a multi-dimensional array of numbers, can have additional metadata logically associated with it that describe things such as the rank of the array, number of elements in each dimension, etc.

HDF is based on the principles of object-oriented programming, where multidimensional arrays, tables and images can be stored in the same file and viewed as discrete objects, rather than a continuous stream of bits. Users interact with these objects only through calls to an HDF library and therefore knowledge of object-oriented programming and of the physical layout of the files is unnecessary. What's most important is for the user to understand the content of the file being accessed in terms of the various HDF data object types.

We adopted the EOSDIS data processing levels, but modified them to suit the CAR data needs (http://science.nasa.gov/earth-science/earth-science-data/data-processing-levels-for-eosdis-data-products/)

Data level	Description
Level-0	Refers to instrument and aircraft data at full resolution combined into one file and stored as digital numbers from 1-65,536. The level-0 also contains communication headers and any communication artifacts.
Level-1A	In level-1A processing, the Level-0 data are separated out into four data types: header data (include aircraft navigation data such as roll, pitch, heading, altitude, latitude, and longitude), science data (10 channels; the 10th channel is reserved for future use), dark current, and engineering (e.g. instrument status info, temp data for detectors and optics, etc). Data is at full resolution, time-referenced, and information on radiometric calibration coefficients appended but not applied. Quicklook RGB images (at single wavelength or using three different wavelengths) are generated to help with the review of data qualitatively.
Level-1B	In level-1B processing, final radiometric calibration coefficients are applied to Level 1A data for conversion to sensor radiance units by the user. Data for each scan line is also georeferenced using parameters such as aircraft pitch, roll, and heading. Each scan line contains 382 pixels (representing a 190° field of regard).
Level-1C	In Level-1C processing, georeferencing parameters are applied to Level 1B data for each scan line. Each scan line contains 361 pixels (representing a

	180° field of regard). CAR data is expanded into 14 two- dimensional arrays and engineering data is excluded. Global attributes are kept to a minimum.
Level-1D	In Level-1D processing, we extract the data collected during the CAR circular flight tracks during the BRDF measurements for each circle. This is the data that we typically refer to as BRDF measurements.
Level-2	Derived geophysical variables at the same resolution and location as Level 1 source data.
Level-3	Variables mapped on uniform space-time grid scales, usually with some completeness and consistency.
Level-4	Model output or results from analyses of lower-level data (e.g., variables derived from multiple measurements).

Next section describes CAR data object types for CAR Level-1 products. Note that higher data levels are not currently available.

Scientific Data Sets (SDSs)

The CAR HDF Data Objects used in Level 1 files uses data objects that are supported by HDF to store science, calibration data and associated metadata, which describe the scope and quality of science data.

These objects contain multidimensional arrays, used to store scientific data. For example, Level 1C employs SDSs to store calibrated science data and any information on the quality assurance data. The SDSs are made self-describing through a set of attributes — data that may be considered "attached" to the SDS. Table 1 below shows various components of an SDS Array. The required components are shown on the second column, and the optional components are shown on the third column.

Table 1: SDS Arrays contains both “Required Attributes” and “Optional Attributes”

	Required Attributes	*Optional Attributes*
SDS Array	*Name*	*Predefined attributes, e.g. label, fill values, etc.*
	Data type (in16, float32, etc.)	User defined attributes
	Dimension	*Dimension, scale*

So the *Required Attributes* needed to provide the minimum information to allow an HDF library to identify the SDS, and organize the data into an array having the correct dimensions and data type are:

- **Name:** A string that defines the name of the SDS and uniquely identifies it.

- **Data Type:** Type of data (e.g., float 32, int 16, etc.) that defines how the data in the array are stored.
- **Dimensions:** The number of dimensions, or rank, of the array.

All other attributes are *optional* attributes. For example,

- **Predefined attributes**, can include:
  - **Labels** for all dimensions and for the data
  - **Units** for all dimensions and for the data
  - A **range** specifying maximum and minimum values for the data set.
  - A **fill value** for representing missing data in a data set.
  - A **coordinate system** to use when interpreting or displaying the data

- **User defined attributes:** can use this feature to define dedicated calibration scale and offset parameters for the calibrated products.

- **Dimension scales:** Scales to be used along the different dimensions when interpreting and displaying the data

DISCOVER-AQ CAR DATA

Data collected during the DISCOVER-AQ/Colorado mission is arranged by flight, where each flight is defined by: aircraft takeoff to aircraft landing. Data collected during each flight has a name in the form:

dataID_platform_measDate_revision_comments.extension

The dataID is "discoveraq-car", platform is "p3b", and extension is "hdf". Comments would be the place for additional information about the file, such as product level, processing date, and unique identifier. The revision should be "R#", where # corresponds to the number of times data has been revised for the particular file or data product. So all CAR Level-1C data files names for the DISCOVER-AQ/Colorado mission looks like this:

"discoveraq-car_p3b_20140708_R0_2037-Level1C-20150613.hdf"

Where "2037" is a 4-digit number (based on historical CAR data records) and is unique to each flight. The first calendar date (yyyymmdd: year, month and day) is when the data was acquired and the second calendar date is when data was processed or last updated (yyyymmdd).

Likewise, all CAR Level-1D data files names for the DISCOVER-AQ/Colorado mission looks like this:

"discoveraq-car_p3b_201407221451_R0_2042-Level1D-20150815.hdf"

Where "2042" is a 4-digit number (based on historical CAR data records) and is unique to each flight. The first calendar date (yyyymmddhhmm: year, month, day, hour and minutes) is when the data was acquired including the start time of BRDF measurements, and the second calendar date is when data was processed or last updated (yyymmdd).

CAR quicklook images for the DISCOVER-AQ/Colorado mission can be found at:

http://car.gsfc.nasa.gov/data/index.php?mis_id=15&n=Discover%20AQ&l=h

Each HDF data file contains calibrated Earth and/or sky view observations for CAR bands 1-9, where the 9th band is selected among the filter wheel (see Table 1, bands 9-14). Data contains:

* Global Attributes: General information about the flight and the data set

* Dimensions: Denote the size of the arrays, and

* Arrays and their Attributes: Physical data parameters as a function of time. Attributes describe each array.

Data conversion (from radiance to reflectance)

The radiance data can be converted to reflectance following van de Hulst [H. C. van de Hulst, Multiple Light Scattering, Tables, Formulas, and Applications, vol. 1., San Diego, CA: Academic, 1980] formulation:

$$R_\lambda(\theta, \theta_0, \Phi) = \pi I_\lambda (\theta, \theta_0, \Phi)/ \mu_0 F_\lambda$$

where I_λ is the measured reflected or scattered intensity (radiance), F_λ is the solar flux density (irradiance) incident on the top of the atmosphere, assuming mean-earth distance, θ and θ_0 are the viewing and incident zenith angles, respectively, Φ is the azimuthal angle between the viewing and incident light directions, and $\mu_0 = \cos \theta_0$. The viewing directions range from 0 –180°. The relative azimuth angles range from 0-360°, where 0° or 360° or 180° coincide with the solar principal plane. To convert the reflectance data to BRDF (bidirectional reflectance distribution function) as defined by Nicodemus et al. (F. E. Nicodemus, J. C. Richmond, J. J. Hsia, I. W. Ginsburg, and T. Limperis, "Geometrical considerations and nomenclature for reflectance," Nat. Bureau Standards, Washington, DC, NBS Monograph 160, 1977), divide $R_\lambda (\theta, \theta_0, \Phi)$ by pi (π).

Level-1C and Level-1D contain SDSs for each of the variables defined above. Also, Level-1D is converted into reflectance units.

Note 1: data for the new Chappuis band at 609 nm looks noisier than for the other bands. This is because of low SNR caused by low optical throughput in the channel and a relatively narrow bandwidth (~9 nm). But the band seems to track the other channels pretty well.

Note 2: All bands saturate when looking at the solar disk. We have not yet developed a good way to identify and flag the saturated pixels; we hope to do so in future. For now, measurements close to the sun should be assumed to be saturated in all bands. For similar reasons, measurements over very bright clouds or sunglint saturate several bands in the visible (472 nm, 682 nm) and NIR (872 nm).

References:

1. Gatebe, C.K., King, M.D., Platnick, S., Arnold, G.T., Vermote, E.F., Schmid, B., 2003. Airborne spectral measurements of surface-atmosphere anisotropy for several surfaces and ecosystems over southern Africa. J. Geophys. Res. 108, 8489. doi:10.1029/2002JD002397.

2. King, M.D., Strange, M.G., Leone, P., Blaine, L.R., 1986. Multiwavelength scanning radiometer for airborne measurements of scattered radiation within clouds. J. Atmos. Oceanic Technol. 3, 513-522.

CAR Data Level-1B HDF Variables (example)

1. Navigation:

float CoordinatedUniversalTime(time) ;

CoordinatedUniversalTime:time_format = "HHMMSS.10thSecond" ;

float AircraftLatitude(time) ;

float AircraftLongitude(time) ;

float AircraftAltitude(time) ;

float AircraftHeading(time) ;

float AircraftPitch(time) ;

float AircraftRoll(time) ;

2. Engineering:

byte ViewingMode(time) ;

long ScanLineCounter(time) ;

byte DoorOpenStatus(time) ;

byte DwellMode(time) ;

byte DwellValue(time) ;

byte FilterWheelPosition(time) ;

byte FilterWheelChannel(time) ;

byte MirrorHeaterStatus(time) ;

short ScanMirrorCondensation(time) ;

short Detector7Temperature(time) ;

short Detector8Temperature(time) ;

short Optics1Temperature(time) ;

short Optics2Temperature(time) ;

short BasePlateTemperature(time) ;

short TelescopeTemperature(time) ;

short CryogenicCoolerTemperature(time) ;

short AmplifierVoltageOffset(time, NUMBER_OF_DATA_PORTS) ;

3. CAR Data:

float CentralWavelength(NUMBER_OF_SPECTRAL_CHANNELS) ;

float ScanAngle1(time) ;

short Darkcurrent(time, NUMBER_OF_DATA_PORTS) ;

short CalibratedData(time, NUMBER_OF_DATA_PORTS, NUMBER_OF_PIXELS) ;

4. Auxilliary Data:

float SolarIrradiance(NUMBER_OF_SPECTRAL_CHANNELS) ;

float SolarZenithAngle(time) ;

float SolarAzimuthAngle(time) ;

HDF Global Attributes:

:Title = "Cloud Absorption Radiometer Level-1B HDF data" ;

:FlightNumber = 2042s ;

:ExperimentName = "DISCOVER-AQ" ;

:FlightDate = "July 22, 2014" ;

:CarOperator = "Charles Gatebe" ;

:FlightSummary = "BRDF over six D-AQ spiral sites in Colorado" ;

:CreationDate = "July 22 2014 19:00:00" ;

:CreateBy = "Rajesh Poudyal (rajesh.poudyal@nasa.gov);

:SoftwareVersion = "1.0 (C++ programming language)" ;

:DataSystemVersion = 0s ;

:CalibrationVersion = 1.f ;

:CarViewingConfiguration = "starboard and BRDF" ;

:JulianDay = 203s ;

:LocalTimeZone = -6s ;

:Credits = "NASA Goddard Space Flight Center: Code 613 " ;

:data_set = "Cloud Absorption Radiometer Level-1B HDF Data" ;

:data_product = "Flight Track" ;

:science_project = "NASA/GSFC Cloud Retrieval Group" ;

:sensor = "Cloud Absorption Radiometer" ;

:platform = "NASA P-3B" ;

:platform_type = "Research Aircraft" ;

:primary_navigation_system = "CANS – CAR Autonomous Navigation System" ;

:parameter_general = "Calibrated Radiance and Navigation Data" ;

:parameter_specific = "CAR Angular Distributed Radiances" ;

:geog_flag = "c" ;

:day_night_flag = "d" ;

:lon_min = xx.xxxxxf ;

:lon_max = xx.xxxxxf ;

:lat_min = xx.xxxxf ;

:lat_max = xx.xxxxxxf;

CAR Data Level-1C HDF Variables (example)

1. Navigation:

float CoordinatedUniversalTime(time) ;

CoordinatedUniversalTime:time_format = "HHMMSS.10thSecond" ;

float AircraftLatitude(time) ;

float AircraftLongitude(time) ;

float GPSAltitude(time) ;

float AircraftHeading(time) ;

float AircraftPitch(time) ;

2. Engineering:

Int ScanLineCounter(time);

3. CAR Data:

float lambda_340nm(time, number of Pixels);

float lambda_380nm(time, number of Pixels);

float lambda_470nm(time, number of Pixels);

float lambda_680nm(time, number of Pixels);

float lambda_870nm(time, number of Pixels);

float lambda_1037nm(time, number of Pixels);

float lambda_610nm(time, number of Pixels);

float lambda_1275nm(time, number of Pixels);

float lambda_1564nm(time, number of Pixels);

float lambda_1657nm(time, number of Pixels);

float lambda_1738nm(time, number of Pixels);

float lambda_2105nm(time, number of Pixels);

float lambda_2202nm(time, number of Pixels);

float lambda_2303nm(time, number of Pixels);

4. Auxilliary Data:

float SolarIrradiance(NUMBER_OF_SPECTRAL_CHANNELS) ;

float SolarZenithAngle(time) ;

float SolarAzimuthAngle(time) ;

float CentralWavelength(NUMBER_OF_SPECTRAL_CHANNELS) ;

float SpectralWavelength(NUMBER_OF_SPECTRAL_CHANNELS); Spectral Response Function

HDF Global Attributes:

:Version = "CAR Level-1C product" ;

:Data Process Date = “July 13, 2015”

:ExperimentName = "DISCOVER-AQ" ;

:Instrument PI = "Charles K.Gatebe" ;

:email = Charles.k.gatebe@nasa.gov

:website = http://car.gsfc.nasa.gov

CAR Data Level-1D HDF Variables (example)

1. Navigation:

float CoordinatedUniversalTime(time) ;

CoordinatedUniversalTime:time_format = "HHMMSS.10thSecond" ; [361]

float AircraftLatitude(time) ; [361]

float AircraftLongitude(time) ; [361]

float GPSAltitude(time) ; [361]

float AircraftHeading(time); [361]

float AircraftPitch(time) ; [361]

2. Engineering:

Not Applicable;

3. CAR Data:

float lambda_340nm(time, number of Pixels);

float lambda_380nm(time, number of Pixels);

float lambda_470nm(time, number of Pixels);

float lambda_680nm(time, number of Pixels);

float lambda_870nm(time, number of Pixels);

float lambda_1037nm(time, number of Pixels);

float lambda_610nm(time, number of Pixels);

float lambda_1275nm(time, number of Pixels);

Below, only one of the filter wheel data is available for each circle.

float lambda_1564nm(time, number of Pixels);

float lambda_1657nm(time, number of Pixels);

float lambda_1738nm(time, number of Pixels);

float lambda_2105nm(time, number of Pixels);

float lambda_2202nm(time, number of Pixels);

float lambda_2303nm(time, number of Pixels);

4. Auxilliary Data:

float SolarIrradiance(NUMBER_OF_SPECTRAL_CHANNELS) ;

float SolarZenithAngle(time) ; [361]

float SolarAzimuthAngle(time) ; [361]

float CentralWavelength(NUMBER_OF_SPECTRAL_CHANNELS) ; [9]

float SpectralWavelength(NUMBER_OF_SPECTRAL_CHANNELS); Spectral Response Function

HDF Global Attributes:

:Version = "CAR Level-1C product" ;

:Data Process Date = "August 15, 2015"

:ExperimentName = "DISCOVER-AQ" ;

:Instrument PI = "Charles K.Gatebe" ;

:email = Charles.k.gatebe@nasa.gov

:website = http://car.gsfc.nasa.gov