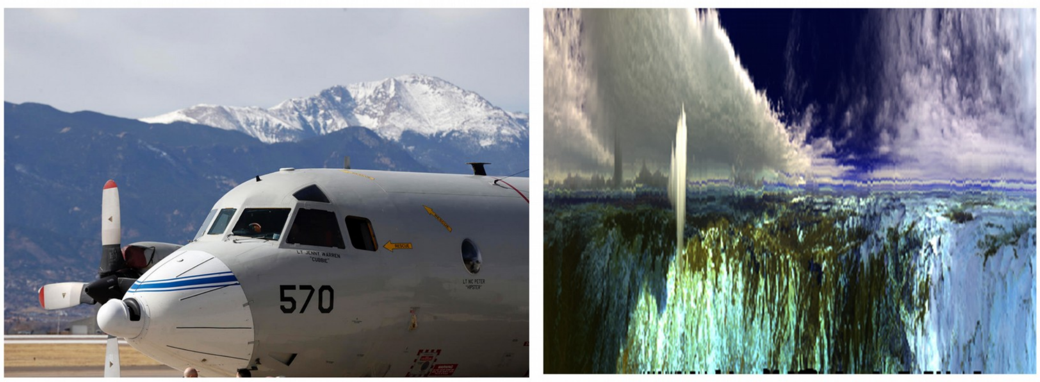
Background: *Cloud Absorption Radiometer (CAR)*

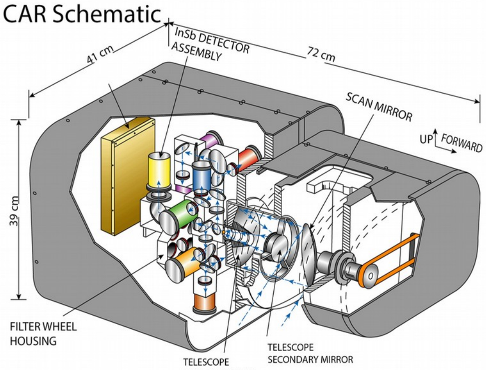
The NASA Goddard Space Flight Center (GSFC) Cloud Absorption Radiometer (CAR) instrument was flown aboard the Naval Research Lab (NRL) P-3 Orion research aircraft during SnowEx Field Campaign (February 6-25). CAR is a multi-wavelength scanning radiometer that measures scattered light in fourteen spectral bands between 0.34 and 2.30 µm, located in the atmospheric window regions of the UV, visible, and near-infrared (cf. Table 1). One of the strengths of this instrument is its unique ability to measure, almost simultaneously, both downwelling and upwelling radiance at nine narrow spectral bands simultaneously. And provides observations of the earth-atmosphere scenes as shown in Figure 1-b.

a) NRL P3 with CAR on nose cone

b) CAR quicklook image from SnowEx campaign



c) CAR Schematic



d) Cloud Absorption Radiometer (CAR) Specifications

Angular Scan Range	**190˚**
Instantaneous field of view	**17.5 mrad (I˚)**
Pixel per scan line	**382**
Scan rate	**1.67 lines per second (100 rpm)**
Spectral channels (µm):	**14 (8 continuously sampled and last six in filter wheel)**
bandwidth (FWHM)	**0.339(11), 0.380(11), 474(21), 687(27), 870(13) 1029(11), 1229(23), 1266(21), 1557(33), 1638(45), 1723(46), 2094(44), 2188(35), 2323(47)**

Fig. 1: (a). The NRL P-3B at Colorado Springs, Colorado, USA in February 2017 during the SnowEx field experiment. (b) CAR quicklook image over Grand Mesa showing the white snow on the surface and cloudy and the clear sky. The 190° aperture allows observations of the earth-atmosphere scene around the starboard horizon from local zenith to nadir. (c) Schematic illustration of NASA's Cloud Absorption Radiometer (CAR), which is mounted in the nose of the NRL P-3B aircraft.(d) Specifications for the CAR, which contains 14 narrow spectral bands between 0.34 and 2.30 µm.

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. 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.

The scan mirror, rotating at 100 rpm, directs the light into a Dall-Kirkham telescope where the beam is split into nine paths. Eight light beams pass through beam splitters, dichroics, and lenses to individual detectors (0.34 - 1.27 µm), and finally are registered by eight data channels. They are sampled simultaneously and continuously. The ninth beam passes through a spinning filter wheel to a Stirling cycle cooler. Signals registered by the ninth data channel are selected from among six spectral bands (1.55 - 2.30 µm). The filter wheel can either cycle through all six spectral bands at a prescribed interval (usually changing filters every fifth scan line), or lock onto any one of the six spectral bands and sample it continuously.

During the 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. During SnowEx, the CAR obtained BRDF measurements of snow covered forests for a variety of conditions including the snow grain size or age, snow liquid water content, solar zenith angle, cloud cover, and snowpack thickness at Grand Mesa, Colorado – one of the largest flat-topped mountain in the world and Senator Beck. To measure the BRDF of the surface–atmosphere system, the NRL-3 banked at a roll angle of about 20° and flew circles about 3 km in diameter above the surface, taking approximately 2 min (assuming an altitude of 600 m above the ground). Multiple circular orbits were acquired over selected surfaces, at different altitudes. The primary target sites for this experiment were the Met towers at Grand Mesa and Senator (Skyway (39.05074° N, 108.06143°W), LSOS (39.05225°N, 108.09792°W), West tower (39.03388°N, 108.21399°W), Eastern tower (39.10374°N, 107.88448°W), Middle tower (39.03954°N, 107.94174°W) and Senator Beck Basin (37.90689°N, 107.72628°W)).

This unique CAR dataset will help to assess the accuracy of snow-covered reflectance and albedo products from satellite measurements for forested landscapes.

More information on the CAR project: https://car.gsfc.nasa.gov/ or contact Charles Gatebe, Email: Charles.k.gatebe@nasa.gov

Table 1: CAR Band Configurations/30-year Period

Band Index	Central Wavelength[bandpass] nm				
	1984-1993	1994-1998	1999-2011	2014	2017
1	502 [16]	472 [21]	472 [21]	480[21]	474 [21]
2	673 [20]	675 [20]	682 [22]	687 [26]	687 [27]
3	754 [19]	300 []	340 [9]	340[9]	339 [11]
			381 [6]	381[6]	380 [11]
4	866 [20]	868 [20]	870 [20]	870 [10]	870 [13]
5	1031 [20]	1038 [20]	1036 [22]	1028 [4]	1029 [11]
6	1220 [22]	1271 [22]	1219 [22]	609 [9]	1229 [23]
7	1270 [21]	1219 [21]	1273 [23]	1275[24]	1266 [21]
8	1547 [30]	1552 [30]	1556 [32]	1554 [33]	1557 [33]
9	1640 [41]	1643 [41]	1656 [45]	1644 [46]	1638 [45]
10	1722 [38]	1725 [38]	1737 [40]	1713 [46]	1723 [46]
11	2100 [39]	2100 [39]	2103 [44]	2116[43]	2094 [44]
12	2200 [40]	2207 [40]	2205 [42]	2203[43]	2188 [35]
13	2289 [23]	2302 [23]	2302 [43]	2324 [48]	2323 [47]

Data:

CAR data are stored and distributed as NetCDF, which is the standard data storage format selected by the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC).

NetCDF allows sharing of self-describing files across different platforms (portable). This implies that the dataset is described by a multi-dimensional array of numbers and has additional metadata logically associated with it that describe things such as the rank of the array, number of elements in each dimension, etc. 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 NetCDF 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 NetCDF 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 sections describe CAR data object types for CAR Level-1 products. Note that higher data levels are not currently available.

Scientific Data Sets (SDSs)

The CAR NetCDF Data Objects used in Level 1 files uses data objects that are supported by NetCDF 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

CAR File Format

Data collected during the SnowEx 2017 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

Which is identified by CAR's campaign name and the flight ID. For example, the dataID for SnowEx is "SnowEx-CAR", platform is "p3b", and data format is given by an extension "nc" – which stands for NetCDF. 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 data files names for the SnowEx 2017 mission looks like this:

"snowex-car_p3b_20170216_R1_2063_Level1C_20170504.nc"

Where "2063" is a 4-digit number (based on historical CAR data records) and is unique to each flight. The first calendar date (yyymmdd: year, month and day) is when the data was acquired and the second calendar date is when data was processed or last updated (yyymmdd).

It is highly recommended if no grouping is necessary for the format to be NetCDF-4 classic, where the file structure will be a single level.

CAR quicklook images for the SnowEx mission can be found at:

https://car.gsfc.nasa.gov/missions/snowex

Each NetCDF 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).

Dataset Metadata Attributes

NASA GES DISC suggests all the data with supporting metadata follow the Climate Forecast (CF) conventions in order to provide a clear and unambiguous description of climate forecast model output as well as observational earth science data and derived products. Therefore, it is critical to identify the conventions.

The other important section of the file attributes is to describe the file contents. These attributes may include a title to describe what is in the dataset, the institute to specify where the original data was produced, the source to indicate the method of production of the original data which could be a model with its version or the observational method, the history to provide an audit trail for modifications to the original data, the references (published or web- based) to describe the data and methods used to generate the data, and the comment about the data.

In order to make the data efficiently searchable, GES DISC recommended the time stamps and spatial information be included in the metadata attributes.

Table 1: CAR L1C Dataset Metadata Attributes

Attribute Titles	**Attribute Contents**
Experiment_Name	"SnowEx "
Instrument_PI	"Charles K. Gatebe"
Email	"Charles.K.Gatebe@nasa.gov"
Website	“https://car.gsfc.nasa.gov"

Dimension Definitions:The followings are the 31 dimensions defined in the CAR's L1C data file.

Scans = ;Angles = ;channels = ; SpectralResponseFunction_ch1 =; SRF_ch1 = ; SpectralResponseFunction_ch2 =; SRF_ch2 = ; SpectralResponseFunction_ch3 =; SRF_ch3 = ; SpectralResponseFunction_ch4 =; SRF_ch4 = ; SpectralResponseFunction_ch5 =; SRF_ch5 = ; SpectralResponseFunction_ch6 =; SRF_ch6 = ; SpectralResponseFunction_ch7 =; SRF_ch7 = ; SpectralResponseFunction_ch8 =; SRF_ch8 = ; SpectralResponseFunction_ch9 =; SRF_ch9 = ; SpectralResponseFunction_ch10 = ; SRF_ch10 = ; SpectralResponseFunction_ch11 = ; SRF_ch11 = ; SpectralResponseFunction_ch12 = ;

SRF_ch12 = ; SpectralResponseFunction_ch13 = ; SRF_ch13 = ; SpectralResponseFunction_ch14 = ; SRF_ch14 = ;

1. Note that "PixelViewingZenith" and/or "PixelViewingAzimuth" provide the coordinates for the "Angles" dimension, where their "long_name" attribute specify the definitions of the angles.2. The "SpectralResponseFunction_chXX" are variables using "SRF_chXX" dimensions. To be able to interpret the "SpectralResponseFunction_chXX", we used "SRF_chXX" as variables using the same "SRF_chXX" dimensions (the dimension and variable names are the same here), where the variable values define bandwidth, sample intervals, etc.

Variables and Metadata

The following tables provide a list of all the variables with their metadata in CAR's L1C and L1D products.

Table 3: CAR's L1C Data Variable Definitions and GES DISC Recommendations

Variable Name	**Attribute Name**	**Attribute Content**
AircraftHeading	Heading	"Aircraft Heading Degrees from true North."
AircraftLatitude	Latitude	"Aircraft Latitude Degrees"
	Units	"Degrees North"
AircraftLongitude	Longitude	"Aircraft Longitude Degrees"
	Units	"Degrees East"
AircraftPitch	Pitch	"Up Positive, down negative"

CentralW avelength	CentralWavelength	"CAR Channel Central Wavelength"
CoordinatedUniversalTime	UTC_time	"HHMMSS"
Date	Data_Aquision_Dat e	"YYYYMMD D"
AircraftAltitude	GPS_height	"GPS height in Meter from Sea level"
	Units	"Meters"
Lambda_340 to Lambda_2303	CAR_ch1to CAR_ch14	"340 nm radiance 0.5 degree interval"
	Fill_ Value	"-9999"

PixelViewingAzimuth	PixelViewingAzimuth	"viewingAzimuthAngle"
PixelViewingZenith	PixelViewingZenith	"viewingZenithAngle"
ScanLineCounter	Scan_line	"Scans"
SolarAzimuthAngle	SolarAzimuthAngle	"SolarAzimuthAngle"
	Units	degrees
SolarIrradiance	Solar_Spectral_Irradiance	

SolarZenithAngle	SolarZenithAngle
	Units
SpectralResponseFunction_ch1 to SpectralResponseFunction_ch14	SRF1to SRF14

Table 4: CAR's L1D Data Variable Definitions

Variable Name	**Attribute Name**	**Attribute Content**
AircraftLatitude	Latitude	"Latitude in degrees for each azimuth angle"
AircraftLongitude	Longitude	"Longitude in degrees for each azimuth angle"
AircraftPitch	AircraftPitch	"AircraftPitch for each azimuth angle"
bandWavelengths	units	“microns”
BRDF_Reflectance_lambda2105 to BRDF_Reflectance_lambda340	brdf2105	"Brdf Reflectance 2105nm"

CoordinatedUniversalTime	Time	"Time Information for each azimuth angle"
GPSAltitude	DataValue	"Altitude in M for each azimuth angle"
SolarAzimuthAngle	SolarAzimuthAngle	"SolarAzimuth angle for each azimuth angle"
SolarIrradiance	SolarIrradiance	"Solar Spectral Irradiance"

SolarZenithAngle	SolarZenithAngle	"Solar zenith angle for each azimuth angle"
Sys_response_function_2105nm to Sys_response_function_340nm	2105nm to 340nm	"System response function"

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), multiply $R_\lambda (\theta, \theta_0, \Phi)$ by pi (π).

References:

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