Research Scanning Polarimeter (RSP) Level-1C data quickstart guide

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1. Introduction

The Research Scanning Polarimeter (RSP) is a passive, downward-looking optical instrument intended to retrieve cloud, aerosol and surface reflectance properties. Observations are made in nine narrow spectral channels, whose band centers range from 410 to 2264 nm. The measurements provide the radiance and linear polarization of the observed scene within a ~105° along-track swath. Two nearly identical versions are available: RSP1 and RSP2. RSP can be mounted on a wide range of (NASA) aircraft.

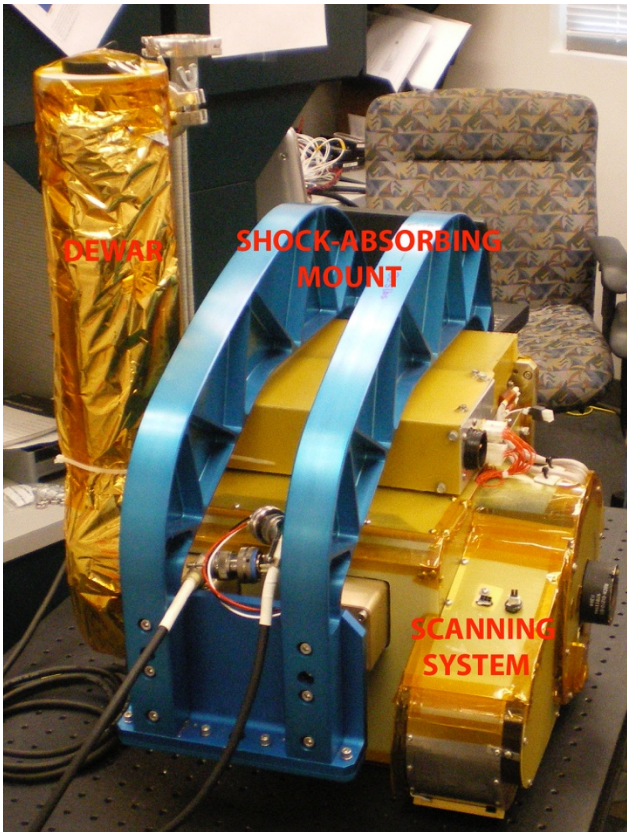


Fig. 1. One of the two NASA GISS Research Scanning Polarimeters (RSP 1), fit for integration on to the NASA Langley B200 King Air aircraft.

2. Data processing

The processing of RSP raw data to level-1C data consists of:

1. **<u>Organizing all data into consecutive straight flight legs</u>**: A straight leg is determined using the coordinates of the ground track. Since Earth is a spheroid, "straightness" is determined based on the distance of the projected sectors from the corresponding great circle. Once projected sectors start to veer off from the great circle, the leg is cut. A leg must contain at least 100 scans with scene data (i.e., with the door being open).

2. **Calibration**: Acquired signals are converted into normalized radiances for the three elements of the Stokes vector *I*, *Q* and *U* (see Sec. 4a below). A solar spectrum based on Thuillier et al. (1998; doi:10.1023/A:1004953215589) and Kurucz (1991; in Solar Interior and Atmosphere, Book ISBN: 9780816512294/9780816538614) as described in Lean (2000; doi: 10.1029/2000GL000043) together with a NIST traceable integration sphere calibration is used to determine normalized radiances.
3. **Geo-location**: The information from the aircraft Inertial Monitoring Unit (IMU) and RSP GPS is incorporated to project each RSP Instantaneous Field of View (IFoV), also named *sector*, to the ground. This defines the geometry of every sector.
4. **Cloud detection**: A simple cloud mask based on reflectance thresholds is applied.
5. **Cloud top height retrieval**: A multi-angle parallax approach is used to determine cloud top height. Details are described by Sinclair et al. (2017; doi:10.5194/amt-10-2361-2017). In addition to a default cloud-top height derived from the 670 nm channel, a cirrus cloud-top height is inferred using the 1880 nm channel, which is located within a strong water vapor absorption band leading to a strong attenuation of light traveling towards the lower atmosphere. The cloud-top height derived using the 1880 nm channel is generally only relevant when RSP is mounted on a high altitude aircraft.
6. **Mapping**: The processing routine searches for all sectors in adjacent scans that are projected the closest to each sector's footprint at nadir ("scene"). This mapping depends on the distance between aircraft and target (generally surface or cloud top). When clouds are detected, mapping is done to the retrieved cloud top height. Data of the 1880 nm channel is mapped to the cloud top height derived from the 1880 nm measurement. For cloud-free scenes, mapping is done to the surface using an elevation database. To manually map data to other altitudes, L1B files should be used. See section 5 for more details.
7. **Water vapor column retrieval**: The 960 nm channel total and polarized reflectances are used to infer two independent water vapor columns. The polarized retrievals are generally only relevant over liquid clouds and can be interpreted as an above-cloud water vapor column.
8. **Water vapor correction at nadir**: Nadir reflectances at 865, 1590 and 2260 nm are corrected for water vapor absorption using the water vapor column retrieved from the total reflectance and stored separately. These data are input for the RSP cloud retrieval algorithms.
9. **Scattering plane rotation:** Polarized reflectances at all wavelengths are rotated into the scattering plane and stored separately. These data are input for the RSP cloud retrieval algorithms. See section 6 for more details.

3. Data Quality

Optimal RSP data quality depends upon:

- **Straight and level course**. The RSP instrument is an along-track scanner and therefore benefits from minimal and stable aircraft yaw and roll. Variations in aircraft pitch can be easily corrected for by offsetting the viewing angle. When scanning spatially limited features (clouds in broken cloud fields, inhomogeneous ground, aerosol plumes, etc.), aircraft yaw significantly affects signal collection since a small feature that is viewed at nadir will not be observed at all other viewing angles. Aircraft roll affects both polar and azimuthal viewing angle and, if not limited to few degrees, causes the RSP instrument to scan uncertain locations therefore spoiling data quality. When flying over specific targets the autopilot should be disengaged, as it tends to overshoot the attitude corrections while manual controls provide provides more stable attitude.

- **Accurate records of aircraft attitude and GPS**. Time stamps should ideally be ≥1Hz. RSP mapping relies on attitude information provided by the aircraft navigation or by other onboard sensors.
- **Accurate alignment information**. The alignment of the RSP instrument with respect to attitude is generally accurately determined post-campaign using observations of reflection features on the surface, or of cloudbows and glories in atmospheric scattering.
- **Instrument cooling**. Shortwave infrared channels (1594, 1880, 2264 nm) require instrument cooling by liquid nitrogen. If liquid nitrogen is not available for a flight, data from the shortwave channels cannot be used (and are filled with fill values).
- **"Housekeeping", instrument health monitoring**. Accurate, time-stamped records of the OPTICS temperature and the TEMP ERR value are available from the instrument's interface.
- **Clear atmosphere above the aircraft**. (Cirrus) clouds or aerosol above the aircraft introduce a source of uncertainty in the determination of the incoming state of solar radiation. RSP data are not corrected for any cirrus or aerosol above the aircraft.

4. Definitions

a. Total and polarized reflectance factors

Total and polarized bi-directional reflectance factors R_I, R_Q, R_U are related to the first three components of the Stokes vector *I, Q and U* (W m^{-2} Sr^{-1}) as follows:

$$R_I = \frac{r_0^2}{\mu_0}\frac{\pi I}{F_0},$$

$$R_Q = \frac{r_0^2}{\mu_0}\frac{\pi Q}{F_0},$$

$$R_Q = \frac{r_0^2}{\mu_0}\frac{\pi U}{F_0},$$

where F_0 is the annual average extraterrestrial irradiance (W m^{-2}), r_0 (dimensionless) is the solar distance in AU, and μ_0 is the cosine of the Solar Zenith Angle (SZA) (Schaepman-Strub et al. 2006; doi:10.1016/j.rse.2006.03.002). Note that 1/π stands for the BRDF (Sr^{-1}) of a Lambertian surface; hence, reflectance factors R_I, R_Q, R_U are unitless. RSP L1C and L1B data files provide unitless normalized radiances

$$\text{“}\textit{Intensity}\text{”} = \frac{\pi I}{F_0},$$

$$\text{“}\textit{Stokes\_Q}\text{”} = \frac{\pi Q}{F_0},$$

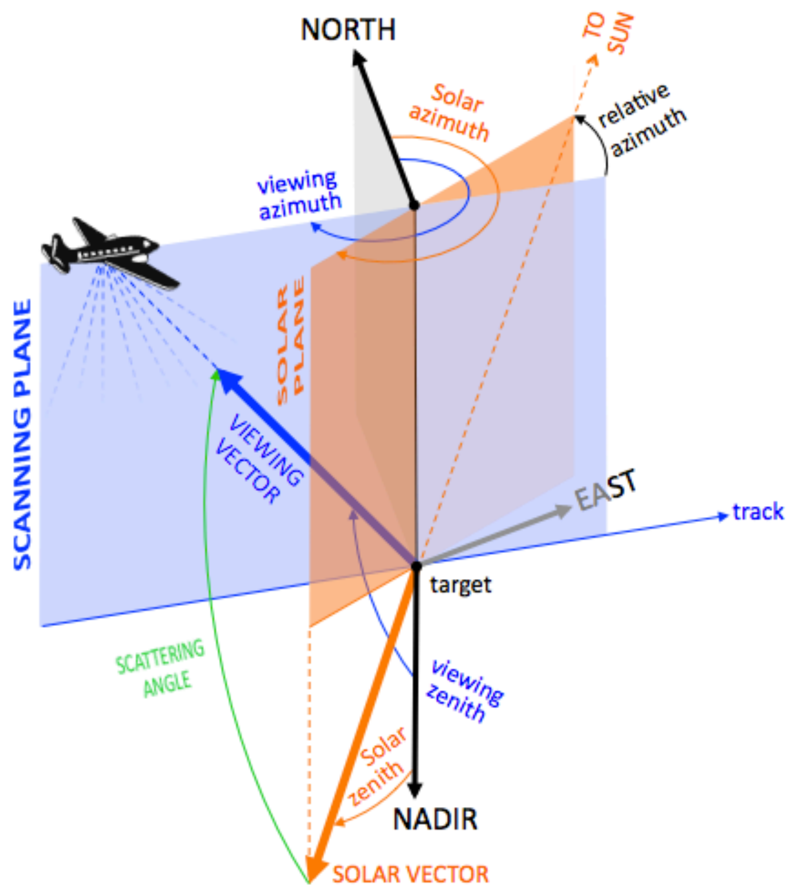
$$\text{“}\textit{Stokes\_U}\text{”} = \frac{\pi U}{F_0}.$$

Thus, to convert these normalized radiances to reflectance factors R_I, R_Q, R_U they have to be divided **by μ_0 and multiplied by r_0^2**. The solar zenith angle and solar distances are provided in the data file.

Note that the RSP design yields two independent measurements of total intensity provided by two redundant telescopes, and stored in the data file as *Intensity_1* and *Intensity_2*. Generally, *the average of both should be used as intensity*.

b. Solar and viewing geometries

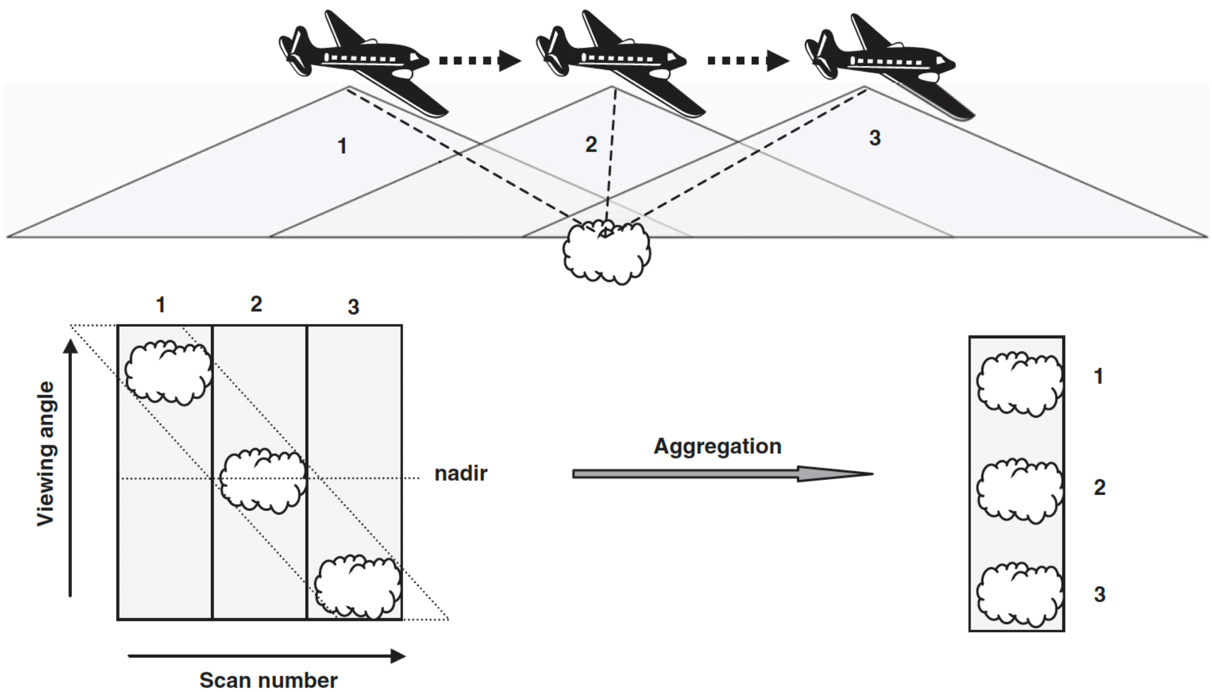
The viewing geometry is defined with respect to a right-handed reference system where the x-axis is due north, the y-axis is due east and the z-axis points at nadir (see figure below). The viewing vector, shown in blue for one of the RSP forward sectors, points from the target to RSP along the axis of the Instantaneous Field of View (IFoV). According to this reference system, solar zenith angles are found in the [0°, 90°] range (0˚ for overhead sun and 90˚ when the Sun is at the horizon), and viewing zenith angles in the [90°, 180°] range (**the nadir-looking direction corresponding to a viewing zenith angle of 180˚).** By subtracting the viewing azimuth angle from the solar azimuth angle (both referenced clockwise from due north and varying in the [0°, 360°) range), one obtains the *relative* azimuth angle, which varies in the (-180°, 180°] range. For example, when flying towards the Sun as in the figure, the relative azimuth of the forward RSP sectors is close to 0°, and that of the aft sectors (move the plane along the track past the target) is close to 180° or -180° depending on whether the Sun is on the left or on the right.



5. Mapping of multi-angular data to cloud top or surface

As illustrated in the figure below (from Alexandrov et al. 2012; doi:10.1016/j.rse.2012.07.012), RSP views a given overflown target (location on surface or cloud) at different viewing angles at different times (i.e. at different aircraft locations). For the L1C data product, data are re-ordered (or "aggregated"), such that, for each footprint at nadir, data obtained at all viewing angles in adjacent scans that are projected closest to that footprint at nadir are provided. As a rule of thumb, if the vertical distance between aircraft and target is x, the aircraft needs to approach the target from a horizontal distance x and fly past the target with a distance x to obtain the maximum number of views on the target. Thus, at an aircraft speed of 165 m/s, it takes about one minute to collect all multi-angle views for a target 5000 m below the aircraft altitude.

L1C data files contain all solar and viewing geometries and total and polarized radiances aggregated to footprints on the surface (if no clouds are detected) or cloud tops (if clouds are detected). Before mapping the data to a location on cloud top, the cloud top height is determined using a multi-angle parallax approach. In addition to a default cloud-top height derived from the 670 nm channel, a cirrus cloud-top height is inferred using the 1880 nm channel, which is located within a strong water vapor absorption band leading to a strong attenuation of light traveling towards the lower atmosphere. Data for all bands are aggregated to the cloud top height determined from the 670 nm channel, except data of the 1880 nm channel, which is aggregated to the cloud top height determined with the 1880 nm channel. **Hence, two sets of aggregated solar and viewing geometries are available in the dataset, corresponding to the aggregation performed for the 670 nm and 1880 nm cloud top heights, respectively.**



6. Rotation into scattering plane

For some applications, it is helpful to convert (or 'rotate') the polarized radiances as were they observed in the scattering plane. In the case of single scattering, the U component of the Stokes vector is zero after rotation. Polarized reflectances rotated into the scattering plane are used for the retrievals of droplet size distribution by matching these observations directly to P12 elements of scattering phase matrices corresponding to various drop size distributions. The L1C files contain arrays in the GEOMETRY folder to perform this rotation, namely Sin_Rot_Scatt_Plane and Cot_Rot_Scatt_Plane. For observed values of Q and U, the rotated values Q_rot and U_rot are obtained as

Q_rot = Cot_Rot_Scatt_Plane * Q + Sin_Rot_Scatt_Plane * U
U_rot = Sin_Rot_Scatt_Plane *Q - Cot_Rot_Scatt_Plane * U

For a detailed example on how to use these rotation arrays, please see section 9. **Note that rotated Q values are readily available in the L1C data for all bands in variable Stokes_Q_Scatt_Plane.**

7. Wavelengths

Approximate band centers (bandwidths) are 410 (30); 470 (20); 555 (20); 670 (20); 865 (20); 960 (20); 1590 (60); 1880 (90); 2264 (120) nm. Spectral response functions for these wavelength bands can be obtained at:
https://data.giss.nasa.gov/pub/rsp/RSP_Utilities/Responses/

8. Data structure

The hdf file names are structured as this example:
CAMP2EX-RSP1-L1C_P3B_20190803155302_R2

The various parts of the filename are explained below

- CAMP2EX: Indicating these data are collected during the CAMP2Ex campaign
- RSP1: RSP1 collected this data, as opposed to RSP2
- L1C: Denoting level 1C data
- P3B: RSP was mounted on the P-3 aircraft
- 20190803155302: UTC date (yyymmdd) and time (hhmmss) at the start of the flight leg
- R2: Processing algorithm version

The hdf file contents is organized in 5 folders ('groups'), namely

- DATA: Normalized radiances, cloud flag and water vapor data
- GEOMETRY: Solar and viewing geometries, target height and location
- PLATFORM: Aircraft and flight path information, land/water mask, solar distance
- CALIBRATION: Instrument calibration settings
- ENGINEERING: Housekeeping, instrument health information

The data structure and variables are listed in the appendix. Generally users only need parameters from the DATA and GEOMETRY folders in addition to solar distance from the PLATFORM folder.

9. L1C data extraction example

This example describes how to extract multi-angle reflectance factors at 555 nm and corresponding geolocation and viewing geometry information. For this example, we will extract data for all viewing angles at the scene with index number 100.
In this example '*' is used as a wildcard, and arrays start at index 0.

Normalized reflectances are found in

> DATA>INTENSITY_1 and DATA>INTENSITY_2
> *dimensions: [# wavelengths, # viewing angles, # scenes]*

To obtain the normalized radiances at 555 nm of scene with index number 100, we use

R_{norm} = (DATA>INTENSITY_1[2,*,100] + DATA>INTENSITY_2[2,*,100])/2

Here, the *normalized* radiances measured by the two redundant telescopes are averaged. In order to convert these into reflectance factors, we need to divide by cosine of the solar zenith angle ($\boldsymbol{\mu_0}$). The solar zenith angle is found in

GEOMETRY>SOLAR_ZENITH
Dimensions: [# viewing angles, # scenes, # aggregation altitudes]

Here, # *aggregation altitudes* = 2. To obtain geometries corresponding to data from the 1880 nm channel, *aggregation altitude* should be set to 1, while *aggregation altitude* =0 should be used for all other channels.

Thus, we extract μ_0 corresponding to the data at 555 nm and scene number 100 as

μ_0 = COS(GEOMETRY>SOLAR_ZENITH[*,100,0])

The solar distance can be found at

PLATFORM> SOLAR_DISTANCE
dimensions: [# scenes]

Thus we define the solar distance for scene number 100 as

r_0 = PLATFORM> SOLAR_DISTANCE[100]

Finally, reflectance factors at 555 nm and at all viewing angles for scene number 100 is obtained by

$R = R_{norm} * r_0^2/\mu_0$.

R has dimensions [# *viewing angles*]. Stokes parameters *Q* and *U* are similarly obtained, while the normalization is not needed for the degree of linear polarization (DoLP), because it is formed as a ratio of radiances.

Similarly to the solar zenith angle, the viewing zenith, viewing azimuth, solar azimuth angles and corresponding scattering angles can be extracted as

VZA = GEOMETRY>VIEWING_ZENITH[*,100,0]
VAA = GEOMETRY>VIEWING_AZIMUTH[*,100,0]
SAA = GEOMETRY>SOLAR_AZIMUTH[*,100,0]
SCAT = GEOMETRY>SCATTERING_ANGLE [*,100,0]

Note that generally not all of the 152 views of RSP contain valid data. Sectors can be blocked ('vignetted') depending on the way RSP is mounted on the aircraft and on instrument configuration. The range (start and end) of *unvignetted* sectors is given by

DATA> UNVIGNETTED_SECTOR_BEGIN
DATA> UNVIGNETTED_SECTOR_END
Dimension: [1]

Note that these assume a convection with arrays starting at index 0.
Thus, an array *R* containing reflectance factors corresponding to unvignetted viewing angles is given by

R[UNVIGNETTED_SECTOR_BEGIN: UNVIGNETTED_SECTOR_END].

The latitude and longitude are given by

GEOMETRY> COLLOCATED_LATITUDE
GEOMETRY> COLLOCATED_LONGITUDE
dimensions: [# scenes, # aggregation altitudes]

Thus, latitude and longitude corresponding to the example scene is extracted as

LAT = GEOMETRY> COLLOCATED_LATITUDE[100,0]
LON = GEOMETRY> COLLOCATED_LATITUDE[100,0]

The corresponding elevation to which the data is collocated is given by

ALT = GEOMETRY> COLLOCATED_ALTITUDE[100,0]

Note that for cloudy scenes, ALT corresponds to cloud-top height.

The MJD time at which the angular measurements are made are given in

GEOMETRY>MEASUREMENT_TIME,
Dimensions: [# viewing angles, # scenes, # aggregation altitudes]

The time corresponding to the nadir observation is given by

DATA>PRODUCT_TIME_SECONDS
Dimensions: [# scenes]

which is in UTC seconds counting from the UTC day of take off.

As discussed in section 6, Stokes vectors Q and U may be rotated into the scattering plane. The rotation arrays are found in the GEOMETRY folder:

GEOMETRY>Sin_Rot_Scatt_Plane
GEOMETRY>Cot_Rot_Scatt_Plane
Dimensions: [# viewing angles, # scenes, # aggregation altitudes]

Rotated, normalized Q and U at 555 nm and at all viewing angles for our example scene 100 can be obtained by

```
Q_norm_rot = Cot_Rot_Scatt_Plane[*,100,0] * STOKES_Q[2, *, 100] +
             Sin_Rot_Scatt_Plane[*,100,0] * STOKES_U[2, *, 100]

U_norm_rot = Sin_Rot_Scatt_Plane[*,100,0] * STOKES_Q[2, *, 100] -
             Cot_Rot_Scatt_Plane[*,100,0] * STOKES_U[2, *, 100]
```

Dimensions: [# viewing angles]

Note that rotated Q values are readily available in the L1C data for all bands in variable Stokes_Q_Scatt_Plane.

For applications where only observations that are closest to nadir are needed, the index of that viewing angle is given by

GEOMETRY> NADIR_INDEX
dimensions [# scenes, # aggregation altitudes]

Note that the nadir index assumes a convection with arrays starting at index 0.
For example, the normalized Q at 555 nm measured at nadir for scene number 100 is given by

DATA>STOKES_Q[2, GEOMETRY>NADIR_INDEX[100,0], 100].

Appendix: L1C data structure and variables

```
group      /Calibration
dataset    /Calibration/Solar_Constant
dataset    /Calibration/cal1
dataset    /Calibration/cal12
dataset    /Calibration/cal2
dataset    /Calibration/da1L
dataset    /Calibration/da1R
dataset    /Calibration/da2L
dataset    /Calibration/da2R
dataset    /Calibration/delta
dataset    /Calibration/dstd1L
dataset    /Calibration/dstd1R
dataset    /Calibration/dstd2L
dataset    /Calibration/dstd2R
dataset    /Calibration/k1
dataset    /Calibration/k1_sector
dataset    /Calibration/k2
dataset    /Calibration/k2_sector
dataset    /Calibration/pre1L
dataset    /Calibration/pre1R
dataset    /Calibration/pre2L
dataset    /Calibration/pre2R
dataset    /Calibration/qscl
dataset    /Calibration/twoeps
dataset    /Calibration/uscl
group      /Data
dataset    /Data/Angle_of_Polarization
dataset    /Data/Cloud_Test_Passed
dataset    /Data/Cloud_Test_Performed
dataset    /Data/Collocation_Correlation_Profile
dataset    /Data/Collocation_Profile_Altitude
dataset    /Data/Corrected_Reflectance
dataset    /Data/Data_Quality_Flags
dataset    /Data/DoLP
dataset    /Data/Intensity_1
dataset    /Data/Intensity_2
dataset    /Data/Product_Time
dataset    /Data/Product_Time_Seconds
dataset    /Data/Stokes_Q
dataset    /Data/Stokes_Q_Scatt_Plane
dataset    /Data/Stokes_U
dataset    /Data/Unvignetted_Sector_Begin
dataset    /Data/Unvignetted_Sector_End
dataset    /Data/Water_Vapor_Pol
dataset    /Data/Water_Vapor_Total
dataset    /Data/Wavelength
group      /Engineering
dataset    /Engineering/Sector_Angle
```

```
dataset    /Engineering/Sector_Normal_To_Instrument_Base_Plate
dataset    /Engineering/adc_count
dataset    /Engineering/scan_count
dataset    /Engineering/scan_error
dataset    /Engineering/temp_elec
dataset    /Engineering/temp_err
dataset    /Engineering/temp_opt
dataset    /Engineering/temp_swir_det
dataset    /Engineering/voltages
group      /Geometry
dataset    /Geometry/Collocated_Altitude
dataset    /Geometry/Collocated_Latitude
dataset    /Geometry/Collocated_Longitude
dataset    /Geometry/Collocated_Map
dataset    /Geometry/Cos_Rot_Scatt_Plane
dataset    /Geometry/Distance_To_Mapped_Sector_Statistics
dataset    /Geometry/Glint_Angle
dataset    /Geometry/Ground_Latitude
dataset    /Geometry/Ground_Longitude
dataset    /Geometry/Land_Water_Flag
dataset    /Geometry/Map_Scenes_At_Altitudes
dataset    /Geometry/Map_Scenes_On_Ground
dataset    /Geometry/Mapped_Altitudes
dataset    /Geometry/Measurement_Time
dataset    /Geometry/Nadir_Deviation
dataset    /Geometry/Nadir_Index
dataset    /Geometry/Scattering_Angle
dataset    /Geometry/Sin_Rot_Scatt_Plane
dataset    /Geometry/Solar_Azimuth
dataset    /Geometry/Solar_Zenith
dataset    /Geometry/Terrain_Height
dataset    /Geometry/Viewing_Azimuth
dataset    /Geometry/Viewing_Zenith
group      /Platform
dataset    /Platform/Day_of_Year
dataset    /Platform/Fraction_of_Day
dataset    /Platform/GPS_Acquisition_Time
dataset    /Platform/GPS_Quality
dataset    /Platform/Ground_Elevation_At_Nadir
dataset    /Platform/Heading
dataset    /Platform/Land_Water_Mask_At_Nadir
dataset    /Platform/Pitch
dataset    /Platform/Platform_Altitude
dataset    /Platform/Platform_Latitude
dataset    /Platform/Platform_Longitude
dataset    /Platform/Platform_Solar_Azimuth
dataset    /Platform/Platform_Solar_Zenith
dataset    /Platform/Pressure
dataset    /Platform/Relative_Humidity
dataset    /Platform/Roll
```

```
dataset    /Platform/Seconds
dataset    /Platform/Solar_Distance
dataset    /Platform/Speed
dataset    /Platform/Temperature
dataset    /Platform/Track
dataset    /Platform/Wingflex
dataset    /Platform/Yaw
dataset    /Platform/Year
dataset    /dim_ADCs
dataset    /dim_Band_Maps
dataset    /dim_Bands
dataset    /dim_Bi_Spec_Input_Bands
dataset    /dim_Cloud_Tests
dataset    /dim_Collocation_Profile_Altitudes
dataset    /dim_Collocation_Stats
dataset    /dim_Map_Altitudes
dataset    /dim_Quality_Flags
dataset    /dim_Scans
dataset    /dim_Scene_Sectors
dataset    /dim_Sectors
dataset    /dim_Temps
dataset    /dim_Volts
```