AIRHARP

AIRborne Hyper-Angular Rainbow Polarimeter

AirHARP Data Quality Statement and User's Guide: LMOS Campaign

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Campaign

Name	LMOS (Lake Michigan Ozone Study)
Dates	19 May – 21 June 2017
Locations	Wisconsin, Illinois, Lake Michigan
UC-12 Remote Sensing	AirHARP, GeoTASO

AirHARP Overview of Data Calibration and Processing to Level 1B

Data Delivery Version	R0
Detector-Relative Corrections (Background, Flatfield, Non-Linear)	13 June 2018
Radiometric Calibration	13 June 2018
Polarimetric Calibration	31 January 2018
Spectral Calibration	13 June 2018

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1 INTRODUCTION and AirHARP L1B Products

The Airborne Hyper-Angular Rainbow Polarimeter (AirHARP) instrument, designed and developed by the Laboratory for Aerosol and Cloud Optics (LACO) at the University of Maryland, Baltimore County (UMBC), participated in the Lake Michigan Ozone Study (LMOS) over Wisconsin, northern Illinois, and Lake Michigan from 25 May to 21 Juen 2017. AirHARP joined the GeoTASO instrument on-board the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) UC-12 research aircraft. This document details the Level 1B processing and data quality of AirHARP datasets during this campaign.

AirHARP observed cloud, aerosol, land, and ocean scenes using radiometric and polarimetric techniques during the LMOS field campaign. Using wide field-of-view (FOV), polarized information from three co-aligned detectors, AirHARP sampled Earth scenes in four channels (unique viewing angles) simultaneously: 440 (20), 550 (20), 670 (60), and 870 (20) nm. All wavelengths and angles are polarization-capable, producing Stokes parameters for total radiance (I) and electric-field-oriented, or *polarized*, radiance (horizontal over vertical - Q, 45° over 135° - U) in L1B processing. AirHARP measurements are gridded to 4000 pixels per geolocated degree on Earth's surface, corresponding to 28m pixel ground resolution at nadir. The pixel ground resolution grows as a function of viewing zenith angle off-nadir. All files are formatted with the HDF5 designation. **This data quality statement refers to AirHARP L1B Version 000 (R0); commentary on any future version revisions will be added as and where necessary in their respective sections.**

2 RADIO-POLARIMETRIC CALIBRATION

2.1 Calibration Summary

Radio-polarimetric calibration (RPC) was performed once before (5 May 2017) and thrice after the LMOS field campaign, (24 July 2017, 31 January 2018, and 13 June 2018) using a 1.01m integrating sphere source at NASA Goddard Space Flight Center (GSFC) Radiometric Calibration Facility. The sphere is National Institute of Standards and Technology (NIST) traceable and is radiometrically calibrated every year over its entire aperture (Cooper, private communication).

AirHARP image background correction is performed using an experimental relationship between dark reference counts and detector temperature derived from the counts in the last 180 pixels of the detector row that are masked from the light path. The telecentricity of the AirHARP instrument allows for *nadir-spread* RPC: calibration coefficients derived at nadir are spread across the entire FOV with assistance from flatfield images. Flatfields are made by illuminating the entire AirHARP FOV with a homogenous source (integrating sphere) and capture relative pixel behavior. Non-linear correction is performed on each detector individually, with coefficients derived using the nadir-spread technique.

Incident light is delegated to three AirHARP detectors through an optimized Phillips prism. Prism coatings and glass angles delegate excesses of S- and P-polarization to three prism output ports. Before reaching the detector, this light first passes through a sheet polarizer, oriented such that each sensor is uniquely sensitive to 0, 45, or 90° linearly polarized light over the entire focal plane array. Lab-generated polarization and co-aligned detector counts are used to derive the *characteristic matrix* (Borda et al. 2009), a mathematical object that translates detector readings to normalized Stokes parameters (Q/I, U/I). The simplest iteration of the polarization calibration involves a wire-grid polarizer on a mechanized rotational stage at the aperture of an integrating sphere (DOP < 0.005). The polarizer is rotated perpendicular to the AirHARP optical axis at incremental angles. The polarizer is tilted 10° off-axis to avoid back reflection and the rotational stage is tunable within 0.001°. AirHARP laboratory DOLP uncertainty is estimated at 0.005 for all channels. Characteristic matrix coefficients are derived using the nadir-spread technique.

AirHARP observes the same GSFC sphere aperture, with no external polarizer, for radiometric calibration. Prior calibrations (5 May, 24 July 2017, and 31 January 2018) illuminated the entire AirHARP FOV, but stray light and cross-talk considerations suggested a reduced aperture; radiometric calibration on 13 June 2018 restricted the sphere light core to the 20° viewing angle in the AirHARP image plane. AirHARP observed the sphere at incremental light levels, and an external Avantes spectrometer monitored the sphere output and spectral response at each level. After background and non-linear correction, the characteristic matrix is applied to the AirHARP sphere observations. The normalized Stokes intensity (I) is juxtaposed with the calibrated radiance levels of the sphere to yield a radiometric gain factor for each wavelength. The radiometric gain factor is derived using the nadir-spread technique. AirHARP absolute radiometric accuracy is estimated at 0.05 for all channels.

AirHARP does not have in-flight RPC mechanisms and must rely on laboratory and vicarious RPCs in-flight to adjust measurement quality. As such, it is difficult to estimate the in-flight stability of the AirHARP radiopolarimetric measurements. Instruments with in-flight calibration ability, like MODIS, VIIRS, and GOES-R may be used at some level to vicariously judge the in-flight stability and adjust AirHARP measurements for co-incident scenes during the LMOS campaign.

2.2 Improvements to Calibration in Later L1B Version Releases

With stray light and cross-talk considerations in account, a full FOV *polarizer dome* mechanism is under development for complete RPC of the AirHARP sensor. This object considers the ray trace of all incident light on the AirHARP front lens such that generated polarization does not alter its state entering the system. The nadir-spread calibration with a flat, wire-grid polarizer has geometrical limitations that invalidate coefficients derived far from the axis shared by the polarizer normal and a position on the AirHARP front lens (Kliger et al. 1992). Theoretically, with a full FOV calibration, flatfield and RPC can be achieved simultaneously and is equivalent to the nadir-spread calibration. Any internal changes to the instrument are calibrated out in one operation as opposed to two with the nadir-spread method. Current investigation is underway with preliminary results slated for an upcoming paper (McBride et al. 2018, in preparation).

3 SPECTRAL CALIBRATION

Spectral calibration for AirHARP was also performed at the NASA GSFC Radiometric Calibration facility, using a continuous scanning monochromatic Ekspla laser system fed into a 20cm integrating sphere. The Ekspla system scans wavelengths at a 5 cm^{-1} maximum linewidth, scanning step of 0.1nm, and total available range from 210 to 2100 nm. An external Avantes spectrometer monitored the sphere output of each Ekspla wavelength. Co-aligned counts from the three detectors applied to the characteristic matrix, calculated during the RPC, produces a Stokes intensity (I) for each AirHARP wavelength.

Spectral response functions found via super-Gaussian fitting of the Stokes intensity in the four AirHARP wavelengths, after smoothing for laser noise variation and total-band spectrometer correction, are presented in Table 1 and Figure 1. The effective bandwidth and center wavelength derived from super-Gaussian (order 5) first and second moments. The reported solar irradiance (F_0) is the equivalent square-band response using the American Society for Testing and Materials Standard Extraterrestrial Spectrum Reference E-490 (ASTM E-490) Air Mass Zero solar irradiance spectrum. Stokes parameters, I, Q, and U reported in the AirHARP HDF files may be reduced to reflectance, from radiance units, by multiplying by a factor of $\pi/F_0(\lambda)$.

In all three sensors, the AirHARP instrument rejects out-of-band illumination to a < 10^{-5} level relative to peak normalization. Wavelength selection in AirHARP is done via stripe filter overlaid on microlens CCD detectors; interpixel cross-talk and stray light under the filters drives < 10^{-2} order in-band leakage from other wavelengths.

Table 1. *Total-band effective center wavelength, bandwidth, and band-weighted solar irradiance F_0*

Channel Name	Center Wavelength (nm)	Effective Bandwidth (nm)	Solar Irradiance (F_0) ($W\ m^{-2}\ nm^{-1}$)
Blue	**441.4**	**15.7**	**1.855**
Green	**549.8**	**12.4**	**1.873**
Red	**669.4**	**18.1**	**1.534**
Near-InfraRed (NIR)	**867.8**	**38.7**	**0.965**

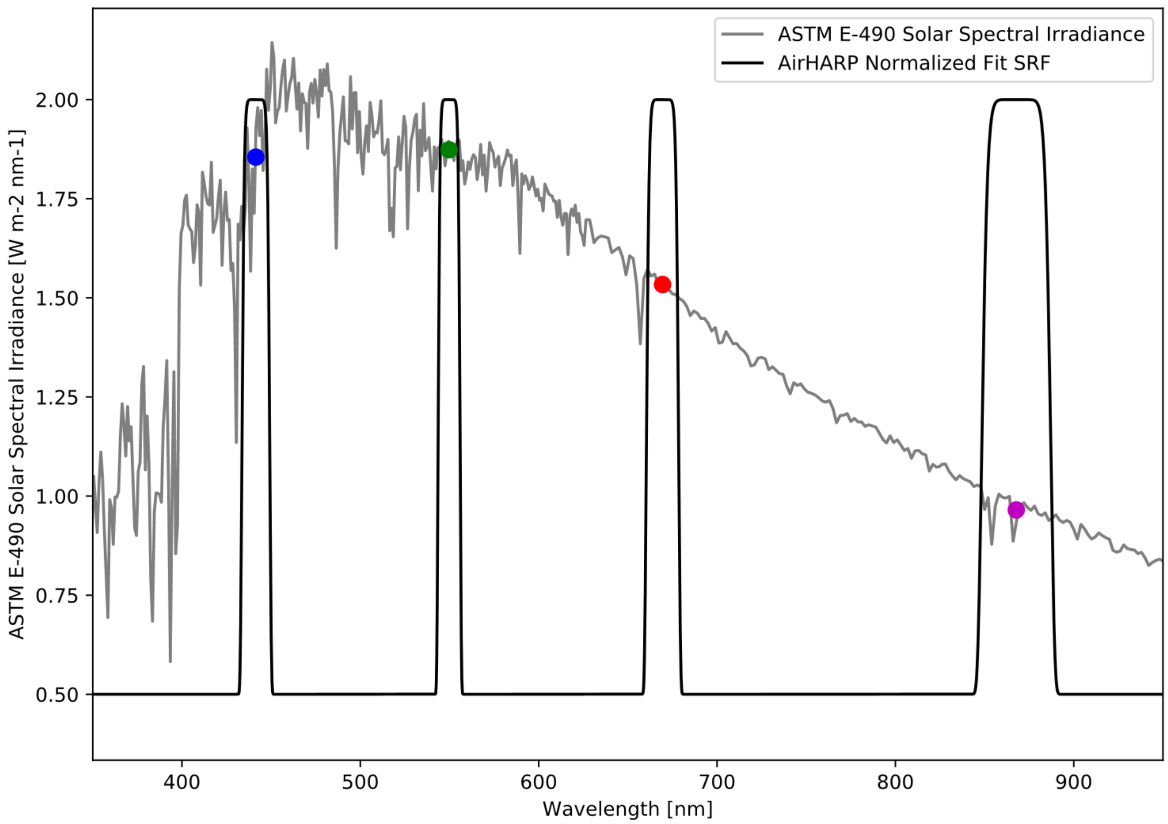

Figure 1. *Solar spectral irradiance function from ASTM E-490 dataset overlaid with AirHARP normalized fit spectral response function, scaled by 1.5 and offset by 0.5 for visual effect. Colored in-band dots represent the integrated solar irradiance (F_0) for each wavelength used for reflectance conversion.*

4 GEORECTIFICATION AND CO-REGISTRATION

Geolocation and co-registration of AirHARP data involves ancillary data, including f-theta distortion tables for front lens pixel projections, magnification, and inertial monitoring unit (IMU) and instrument mounting statistics from the science flights. All data included in the HDF is projected at 4000 pixels per degree. This is necessary as the pixel projection distorts relative to view zenith angle; at nadir, the gridded pixel ground resolution is 28m. For example, the native pixel ground resolution grows by a factor of 3.3 from nadir to ±57° on the along-track scan line of the AirHARP focal plane array, and 2.1 from nadir to ±47° cross-track.

Band-to-band relative co-registration and detector co-alignment are the factors that most affect geospatial accuracy. The current AirHARP L1B Version 000 (R0) data does not include a comprehensive topography map. All pushbrooms are geolocated to a geographically-averaged altitude of region or sector of interest (i.e. Wisconsin coastline or sea-level for ocean surface projections). A dedicated topography algorithm is underway that will include an ancillary digital elevation map (DEM) and a pointing-vector scheme for collocating the altitude of objects as a function of view angle. Data gaps due to pitch modulation of the UC-12 aircraft in-flight affects far-forward or aft angles more strongly than nadir due to the extended ground projections and limited pixel allocation for those angles. Turbulence during flight will appear as a jerky segment of the gridded, geolocated pushbroom and those regions may not be of science quality. These limitations and current mitigation work is discussed in more detail in Section 5 below.

5 KNOWN DATA QUALITY ISSUES UNDER INVESTIGATION

5.1 Flatfield optical interference

Proper flatfield measurements for each AirHARP sensor are performed in the laboratory using either the GSFC sphere, a 0.5m SphereOptics integrating sphere or 16.4cm integrating hemisphere at the UMBC LACO facility. AirHARP responds differently to each sphere due to narrow bandwidths in the 4 HARP channels and the unique spectral responses of each source; the flatfields that best represent the flight conditions are used for L1B processing. Preliminary inter-comparisons with other polarimeters during the Aerosol Characterization from Polarimeter and LiDAR (ACEPOL) campaign (Oct/Nov 2017) show the global flatfield is successfully spreading the RPC across the FOV and yielding comparable results for the evaluated cases.

AirHARP flatfield images reveal a shallow Newton's rings-like effect when observing a homogenous source, and light linear fringes also appear superimposed on the images parallel to the axis of each detector polarizer. These features modulate the detector counts by no more than 2% and are robust; a proper flatfield measurement exactly corrects for these features at room temperature. In flight, internal temperatures reach 0° on the instrument busbar (close to the optical train), compared to 23°C in lab. The AirHARP Stokes parameter pushbrooms from LMOS data, processed with the lab flatfield, still show interference fringes, suggesting that the lab flatfield does not completely account for temperature-dependent changes to the optical train during flights. Current work is underway on a (1) temperature-dependent model for our optical interference, and (2) mid- or post-processing correction for extraneous fringing. The latter option is successful in removing fringes in DOLP pushbrooms after processing for a significant improvement in data quality, shown in Figure 2.

This issue does not affect our calibration coefficients derived using the nadir-spread technique; the flatfields are normalized to the same nadir locations used in calibration activities. The extraneous fringes created in field data processing only contribute to the accuracy of the AirHARP field measurement.

In-flight flatfield calibration is proposed for future AirHARP deployments; this operation is already planned for the HARP-2 platform on the PACE mission: a field-stop diffuser combined with frequent solar calibration will counter and correct for any similar optical interference. Currently, flatfield optical interference is the largest field contributor to the AirHARP error budget, and the overall contribution to DOLP and reflectance uncertainty is under study.

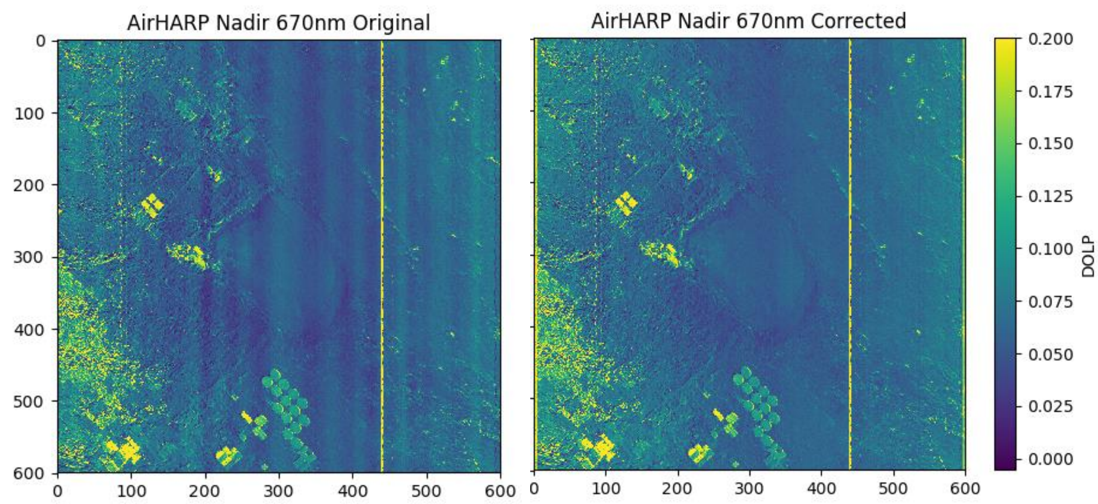

Figure 2. *Nadir gridded 670nm DOLP pushbroom sector during an ACEPOL science flight over the Rosamond Dry Lake on October 25, 2017. Note the stable linear fringes in the L1B processed image (left) that are removed in a simple post-processing correction (right). The bright linear streak in both images is an unmasked hot pixel. Flight direction is toward the top of the image.*

5.2 UC-12 turbulence, cross-winds, and data gaps

As a wide FOV instrument, angles further from nadir see elongated pixel projections on the ground, relative to the aircraft altitude. The L1B pushbroom processing for each angle requires that there are enough pixels per viewing angle such that two consecutive images will stitch together or overlap and form a continuous pushbroom. The AirHARP data compression algorithm takes the nominal aircraft altitude and velocity into account when selecting how many pixels are appropriate for continuous overlap, at each viewing angle. For much of the campaign, the UC-12 aircraft experienced bouts of turbulence and high cross-winds, both of which negatively affect our compression scheme. While turbulence affects the accuracy of geolocation, cross-winds degrade the AirHARP angular coverage by forcing a yaw between the aircraft nose and bearing direction. Any cross-wind yaw cuts down on the overlap between viewing angles and cross-track coverage. Turbulence related to pitch modulation also overextends the projection of far-forward/aft angles and leads to data gaps during pushbroom processing.

To compensate, the AirHARP L1B algorithm interpolates data gaps during gridding. Current evaluation is underway on stronger interpolation schemes and/or setting data gap to fill value status in future AirHARP L1B version releases.

5.3 Lens condensation

During LMOS, the AirHARP instrument did not have an in-flight dry purge or temperature control mechanism for the front lens. Therefore, the instrument was not able to evaporate moisture or remove contaminants from the front lens during flights. In few cases, images from the first acquisitions during a science flight have a shallow blurring at the center of the lens that disappears quickly beyond the 20° view zenith angle.

L1B pushbrooms may show a thin center strip with decreased brightness compared to the rest of the image, for angles inside this range. Because this feature appears homogenous, it appears that the front lens acquired boundary-level moisture as the aircraft ascended; a shallow film of liquid water gathered at the tip of the lens and likely froze at sub-zero flight temperatures. We do not see any stray light artifacts in the images themselves from this feature, leading us to believe glassy ice, not crystal aggregates, is the cause. A dry nitrogen purge element external to the front lens and/or optical train temperature control are strongly recommended for future AirHARP deployments.

The impact of lens condensation on data quality of AirHARP L1B images is currently under study. This issue does not affect all datasets or science flights, and to first-order, serves to decrease the spatial resolution of affected sectors. A similar post-processing correction for flatfield fringes in Section 5.1 can also account for lens condensation in AirHARP images.

5.4 Enclosure vignetting

The machined front plate for the AirHARP instrument partially vignetted the instrument FOV during LMOS, restricting the cross-track coverage of far forward/aft angles compared to the nominal AirHARP FOV. AirHARP L1B data includes observations at all angles but note that the pushbroom composites for angles beyond ±45° scan line view zenith angle (SLVA), as given in the HDF internal filenames, may be subject to artificial cross-track vignetting. Unfortunately, this issue is unique to the LMOS datasets and cannot be mitigated in L1B processing; the front plate was machined differently for the ACEPOL campaign to avoid any FOV vignetting. Any future AirHARP deployment will use the ACEPOL front plate or a similar design for aircraft integration.

5.5 Quality flags and HDF file structure

Currently, AirHARP L1B data processing does not have a quality flag registry for data considered science-usable to sectors with calibration artifacts or no data. Only pixels that are saturated, as defined by our current L1B algorithm, are masked with fill value, a number that matches all out-of-bounds data sectors. Quality flags in upcoming Version 001 (R1) will screen rare cases of unphysical values and hot pixels brought on by limitations in our current masking algorithm. The HDF file skeleton will also undergo a cosmetic makeover for user ease in future version releases.

6 REFERENCES

Borda, R.F., E. Waluschka, S. Pellicori, J. V. Martins, L. Ramos-Izquierdo, J.D. Cieslak, P. Thompson (2009), Evaluation of the polarization properties of a Phillips-type prism for the construction of imaging polarimeters. *Polarization Science and Remote Sensing IV*. Proc. of SPIE. **7461**, 1-13. doi:10.1117/12.829080

Kliger, D. S., J. W. Lewis, and C. E. Randall (1990), *Polarized Light in Optics and Spectroscopy.* Academic Press, 27-58.

McBride, B.A., J. V. Martins, H. M. J. Barbosa, R. F. Borda (2018), in preparation.

7 HDF USERS GUIDE

The AirHARP HDF skeleton can be externally viewed using free software like HDFView (https://support.hdfgroup.org/products/java/hdfview/). The filenames are in the required ICARTT format on the NASA LMOS data archive (https://www-air.larc.nasa.gov/missions/lmos/index.html) . AirHARP L1B products are in HDF5 format. The actual content of the images shown below may be different from the actual values and nomenclature in the HDF based on version. Images shown are from a pre-release version of the AirHARP L1B HDF (the skeleton did not change between versions).

The HDF is comprised of four internal master folders: **Coordinates, blue, green, nir, red**. The Coordinates folder includes the gridded Latitude and Longitude matrices for the dataset. All information included in this HDF can be projected and displayed using these two coordinate matrices. The Latitude and Longitude files themselves include *attributes*, as shown in Figure 3, in a screenshot from HDFview.

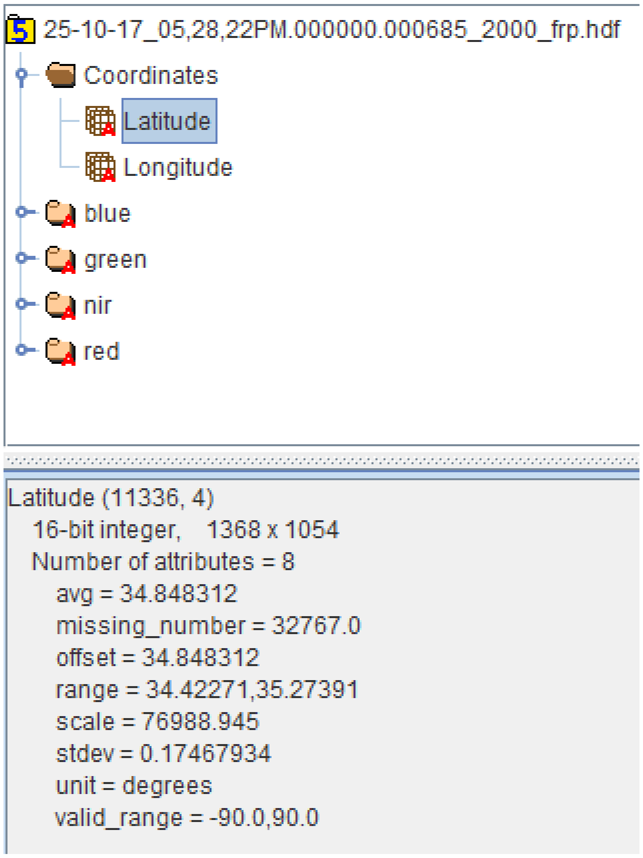

Figure 3. *AirHARP L1B HDF file structure, with Latitude coordinate matrix file selected. Note the attributes listed in the bottom-half of the image, corresponding with the Latitude file.*

Latitude and Longitude coordinate files are int16s and can be reshaped into 1368x1054 (along-track x cross-track). Avg and stdev fields are for internal checking. Fill value ("missing number") is assigned to regions of no data. Range gives the range of all values in this dataset, while valid range is an internal check on the total possible range of Latitude information. Longitude includes different values with the same structure.

All files in the AirHARP HDF are optimized to minimize total HDF file size; all float32 data values are scaled and offset to maximize the resolution of their int16 packaged format. These **scale and offset** parameters are included as attributes in Figure 3 and are such for all files in the HDF. Equation 1 defines how these are applied:

$$DATA_{float32} = \frac{DATA_{int16}}{scale} + offset \qquad [1]$$

All AirHARP data files in the HDF require scaling and offset before science use.

The other four internal master data folders include the polarization and viewing geometry information for each wavelength and viewing angle. Figure 4 outlines the structure of the blue folder, as an example.

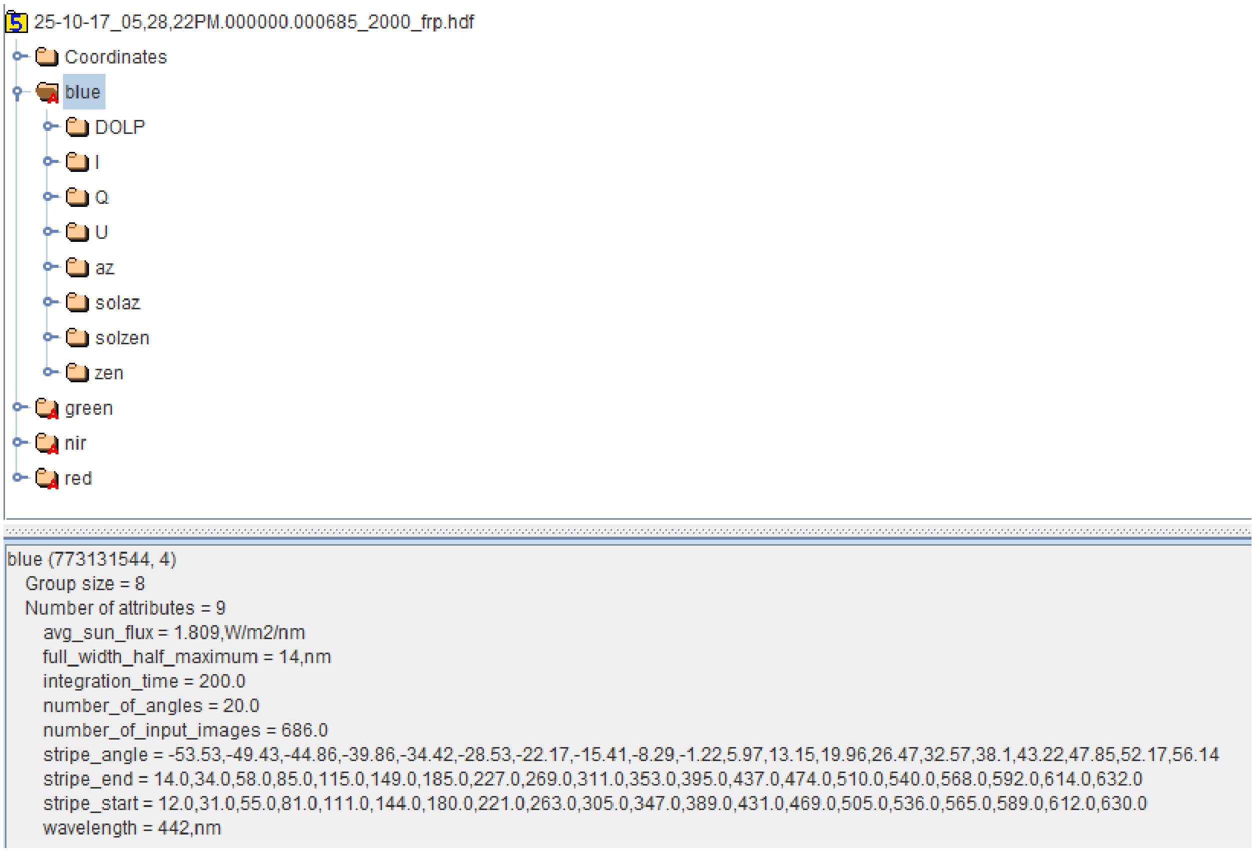

Figure 4. *AirHARP L1B HDF file structure, with blue internal master folder selected. Note the attributes listed in the bottom-half of the image, corresponding with the blue wavelength.*

Inside the blue internal master folder, the gridded and calibrated polarization fields are included: the degree of linear polarization (DOLP), and absolute Stokes parameters (I, Q, and U). The last four subfolders include information on the solar zenith (solzen), solar azimuth (solaz), viewing zenith (zen), and viewing azimuth (az) gridded fields.

Note in the attributes for the blue in the gray box of Figure 4, the equivalent square-band extraterrestrial solar irradiance (avg_sun_flux, W m^{-2} nm^{-1}), spectral bandwidth (full_width_half_maximum, nm), integration time (*0.1, msec), global viewing angle number density in the detector (number_of_angles), total number of acquired raw images in the dataset (number_of_input_images), and center wavelength (wavelength, nm). All other fields are for internal checking. Green, nir, and red internal master folders all have different values but similar structure to their attributes.

Figure 5 examines the internal structure of the DOLP Stokes parameter sub-folder.

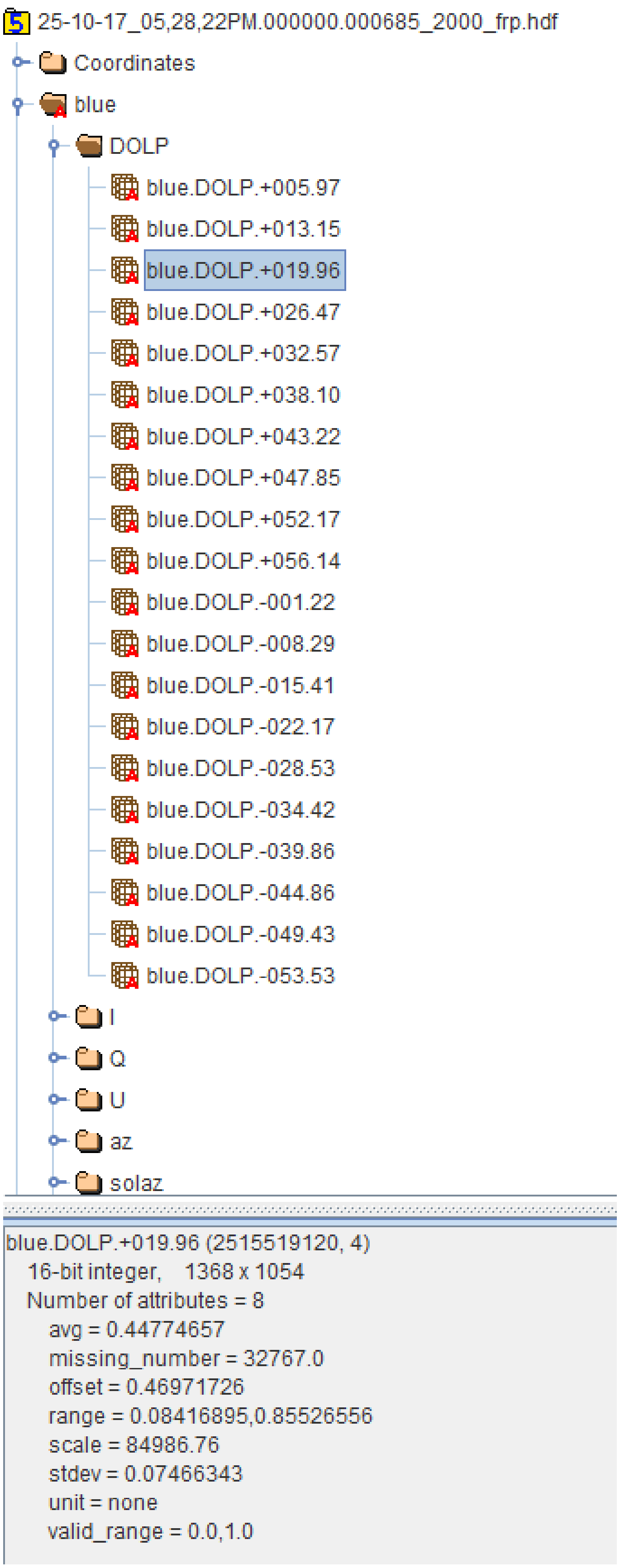

Figure 5 (left). *AirHARP L1B HDF file structure, with the DOLP measurement at the unique viewing angle +19.96° for the blue wavelength. Note the attributes listed in the bottom-half of the image, corresponding with this measurement matches the structure seen in Figure 3.*

Note here that in the blue DOLP subfolder, 20 unique data files, corresponding to the 20 blue global viewing angles in the detector, exist. Each are gridded, calibrated pushbrooms of the Earth scene at one particular viewing perspective.

The angle given in the filename corresponds to the viewing zenith angle of the pixel along the scan axis (along-track center line) of AirHARP for that observation: the **scan line view angle (SLVA)**. It does not represent the viewing zenith angle for all pixels in the image. Plus (+) and minus (-) characters before the angle signify the observation is toward the top of the detector (forward, +) or toward the bottom of the detector (aft, -). Angle values are relative to nadir (0°).

Absolute Stokes parameters I, Q, and U and geometry files have the same structure as the DOLP file folder. Each SLVA corresponds to unique Stokes parameter and geometry files. Note an SLVA for the blue wavelength is unique and will not be shared with green, nir, or red because it references unique rows of detector pixels; the same goes for SLVAs for other wavelengths.

Note that the green and nir internal master folders have the same amount of data as the blue master folder, as they sample 20 global viewing angle locations in the detector. The red internal master folder contains 3x as much information due to observations at 60 unique detector viewing angles.

Note that global data information is included in the attributes of HDF itself (i.e. flight altitude (meters), etc).